welded construction

QUALITY ASSURANCE OF WELDED CONSTRUCTION

SECOND EDITION

Edited by

N.T. BURGESS

Taylor & Francis
Taylor & Francis Group

Quality Assurance of Welded Construction

Second Edition

Quality Assurance of Welded Construction

Second Edition

Edited by

N.T.BURGESS
Managing Director,
Quality Management International Ltd,
Egham, Surrey, UK

ELSEVIER APPLIED SCIENCE
LONDON and NEW YORK

ELSEVIER SCIENCE PUBLISHERS LTD
Crown House, Linton Road, Barking, Essex IG11 8JU, England

Sole Distributor in the USA and Canada
ELSEVIER SCIENCE PUBLISHING CO., INC.
655 Avenue of the Americas, New York, NY 10010, USA

WITH 28 TABLES AND 61 ILLUSTRATIONS

First edition 1983

This edition published in the Taylor & Francis e-Library, 2005.

Second edition 1989

British Library Cataloguing in Publication Data

Quality assurance of welded construction.
—2nd ed.
1. Welding. Quality assurance
I. Burgess, N.T.
671.5′2′0685

ISBN 0-203-97580-4 Master e-book ISBN

ISBN 1-85166-274-X (Print Edition)

Library of Congress Cataloging-in-Publication Data

Quality assurance of welded construction/edited by N.T.Burgess—
2nd ed.
p. cm.
Includes bibliographical references and index.
ISBN 1-85166-274-X (Print Edition)
1. Welded joints—Testing. 2. Welding—Quality control.
I. Burgess, N.T.
TA492.W4Q35 1989
671.5′20423-dc 19 88–23523 CIP

Preface to the Second Edition

Since the first edition of this book, most developments have been with the quality assurance element of its contents rather than with the welding technology part.

Of considerable significance to all parts of the construction industry, not least the fabrication side, was the issue of the International Standards Organisation's document ISO 9000 series, which effectively set the same quality management criteria worldwide. In the UK, this was issued as BS 5750:1987, and the subject is addressed further in this book.

The development in industry towards greater quality assurance is very substantial and, whereas in 1983 assessment of a manufacturer's capability was mostly left to the clients, particularly the major ones, in 1988, a significant number of fabricators have sought recognition for their quality management arrangements by obtaining certification from an independent third-party body. Indeed, 1988 saw the launch of the industry's own QA Certification Scheme by the British Constructional Steelwork Association, with several successful registrations. This new scheme (details from BCSA, 35 Old Queen Street, London SW14 9HZ) has its own Schedule which translates the more general requirements of BS 5750 (ISO 9000) to the particular needs of the fabricator and his customer.

This scheme, almost unique in the world, augments the more general schemes available from the other certification bodies in the UK, the BSI and Lloyds Register Quality Assurance Ltd. This trend is likely to have an impact in Europe now that the plans for a single market by 1992 have been announced. Construction products and certification figure prominently in the legislation.

The objectives for this book remain the same, but the opportunity afforded by reprinting has been taken to include new authors, new material and new ideas. In particular, there are now two chapters on design, both by a well-respected contributor who offers sound advice from a background which spans fatigue research, and offshore and structural consultancy around the world. Chapter 2 embellishes the traditional role of welded products design by sound quality advice. The organisation and execution of good design work is discussed along with education and training aspects, sources of information, etc.

In Chapter 3, more specific advice is given by the same author relating to design concepts, detail design and the critical parameters to be considered if quality weldments are to result. The requirements of Design Review, addressed in ISO 9000, are covered.

The opening chapter, now entitled 'Fundamentals', reiterates the earlier precepts since many of those improvements required are still overlooked in the rush to get certification. The bumper sized chapter on quality in shop operation remains at the 'heart' of the book, containing as it does experiences and recommendations of a well-established welding engineer turned quality executive!

Similarly, site operations are covered in Chapter 5, now enhanced by the author's direct involvement with one of the most important welded structures of our times—the revolutionary concepts in the Hong Kong & Shanghai Bank building. The essential topics of defects and inspection have been reviewed, essentially to bring them up to date even though the topics and practices covered therein have changed little in the intervening years.

A new author for Chapter 8 on the critical subject of NDT has resulted in a new approach and some very valid observations and recommendations. Mr Mudge has crystallised for the reader the crucial arguments relating to design of joints for NDT purposes and the like, as well as reviewing, very thoroughly, all of the key NDT methods in the light of today's experiences. Of particular value is a very extensive list of references and a selection of international standards on NDT, nowadays a QA technique considered as an 'integral part of the fabrication process'.

The concluding chapter by Professor Rogerson brings the reader up to date with the relevant codes both in welding and in QA, although this scene is continuously changing.

The contributors hope that the extended coverage of the subject offered by the book will continue to benefit planners, spec. writers, managers, auditors and all those on the fringe of, but essential to, those principal people who have the responsibility for getting it 'right first time'.

N.T.BURGESS

Preface to the First Edition

The growing application of quality assurance both as a regulatory and contractual requirement and as a management discipline for the modern supplier has had significant impact on welding, the most important of the manufacturing processes.

At the same time, the uses of welding increase daily with the drive towards more economic construction for an ever widening range of industries. Problems with welded equipment still arise from a variety of causes, many of which are dealt with in this book. In the early days of welding both manufacturers and users were tolerant of fabricating and construction difficulties but this is no longer possible as the cost of failure, re-work and inspection increases. Further, the development of welding techniques themselves, the metals that can be joined and the range of thicknesses involved, have contributed more problems. There is a need to minimise at every point the influence of these factors on potential failure and on the avoidance of defects.

Quality assurance has developed as a total control concept without specific relevance to welding or indeed any manufacturing method, and it has demonstrated its value in maintaining and improving quality and safety standards, wherever possible in an economic fashion.

The object of this book is to bring together, it is believed for the first time, the basic principles and techniques of quality assurance in relation to a specific area of industry, tailored to a major construction method. It has, within the confines of one volume, been difficult to decide what to include and what to exclude and since quality assurance can be said to embrace design phase and metallurgical aspects, as well as construction practices, it has only been possible to concentrate on the cardinal issues and on some valuable ideas from the contributors. Whilst the basic concepts and procedures contained herein are applicable to any welded construction the authors have in general been drawn from the 'heavy' end of industry and therefore examples and case studies referenced relate thereto. This will be very relevant to those industries that typically use pressure vessels, pipework, process plant, bridges, mechanical handling and like structures. As such, welding is most evident in the context of metal arc, inert gas, submerged arc and related methods, although resistance spot welding, for example, amongst other joining techniques, is not discussed. Since both quality assurance and welding principles span international boundaries reference is made where possible to internationally used specifications and practices from several countries.

The authors selected for this work have together and individually a vast experience of the application of welding in many industries, particularly those now grappling with the application of quality assurance. They are authorities in their own right and their backgrounds cover the academic field, research, manufacturing, design and consultancy. The Editor's past spans the energy field including nuclear generation, the process plant industry and, more recently, the offshore oil and gas business. His opening chapter is intended to brief the unwary on some aspects of quality assurance that may not be apparent from the contract, the text books or indeed national standards.

It is generally accepted that up to 80 % of engineering problems are ultimately attributable to the design stage and in Chapter 2 Dr Jubb has provided some well-chosen examples of how welded design must take account of modern thinking and the latest knowledge. The author of the extensive coverage on manufacturing, Mr Gifford, had the benefit of working as a manufacturing welding engineer before becoming a QA manager and his insight into shop floor problems, particularly in the boiler and pressure vessels field, is extensive. Much welded work for the industries that form the basis of this treatise takes place at site, be it nuclear power station, oil refinery or gas pipeline, and to complement the workshop operations Mr Butler has provided direct experience of site practices with a bearing on quality assurance. A sound knowledge of the relevant artefacts is essential equipment for the practising quality assurance engineer and Dr Rogerson has succinctly reviewed the key information and commented on defect significance. This is particularly important in relation to acceptance criteria, which are discussed here and in other chapters. Inspection is the subject of many clauses in the national standards on welded plant and the author of this chapter has therefore limited his contribution to those aspects that have a strong bearing on quality assurance such as human aspects and qualification, referencing the techniques which are relevant.

The widespread use of non-destructive testing (NDE in many countries) has confirmed that when used correctly this is a major tool in assuring the quality of weldments. The emphasis in this chapter by Mr Jessop is not merely on techniques, as this can be studied from the textbooks, but on the limitations of the methods in relation to specific defects, and on the consideration of the scientific principles involved. Finally, since the core of a good QA programme rests on an understanding of what is considered ‘good practice’ between supplier and client, there is a review of standards and codes related to welding which highlights the strengths and weaknesses to which a QA man should address himself.

This then is a book about quality assurance in welding which indicates what is achievable and necessary rather than merely ‘How to make good welds’. As such the contributors hope that readers, whether they be quality engineers seeking a greater understanding of welding, or welding people faced with the needs of quality assurance, will be able to tackle their work more effectively.

N.T.BURGESS

Contents

List of Contributors

N.T.BURGESS

Managing Director, Quality Management International Ltd, Runnymede Malt House, Runnymede Road, Egham, Surrey TW20 9BO, UK

B.S.BUTLER

Viking-Ord Ltd, Clyde House, Spennithorne, Leyburn, North Yorkshire DL8 5PR, UK

A.F.GIFFORD

Executive Quality Manager, International Combustion Ltd, Sinfin Lane, Derby DE2 9GJ, UK

J.G.HICKS

Consultant in welded design and fabrication to the civil, structural and mechanical engineering industries, 35 Boxworth Road, Elsworth, Cambridge CB3 8JQ, UK

P.J.MUDGE

Head of NDT Section, The Welding lnstitute, Abington Hall, Abington, Cambridge CB1 6AL, UK

J.H.ROGERSON

Professor of Quality Systems, School of Industrial Science, Cranfield Institute of Technology, Cranfield, Bedford MK43 0AL, UK

1
Fundamentals of Quality Assurance

N.T.BURGESS

Quality Management International Ltd, Egham, Surrey, UK

INTRODUCTION

Once the satisfactory design of a product or construction has evolved, and been detailed and checked, there is a need to specify quality characteristics against which to produce.

The quality of manufactured products is frequently dependent upon the effectiveness of the manufacturer's control of fabrication, inspection and testing operations. In consequence, manufacturers are responsible for instituting such controls over operation, processes and checking, as are necessary to ensure that their products conform to the specified requirements. Today, manufacturers are also often obliged to provide objective, verifiable evidence that they have carried out all necessary activities. This means that a supplier is expected to supply not only products and services but, in addition, proof that the product has been properly made and tested. A measure of assurance can be gained by (the customer) ensuring that everything necessary has been done to achieve the required integrity of each characteristic of the finished product. Thus, 'quality assurance'!

QUALITY ASSURANCE: DEFINITIONS

The generally accepted definitions of quality assurance (QA) and related terms are based on those promulgated by the International Standards Organisation, who issued ISO 8402 in 1986:

(1) *Quality.* The totality of features and characteristics of a product or service that bear on its ability to satisfy stated or implied needs.
(2) *Quality assurance.* All those planned and systematic actions necessary to provide adequate confidence that a product or service will satisfy given requirements for quality.
(3) *Quality control.* The operational techniques and activities that are used to fulfil requirements for quality.
(4) *Inspection.* Activities such as measuring, examining, testing and gauging one or more characteristics of a product or service and comparing these with specified requirements to determine conformity.
(5) *Quality surveillance.* The continuing monitoring and verification of the status of procedures, methods, conditions, processes, products and services, and analysis of records in relation to stated references to ensure that specified requirements for quality are being met.

The issue of quality and quality activities has moved ahead since the publication of the first edition of this book in 1983. Most industrialised countries are party to the ISO series of standards ISO 9000, issued in 1987, which set down criteria applicable to any product or service. Welded constructions are no exception and, indeed, because welding remains such an important manufacturing tool it has always been subject to a great deal of attention in relation to welding quality. However, the emphasis in welding, as with other manufacturing processes, is now on the prevention of problems, rather than their detection.

Thus, quality management is now a normal part of the management process used increasingly to distinguish good companies from bad, and successful business from failure.

These basic definitions go to make up the subject of Quality Engineering—that branch of engineering which deals with the principles and practice of product and service quality, assurance and control.

A quality engineer may need to be qualified in some or all of the following aspects:

(1) Development and operation of quality assurance and control systems.
(2) Development and analysis of testing, inspection and sampling procedure.
(3) An understanding of the relationship of human factors and motivation with quality.
(4) Facility with quality cost concepts and techniques.
(5) The knowledge and ability to develop and administer management information, including the auditing of quality programmes to permit identification and correction of deficiencies.
(6) The ability to arrange appropriate analyses to determine those operations requiring corrective action.
(7) Application of metrology and statistical methods to the analysis of quality parameters for both control and improvement purposes.

THE BACKGROUND TO QUALITY ASSURANCE

Quality assurance concepts grew out of quality control which, in the stage of industrial development after the Second World War, became a necessity in many industries. In the USA the use of statistical techniques, particularly in the continuous production industries, telecommunications, etc., was a prime tool in measuring the performance of processes, men and machines. It was possible to predict the likely level of defects in a given situation and therefore attempt to prevent or reduce them. Quality control, as a management or production discipline, became standard practice in the USA and, later, in Japan, although application to ‘one off’ structures, power stations, oil refineries and the like was much slower. In many countries the development of quality control practices progressed through defence equipment to electronics generally, nuclear plants and conventional power stations and to many critical structures.

The incentive for manufacturers to reduce defects, and therefore costs, led to extensive development of quality control, except perhaps in those industries where the purchaser has traditionally taken some responsibility for quality control. In ‘one off’ and heavy engineering industries, often involving welded construction, customer inspection, or rather witnessing inspection, has been the convention and it is claimed by many that this led to minimum quality control efforts by respective manufacturers. This appears to be true when compared with industries supplying retail or consumer outlets, where market pressures forced a tighter control of quality aspects of the product. ‘Quality control’, as a tool for suppliers, therefore preceded ‘Quality assurance’ for customers. (Quality control has been used since the 1940s as a term to include all methods used to control quality, including inspection and non-destructive testing (NDT).)

‘Quality assurance’, on the other hand, is a term which has grown in the Western world mainly since the 1960s. The term connotes much broader concepts of quality and reliability achievement and involves action by, and responsibilities on, the purchaser/user. (The Allied Quality Assurance Publications (AQAPs) used by NATO are customer-produced requirements that formed the basis for many similar customer-related requirements.)

In welded construction, many aspects of controlling quality have been developed inherently or instinctively, e.g. the selection and use of correct and proven welding parameters. Indeed, resistance spot and similar automatic methods have always lent themselves to quality control—to the exclusion of individual weld inspection.

The extensive use of welding as the most important constructional method and the rapid developments in welding technology itself are two factors that have inevitably contributed to engineering quality problems. Other factors are the more onerous service required of many welded structures or components, the progressive reduction of safety margins and the use of more economic or conservative design criteria, as well as developments in materials to be welded.

Problems with welding, both during manufacture and in service (by way of failure), have led, over the years, to a tremendous growth in weld inspection (often on a 100% basis) by customers as well as manufacturers, as an obvious, although sometimes misguided, defence. Third party inspection (by the State, an approved body, or by inspection organisations) has flourished in most countries and in direct relationship to the increase in use of welding. This is especially noticeable in the heavy engineering sector, power plants, oil refineries, ship building and so on, particularly where pressure plant and other potentially dangerous equipment is being constructed. Unfortunately, much of this effort has been ineffective, or indeed counterproductive, and throughout this book there are indications as to how this situation can be improved.

Admiral Rickover, in his now famous 1962 address to the 44th Annual Metal Congress in New York, said ‘The price of progress is the acceptance of more exacting standards of performance and relinquishment of familiar habits and conventions rendered obsolete because they no longer meet the new standards. To move but one rung up the ladder of civilisation man must surpass himself.’ He followed with a catalogue of quality problems besetting the nuclear industry (particularly in nuclear submarines) at that time. The author believes that this paper was a turning point in the move towards quality assurance around the world, subsequently to be taken up in most technological industries and in many countries.

Some of the best publicised failures, such as that of the Kings Bridge in Melbourne in 1962, demonstrated a serious lack of quality control. Several pressure vessel failures during tests in the UK and elsewhere during the 1950s and 1960s had direct or indirect relevance to a lack of quality control.

Rickover also reported further on serious deficiencies in U.S. manufacturing practices: ‘During the past few years, hundreds of major conventional components such as pressure vessels and steam generators, have been procured for naval nuclear propulsion plants. Less than 10% have been delivered on time. 30% were delivered six months to a year or more later than promised. Even so, re-inspection of these components after delivery showed that over 50% of them had to be further re-worked in order to meet contract specification requirements’.

And again: ‘there are 99 carbon steel welds in one particular nuclear plant steam system. The manufacturer stated that all these welds were radiographed and met specifications. Our own [U.S.Navy] re-evaluation of these welds—using correct procedures and proper X-ray sensitivity—showed however that only 10% met ASME standards; 35% had defects definitely in excess of ASME standards and the remaining 55% had such a rough external surface that the radiographs obtained could not be interpreted with any degree of assurance.’

Serious failures and delays in the UK power programme due to poor quality control blighted the construction programme of the 1960s. Excessive failure levels in welds made by oxy-acetylene welding, by flash welding, at attachments to boilers, and with defective boiler tubes, as well as large turbine castings, were reported. Since the worst performance came from conventional power plant components rather than nuclear items, the initial corrective programme was in that sector. Major failures associated with welding have been experienced by most industries.

In recent times, so much has been learnt and applied that these failures and problems as mentioned above are rare. Pressures today stem from ‘economic’ factors—manufacturers can no longer afford to make defective goods, especially when competition from the international market is common. In addition, the growth of welded items in nuclear power stations, offshore structures, highways and bridges requires continuous attention to those elements of good practice that are implicit in the phrase ‘quality assurance’.

QUALITY ASSURANCE: A GROWING REQUIREMENT

Some of the reasons why quality assurance is required by purchasers and plant users are:

(1) The recognition that inspection and tests alone do not *prevent* defects—they may not even prevent them getting into service.
(2) No one can *inspect* quality into a product—it has to be designed or built in.
(3) It costs more to make defective welds than good ones, and someone has to pay for those defective goods.

Control of quality must be planned and organised, just like any other business parameter.

It is clear that, because of the nature of welding operations, inspection (including examination) and monitoring surveillance will be necessary. However, it is fundamental to quality assurance that ‘quality is best controlled by those responsible for the product and by those closest to the point of manufacture’. This must mean the supplier himself and not the purchaser. (This aspect is dealt with further in Chapter 7.)

This is particularly important today, since product liability concerns many countries and many industries. The responsibility for accidents resulting from poor quality design and manufacture is generally placed with the designer or manufacturer.

Whose Responsibility is Quality Assurance?

Basically, a quality assurance approach by an industry, a user or a supplier requires at least:

(1) A top management policy decision, followed through to line management.
(2) A quality assurance specification or programme identifying the ‘management’ criteria.
(3) An obligation to evaluate and audit control processes, procedures and instructions as a preliminary to quality control surveillance.

There is no single factor in the avoidance of failures in welded construction; many different factors may be involved, not only within a particular company, but outside, with suppliers, sub-contractors, customers, inspection authorities, etc. What can be achieved is a more disciplined approach to all quality related activities from ‘cradle to grave’ of a product or component. This includes the salesman who should not

TABLE 1

CROSS-REFERENCE LIST OF QUALITY SYSTEM ELEMENTS (FOR INFORMATION PURPOSES AND NOT AN INTEGRAL PART OF STANDARD)

Clause (or sub-clause) No. in ISO 9004	Title	Corresponding clause (or sub-clause) No8. in					
ISO 9001		ISO 9002		ISO 9003			
4	Management responsibility	4.1	●	4.1	◐	4.1	○
5	Quality system principles	4.2	●	4.2	●	4.2	◐
5.4	Auditing the quality system (internal)	4.17	●	4.16	◐	–	
6	Economics—Quality-related cost considerations	–		–		–	
7	Quality in marketing (Contract review)	4.3	●	4.3	●	–	
8	Quality in specification and design (Design control)	4.4	●	–		–	
9	Quality in procurement (Purchasing)	4.6	●	4.5	●	–	
10	Quality in production (Process control)	4.9	●	4.8	●	–	
11	Control of production	4.9	●	4.8	●	–	
11.2	Material control and traceability (Product identification and traceability)	4.8	●	4.7	●	4.4	◐
11.7	Control of verification status	4.12	◐	4.11	●	4.7	◐

Clause (or sub-clause) No. in ISO 9004	Title	Corresponding clause (or sub-clause) No8. in					
ISO 9001		ISO 9002		ISO 9003			
	(Inspection and test status)						
12	Product verification (Inspection and testing)	4.10	●	4.9	●	4.5	◐
13	Control of measuring and test equipment (Inspection, measuring and test equipment)	4.11	●	4.10	●	4.6	◐
14	Nonconformity (Control of nonconforming product)	4.13	●	4.12	●	4.8	◐
15	Corrective action	4.14	●	4.13	●	–	
16	Handling and post-production functions (Handling, storage packaging and delivery)	4.15	●	4.14	●	4.9	◐
16.2	After-sales servicing	4.19	●	–		–	
17	Quality documentation and records (Document control)	4.5	●	4.4	●	4.3	◐
17.3	Quality records	4.16	●	4.15	●	4.10	◐
18	Personnel (Training)	4.18	●	4.17	◐	4.11	○
19	Product safety and liability	–		–		–	

Clause (or sub-clause) No. in ISO 9004	Title	Corresponding clause (or sub-clause) No8. in					
ISO 9001		ISO 9002		ISO 9003			
20	Use of statistical methods (Statisticat techniques)	4.20	●	4.18	●	4.12	◐
–	Purchaser supplied product	4.7	●	4.6	●	–	

Key

● Full requirement

◐Less stringent than ISO 9001

○Less stringent than ISO 9002

– Element not present

NOTES

1 The clause (or sub-clause) titles quoted in the table above have been taken from ISO 9004; the titles given in parentheses have been taken from the corresponding clauses and sub-clauses in ISO 9001, ISO 9002 and ISO 9003.

2 Attention is drawn to the fact that the quality system element requirements in ISO 9001, ISO 9002 and ISO 9003 are in many cases, but not in every case, identical.

This extract from BS 5750: Part 0: Section 0.1: 1987 (which is identical with ISO 9000–1987) is reproduced by permission of BSI. Complete copies of the standard can be obtained from BSI at Linford Wood, Milton Keynes, MK14 6LE, UK.

give promises to the client, the metallurgist who is too often confined to the laboratory, and the client who seeks technological impossibilities.

It should also be recognised at the outset that such assurance has to be paid for, either from reduced scrap, by fewer repairs or by less routine inspection (see p. 154). This can be achieved if all parts of an enterprise, from chairman or managing director to the packer and despatcher, understand the importance of meeting quality objectives. These in turn must be spelled out in sufficient detail at contract stage, in the specification, or on the drawing. These elementary principles of quality assurance are explained in detail in specifications which most developed countries now have, or are developing (ref. 9 and Table 1).

The NATO Allied Quality Assurance Publications spell out the same principles which are largely based on the original U.S. Military Specification Mil-Q-9858a. The nuclear power industry has adapted the same principles.

Most standards refer to 18 separate criteria and Table 1, which is reproduced from ISO 9000, lists these.

Where to Start

Assuming that top management is committed to a quality policy and all of its obligations, certain initial steps would be sensible. A supplier must first determine where quality problems are occurring (using pareto analysis), e.g. design and specification, procurement, material, manu facture, inspection or site construction. Figure 1 illustrates an analysis of problem areas and presents the approximate situation according to one UK

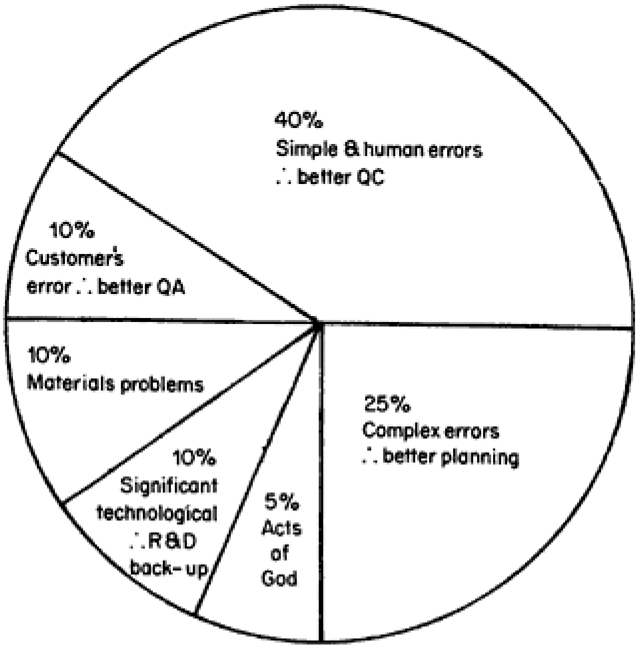


FIG. 1. Typical analysis of quality problem areas.

pressure vessel manufacturer. Discussions with other manufacturers in other industries around the world confirm this general picture.

The significance of the individual must be considered. Welding introduces particular problems, e.g. whilst designers and engineers are professionally qualified and trained, welders and operators rely more on personal skills. The results of these efforts are judged by others who may have inadequate training or experience to take the critical decisions required of them (see Chapter 7). Thus the skills involved in making successful weldments are as follows:

Designer	Professional training
Welding engineer	Professional training
Welder	Artisan skills
Welding inspector }	Decision maker
Non-destructive tester	

Therefore, the training elements of QA are clearly spelt out in system requirements.

The Purchaser's Responsibility

Most progress in obtaining and operating safe and reliable welded plant made to sound quality assurance principles has been in those industries where the purchaser has been wise enough to recognise the real benefits that accrue from a quality assurance policy. The obligations upon such purchasers are similar to those listed earlier, i.e. top-level commitment, a QA requirement or specification and the allocation of appropriate resources. Equally important, however, is the need for the purchaser to recognise that improvements in performance are worth paying for and that proper costing of quality aspects of the product (or project) are required. Thus, he should encourage suppliers to develop better quality practices, for example, by employing vendor rating, by favouring good performance and by using life cycle costing at the contract placing stage.

It is also important to recognise that poor customer documentation is a contributor to poor quality. Figure 1 shows how the poor customer QA is responsible for 10% of problems experienced by a typical heavy engineering fabricator.

TABLE 2
CONTROLS AND CHECK POINTS IN PRESSURE VESSEL CONSTRUCTION ACCORDING TO IIW COMMISSION IX WORKING GROUP ON QUALITY ASSURANCE[a]

Controls	*Number of check points*
Examination of plans and calculations	6
Receipt and control of base materials	20
Receipt and control of consumables	20
Qualification of welding procedures	30
Qualification of welders	23
Control of work preparation before welding	4
Control during welding	15
Control after welding	20
Control of heat treatment	20
Final tests	6

[a] From a review by the International Institute of Welding Commission on Pressure Vessds (Working Group on Quality Assurance).

Management's Responsibility

It is now generally accepted that the majority of errors and faults in engineering may not be the result of human error, but of poor management (see below).

Most textbooks on QA and analyses of actual problems suggest that features such as 'lack of proving' and 'inadequate specification' are management's responsibility. Of course, lack of planning and poor communication also fall in the 'management area'. It is significant that in the ISO standards 'contract review' is an important addition that rarely appeared in national standards from earlier times.

The list below indicates some root causes identified by 20 quality assurance managers, both purchasers and suppliers, following a survey conducted by the author:

Pressure of production over quality

Lack of authority of quality personnel

Lack of clear QC systems

Inadequate in-process/final inspection

Poor manufacturing equipment

Inadequate briefing on specification/lack of understanding

Inadequate direction, poor management, poor control

Disinterested workforce

Poor control of sub-contractors

Lack of day to day QA implementation

Middle management apathy

Poor customer specifications and contractual requirements

Poor QA staff

Belief that quality costs money

The Designer's Responsibility

The inclusion of two chapters on design in this book emphasises the importance of design quality assurance. Detailed examination of failures, including weld failures, suggests that some 80% originate at the design stage, or at least the failure could have been avoided by action at the design stage. Design, in this context, includes material selection, and design detail as well as conceptual design and adequacy of specifications. Of particular importance in design assurance is inspectability, i.e. can the weld be inspected both during construction and during later maintenance checks? One of the techniques of QA utilised at the design stage is design review. Design reviews are systematic critical studies of the design or its elements at various stages by specialists not necessarily directly engaged in the design, to provide assurance that the final design will satisfy the specifications. The factors considered at such a review might include:

(a) comprehensiveness of design inputs;
(b) adequacy of assumptions used;
(c) appropriateness of design methods;
(d) correct incorporation of design inputs;
(e) adequacy of the output;
(f) the necessary design input and verification requirements for interfacing organisations, as specified in the design documents, or in supporting procedures or instructions.

Reviews may be performed at the various stages of the design process (e.g. conceptual, intermediate or final) and may be performed by persons drawn from various disciplines (e.g. engineering, design, manufacturing, quality assurance, marketing, financial, personnel or legal) as appropriate to the product or the state of the design. Prior to the design review, a check list of topics to be considered should be established. Chapter 2 deals more fully with the work of the designer.

Quality is Everyone's Responsibility

nce, the elementary requirements of QC/QA can be expressed:

QA {

QC {

Plan what you do (written procedures)

Do what you say	(practice)
Record that it has been done	(records)

THE ECONOMIC ASPECTS OF QUALITY

Too often, quality assurance only emerges as a policy issue when governments, users or traumatic situations force managements to consider that which should be a standard business discipline. Of course, the degree to which QA is applied will vary from industry to industry. The factors to be considered in following a QA policy may include the following:

For the Supplier

Does the purchaser have a QA requirement or policy?
Will he enforce this in his procurement of plant and equipment?
Does our company want to be in this business?
Will our management support and fund it?

For the Purchaser

Is the industry generally committed to QA?
Do the contractors and suppliers understand QA?
Do I have the necessary detail in my engineering and purchasing specifications?
Am I prepared to accept all of the obligations of a QA programme?

These and other questions must be asked because, as with other business activity, success depends on commitment. Too often, quality assurance is accepted as a necessary evil, or to obtain a particular contract, or to be on an ‘approved list’, without proper commitment from those whose efforts will determine success or failure.

The economic motive is strong, and it is not difficult to see why some purchasers call up quality assurance as a major platform in its defence against:

(1) costly outages and unplanned shutdown due to premature failure;
(2) serious manufacturing and construction delays;
(3) government safety or environmental legislation;
(4) high cost of replacement or repair;
(5) inefficient suppliers.

Suppliers take up quality assurance to:

(1) Reduce scrap, repair, rectification and wasted time.
(2) Ensure customer satisfaction.
(3) Meet statutory or contract requirements.
(4) Keep one step ahead of the competition.
(5) Improve efficiency and cost effectiveness.
(6) Reduce customer inspection visits and customer interference.

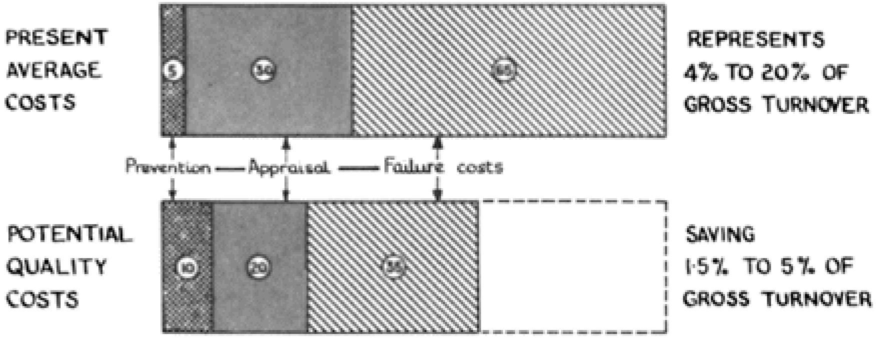


FIG. 2. Investment in prevention reduced failure costs.

It must be understood that effective quality assurance is a ‘two-way’ function between supplier and purchaser, and that shallow QA systems entered into with inadequate discussion between the contracting parties are often wasted effort costing a great deal of money.

Many major users devote financial and management resources to quality assurance because of the high costs incurred when situations noted earlier occur. The power industry quotes costs up to £40000 for each day that high merit plant is out of service, and other similar process plants incur similar costs.

The defence industry measures failures in other terms. In all industries, welding is a predominant element and it is not surprising that weldments are involved in failures.

Quality Costs

For the supplier quality costs can be divided into:

(a) *Prevention costs*—the cost of any action taken to prevent or reduce defects and failures.
(b) *Appraisal costs*—the cost of assessing the quality achieved.
(c) *Internal failure costs*—the costs of failure to meet quality requirements prior to the transfer of ownership to the customer.
(d) *External failure costs*—the costs of failure to meet quality requirements after the transfer of ownership to the customer.

Investment in prevention and appraisal can substantially reduce internal and external failure costs (Fig. 2). Furthermore, reductions in external complaints are important not only in reducing costs, but also to maintain customer goodwill.

The British Standard Guide to Quality Related Costs suggests the following groupings for the various items of cost, and the headings can readily be adapted to the specific case of welding:

Prevention Cost

(1) Quality engineering

  (i) quality control engineering

(ii) process control engineering

(2) Design and development of quality measurement and control equipment.
(3) Quality planning by other functions.
(4) Calibration and maintenance of production equipment used to evaluate quality.
(5) Maintenance and calibration of test and inspection equipment.
(6) Supplier assurance.
(7) Quality training.
(8) Administration, audit and improvement.

Appraisal Cost

(1) Laboratory acceptance testing.
(2) Inspection and test (including ‘goods inward’).
(3) In-process inspection.
(4) Set-up for inspection and test.
(5) Inspection and test material.
(6) Product quality audits.
(7) Review of test and inspection data.
(8) Field (on-site) performance testing.
(9) Internal testing and release.
(10) Evaluation of field stock. and spare parts.
(11) Data processing inspection and test reports.

Internal Failure

(1) Scrap.
(2) Rework and repair.
(3) Troubleshooting or defect/failure analysis.
(4) Re-inspect, retest.
(5) Scrap and rework—fault of vendor—downtime.
(6) Modification permits and concessions.
(7) Downgrading.

External Failure

(1) Complaints.
(2) Product or customer service.
(3) Products rejected and returned.
(4) Returned material repair.
(5) Warranty costs and costs associated with replacement.

CLASSIFICATION OF WELDED JOINTS: A KEY QUALITY ASSURANCE STEP

The International Standards Organisation Technical Committee—Welding, has proposed that the factors to be considered by the designer in fixing the service requirements for each welded joint in a construction are:

(a) the degree of certainty which must be obtained that the joint will perform satisfactorily for its design life;
(b) the consequences of failure;
(c) the factors influencing the performance of the joint.

The joints can be categorised into the highest service requirements: Type 1 where joints are under 'most severe conditions and/or the failure of which would have any catastrophic consequences', down progressively to Type 4 for 'joint under non-critical conditions, the failure of which would not affect the efficient performances of the construction as a whole'. This subject has been a topic for countless committees, both national and international. The International Institute of Welding, Commissions V, XI and XV, has debated the subject and its journal *Welding in the World* contains many papers and surveys on the subject. This is because, as is shown elsewhere, the costs of inspection, including NDT, can outweigh the costs of welding and, since the amount of inspection is directly related to the classification of welds, the amount of inspection, the stages of inspection and the methods of inspection should be determined as a result of a detailed study of factors, generally termed 'influencing factors'. Often, as in the past, we resort to a 'code'—it is to be hoped that code writers have studied the work and papers on the subject.

The best approach to quality assurance comes from a sound understanding of technical factors, and nowhere is this more important than in welding. It could be argued therefore that quality assurance procedures should be based on such knowledge and considerable guidance given in ISO document 3088 (1975), Factors to be Considered in Specifying Requirements for Fusion Welded Joints in Steel.

The quality control procedures, including process controls, design checks, inspection, etc., should take account of such factors as:

Materials (Parent and Filler)

Chemical composition, homogeneity, surface condition, thickness, etc.

Property and size of the heat affected zone.

Compatibility of weld metal.

Properties of the weld metal.

Welding Processes and Procedures

Must be compatible with the materials.

Differences between shop and site welding.

Profile and finish may be affected.

Heat inputs from different processes may be critical.

Stresses

Facts of fatigue must be understood.

Stress concentration factors depend on type of joint geometry, defect direction and orientation.

Residual stresses.

Fillet weld configuration.

Geometric Effects

Distribution of stresses should be disturbed as little as possible by joint geometry.

Avoid severe changes in section.

Junction of thick to thin sections require special consideration.

Environment

Joints subject to corrosive or erosive environments, geometry, protective coatings, etc., require consideration.

Specifications, both for welding and quality control require that these, and all other relevant features are incorporated. Design review will ensure that they have been considered.

HUMAN FACTORS IN QUALITY ASSURANCE

Perhaps the most important factor in quality assurance is the human one, partly because its effects permeate design, manufacture, inspection and operational stages.

Further attention is given to this aspect in Chapter 7, but those characteristics that must be recognised, particularly by quality assurance managers onto whom much of the responsibility for an organisation's quality system falls, are: cutting corners, boredom, fatigue, ignorance, lack of training, ambiguous instructions, poor communications, weak supervision, failure to obey rules, concealment of mistakes, personal unsuitability for given task, carelessness and a measure of arrogance.

It will be clear that, whilst some of the factors listed above are difficult if not impossible to control, others can form part of the training programme for individuals whose work will be seriously affected by particular deficiencies, or for individuals who have displayed weaknesses. However, much can be overcome by better instructions and procedures, by management and supervisor motivation, and by audits to determine adequacy of procedures and adherence to instructions.

QUALITY AUDITS AND SURVEILLANCE

No book on quality assurance would be complete without some reference to auditing, since this aspect remains a key element of a quality assurance system in the field of welded construction.

A suitable definition of quality audit is 'a systematic and independent examination of the effectiveness of the quality system or of its parts'. An audit is a a prime method of obtaining factual information from an unbiased assessment of objective evidence rather than subjective opinion. It can relate to products, processes (e.g. welding) or organisations. It

DATE/TIME	TOPIC	
	Pre-audit conference—scope, agenda	
Audit of management, design and procurement	Audit of manufacturing, assembly and test	
	Quality assurance programme	Manufacture planning
Planning and reporting		
Internal and external	Receipt inspection area	
Audit files	Material stores area	
Corrective action	Material handling	
Design control	Process control	
Document control	Assembly and test area	
Procurement control	Inspection	
Records system	Test control	
Personnel training and qualification	Non-conformance control	
	Calibration Records	
Post-audit conference—findings, agreements, commitments		

FIG. 3. Typical agenda for a comprehensive suppliers audit (from Sayers and Macmillan [15]).

generally includes an evaluation of the suitability of the requirements as well as compliance with them.

The effectiveness of audits depends on the co-operation of all parties concerned, and its objectives should not be confused with routine inspections and surveillance activities. Figure 3 shows a typical agenda for a comprehensive supplier audit.

As an example of what can be included in a quality system for welded pressure vessels, the work of Commission IX of the IIW can be cited. They appointed a working group which has identified the controls and checks to be used as part of quality assurance (see Table 2).

As noted earlier, quality surveillance is the supervision of a contractor's quality assurance organisation and methods, generally as set out on his quality system, his programme or his quality manual.

Some of the factors to be considered by a purchaser when developing a surveillance strategy with a particular contractor are given below. An assessment (or audit) against these features will identify weaknesses which must be the subject of special action during surveillance.

FACTORS TO BE CONSIDERED IN PREPARING A QUALITY ASSURANCE PROGRAMME

Plant Item Criticality (See Classification of Welded Joints)

Identification of statutory or regulatory requirements.

User experience of plant and operational problems.

Performance Capabilities of Contractor

Supplier facilities records.

Supplier performance records.

Supplier evaluation reports.

Contract Planning and Engineering

Review of contract specification requirements.

Review special customer requirements.

Examine programme control proposals.

Examine design/engineering proposals.

Examine work instructions, standards, drawings, etc.

Monitor design change and concession controls.

In-house Manufacture, Inspection and Test

Material verification.

Processes examination review and approval.

Personnel examination review and approval.

Monitor contractor's control of manufacture, inspection and test.

Inspections and tests during manufacture.

Final inspections and tests.

Purchasing and Sub-contracts

Review of proposed/selected sub-contractors.

Examine technical content of sub-orders.

Examine contractor's proposals for control of sub-contracts.

Monitor contractor's control of sub-contracts and press for improvement where appropriate.

Surveillance of sub-contracts.

Site Erection and Commissioning

Review of proposed site erector.

Monitor material handling, storage and control.

Monitor site manufacturing processes.

Monitor site assembly and erection; stage final inspection and test.

Assist during commissioning and setting up of work.

In the chapters that follow, many of the above concepts and practices will be discussed in greater detail.

REFERENCES

1 . European Organisation for Quality Control, Glossary of Terms, 6th Ed. EOQC Berae, Switzerland, 1986.

2 . Allied Quality Assurance Publications, available from Government Offices of NATO (Defence Department).
3 . Rickover, Admiral, Quality—the never ending challenge. Paper to 44th Annual Metal Congress, 1962. ASTM, Philadelphia, USA, 1963.
4 . A Report of the Royal Commission on the Failure of Kings Bridge, 1962. State of Victoria, Australia.
5 . Brittle fracture of a thick walled pressure vessel. *BWRA Bulletin,* June 1966.
6 . Report on the Brittle Fracture of a High Pressure Boiler Drum at Cockenzie Power Station. Report of the South of Scotland Electricity Board, January 1967.
7 . Burgess, N.T. and Levene, L.H., The control of quality in power plant—a large user's campaign against manufacturing defects, Paper 12, Inst. Mech. Engrs. Conference, University of Sussex, 1969.
8 . *Health and Safety At Work Act* (particularly Section 6). HMSO, London.
9 . International Standards Organisation Technical Committee, TC-176. Refer to national standards organisation of particular country.
10 . Belbin, R.M., Quality Calamities and their Management Implications. OPN8, British Institute of Management, 1970.
11 . Burgess, N.T., The development of quality assurance in major engineering projects. Paper to Institute of Quality Assurance World Conference, London, October 1980.
12 . BS 6143: 1981, Determination and Use of Quality Related Costs, British Standards Institution, London.
13 . Document 3041, 1975.
14 . Document 3088, 1975.
15 . Sayers, A.T. and MacMillan, R.M., Auditing the quality systems of suppliers to the CEGB. *Quality Engineer,* **37** (7/8) (1973).

2

Quality Management in Welded Product Design

J.G.HICKS

Consultant, Cambridge, UK

INTRODUCTION

The design of a successful welded product requires a greater understanding of the fabrication process by the designer than is required for most other manufacturing processes. The reasons for this are that the act of welding fuses the two parts irrevocably, and changes the metallurgical structure of the material local to the joint in a way which can render its performance inferior to the parent metal in a number of ways. In addition, the configuration and distribution of the welded joins within the product can affect the manner in which the welding can be done and has implications in terms of distortion. The selection of materials for the welded products requires an attention to the means of welding them so that the material and the joining process are compatible.

These points, taken individually or together, carry the inference that the method of fabrication has to be considered as a constraint in the design activity, so that compromising changes do not have to be made prior to fabrication.

This chapter sets out the features which need to be established in the organisation and execution of design, particularly, but not necessarily uniquely, for welded products. The ease with which these features can be implemented will vary depending on the nature of the product but, more strongly, on the type of manufacturing organisation. In a company which designs and makes it products on one site there can be ready communication across the design and fabrication interface. Where the product range does not vary greatly and standard specifications are used it should be possible for design procedures to reflect very closely the restraints imposed by the process of welding. The opposite situation to this is where a one off design is executed in an office which is geographically remote from the manufacturing site, and where the manufacturing organisation is not the same one as that executing the design. Civil or structural engineering projects are examples of these, including bridges, power stations, offshore platforms and hydropower schemes. In many parts of these projects the engineer prepares a design which is then extended in detail by the contractor.

What then is the strategy that a company should adopt to ensure that quality of welded design is such as to respond to the customer's specification's or expectations? Within the formalised systems referred to in Chapter 1 one would expect to see attention to the matters discussed in the following sections of this chapter. For simplicity of explanation, a design office is assumed to be totally concerned with welded construction; for those who are not it can be taken to apply to any section, group or other unit.

EDUCATION AND TRAINING

Within the conventional practices of a design office the use of welded joints requires specific attention to the creation of an awareness on the part of personnel of the subject of welding and associated technologies; provision of relevant technical information is required to support this awareness. The degree to which this has to extend throughout the design office will depend on the nature of the product. If only a small self-contained part of the product is to be welded then it will be sufficient for the specialist group dealing with that item to be aware of the implications of welded construction. However, where the great proportion of the product is welded a general level of awareness must be in evidence and supported, if thought necessary, by a specialist, or at least a member of staff with particular responsibility for matters relevant to welded construction.

The Quality Manual should include a statement on education and describe how the following requirements are implemented.

‘All design office technical staff are to have attended a course giving an overview of welding and associated technologies.’

The course material should include:

Basic strength of materials and metallurgy

Principles and practice of welding processes

Engineering performance of welded joints

Fabrication methods, including weld preparations

Distortion and residual stresses

Origins and nature of weld defects

Methods of non destructive testing

The scope of such a course should be relevant to the company’s products; for example, if nothing but steel were used then that would be the only material considered. If the company made only products which were statically loaded then fatigue need not be introduced.

Such courses are offered by a number of institutions, firms or individual consultants. Some which are publicly advertised may well fit a company’s requirements, in which case staff will have to be sent away for a one- or two-day course. An alternative is to have the course presented ‘in house’, the benefits of this being that the material can be tailored to fit the company’s own interests. Depending upon the number of personnel, this may be cheaper or more expensive than the standard course, against which there is no cost of staff travel and subsistence. With such a short course there is no opportunity for examination of the student’s assimilation of the material, and one has to accept that there will be a variety of benefit depending on their previous knowledge and general motivation. The knowledge gained on such short courses is easily forgotten unless it is reinforced by immediate regular usage or top-up sessions by more experienced company personnel or external consultants.

There are a number of textbooks and monographs on the market and, provided that they are chosen carefully to meet the needs of the office, they can be of considerable value. In addition, an extensive range of educational material is available on videotape; this is more easily assimilated than book material and, if available on loan, tapes tend to be more up to date than purchased books. (Beware! Not all films and tapes are recent productions, and advice should be sought from the lender.)

Depending on the size of the company or project, it may be beneficial to employ an in-house specialist or a part-time consultant who will then take charge of all matters connected with welding and, at the same time, act as an adviser to the design office in general. An historical source of quality assurance engineers has tended to be the fabrication industry, and one finds many such people working under two hats, those of quality assurance engineer and welding engineer. This is not really a sound practice as the two responsibilities may clash, and the benefits in the long run may not match the apparent cost effectiveness of this position. On the other hand, the business of welding requires so strong an interface between the fabricator and the designer that the best quality assurance engineer might well be one with a welding background.

INFORMATION

Sources

On an operating level, it has to be acknowledged that most designers obtain their information about the design of welded products from standard specifications. This is not really their purpose, and may even be dangerous if the specification is not matched to the job in hand.

The maintenance of an up-to-date technical library is vitally important to the quality of design; the procedures by which this is done should be within the scope of the attention to quality assurance. It requires co-operation between the engineer and the librarian to identify relevant material and then make decisions as to which should be purchased or borrowed. In general, the librarian will have access to the newsheets published by the standards bodies, which will identify amendments to existing standards and announce new ones. The engineer should also get to know of changes or new material from his professional institution, client's demands and his own professional contacts. Putting these sources together should provide a coverage which, if properly exploited, will ensure that up-to-date technical information is always available and, equally important, that obsolete material is withdrawn, although not necessarily thrown away.

External sources of information and advice are available in a number of forms, and most countries have a national welding institution which will provide information and advice, although in some cases this service may be available only to subscribing members.

Data Bases

In the context of this chapter the phrase 'data base' is used to mean a stored and verified collection of parameters which can be retrieved and used in engineering design work. It may comprise specific data, such as the results of soil investigations for use in designing foundations for a building, or it may be an oil company's analysis of the product of a well. Other types of data are more general in their application, such as the properties of rolled steel sections or the fatigue strength of weld details.

An important consideration of all data bases is that they must be secure. This is not too much of a problem if they are held as printed documents; any interference with these is easily spotted and the choice of the correct data can be made by identifying the appropriate sections from their titles. However, the position is not so clear where computer facilities are used. The usual security systems employing passwords may well be sufficient to protect the data once stored, but it is most important that the input to the data base is checked and that any authorised amendments are correctly made. This may well require a special procedure incorporating checking facilities. It is equally important to check purchased information on tape or disk either by examining it or by running it in a calibrated program.

FIG. 1. Beam sections.

Validity of Data

Much of the data developed for the design of welded products, such as fatigue life of weld details or fracture toughness requirements for parent or weld metal, has been reduced from experimental results and does not represent scientific abolutes such as specific heat or viscosity. The results have been assessed quite properly by specialists and, for the convenience of design practice, have been reduced to simple lines or just numbers. Naturally, where there has been a wide difference in the results for the same condition a conservative view has been taken, again quite properly.

Sometimes the data has been derived for a particular product and incorporates influences which may not occur in other products.

Two reservations must then be expressed, of which the first is that data for one product should not be taken and applied to another without understanding the potential sources of discrepancy which could lead to an unsafe or uneconomic design. The second reservation is on any limitations in application which are not explicitly stated in the data, and this can be detected only by the user of the data having a sound understanding of its derivation.

An example is to be found in the fracture toughness requirements for pressure vessels and storage tanks, BS 5500 and BS 4741. BS 5500 appears to be less demanding than BS 4741 for Charpy test properties, as indeed it is. However, the reason for this difference is that in BS 5500 pressure vessels have to be proof tested before use. This has been shown to improve the resistance to brittle fracture, and so a lower fracture toughness can be initially accepted compared with storage tanks, for which proof testing is usually impracticable.

Another example is in the fatigue data in BS 5400 for welded steel details in bridges. These have been derived from a large number of test results. The S/N curves do not represent the lowest performance measured in the test; indeed the curves (actually straight lines in the log-log plot used) have been based on a statistical analysis and then rotated so that they give a continuously graded set of curves. As a result, if a large number of similar details were designed on the basis of these curves a small proportion of the details (around 2·5%) would be expected to crack before the fatigue life were reached.

DESIGN EXECUTION

Engineering Formulae

Most engineers are brought up to have implicit faith in formulae such as the engineer’s theory of bending:

$$f/y = M/I = E/R$$

This does not actually work for any section which does not have the flange material concentrated on each side of a web which itself has no bending stiffness; for compact rectangular sections it can be erroneous, yet it is always used as if it were of limitless validity:

FIG. 2. Pictorial view of the fillet weld.

That it has never been systematically shown that its invalid use has resulted in failure may be that all the other inputs are so variable that there is no pattern attributable to the one invalidity. More specific evidence has been derived for the formulae used to predict stresses in tubular nodal joints, particularly for offshore platforms. A study has shown that the so-called parametric formulae which have been used in the design of many offshore platforms can predict stresses which range from five times to only a half of the measured values, which themselves can vary between nominally similar joints.

However, there are other sources of variation which have been identified, so that on the basis of design calculations one cannot say that the structures as designed are inadequate. It can be said that there is a level of unreliability in such design formulae. These formulae have been derived for design and so have a built-in conservatism which should be acknowledged if it is required to predict actual performance using a so-called 'realistic' analysis rather than a conservative one.

Recognition of these intricacies is important to the quality of the engineering design and is acquired through attention by senior engineers to the basis of the calculation methods.

Indicating Welds on Drawings

The engineering drawing is the primary means of communication between the designer and the fabricator. The comprehensiveness and clarity of the drawings must then contribute to the achievement of quality. The level of detail which can be shown on the drawing depends on the nature of the product and, as was shown earlier, it may be that the designer's drawings are added to by the fabricator to reflect his own practices.

Welds may be shown on drawings in a pictorial form with descriptive text, e.g.:

This is suitable for very simple items but soon becomes unwieldy and ambiguous in more complex assemblies. It is then more effective to use one of the standard sets of symbols, e.g. BS 499, AWS A 2·4 or ISO 2553.

The designer's responsibility includes the definition of the type of weld as a butt weld, fillet weld, etc., by the form of the symbol. For fillet welds the size is a necessary piece of information unless it truly is of no consequence to the performance of the product; in that case a note should be made to that effect so that it is clear that the choice of the size of weld lies with the fabricator, but in the end the designer should approve the choice as the only authority for the performance of the item.

The details of the way the welds are made may in some circumstances be left to the fabricator, who will choose or compile a welding procedure which may then be identified on the weld symbol, as will non-destructive testing if required. However, there are situations where the detail of the weld affects the performance; an example is under fatigue loading where the fatigue life of a butt weld transverse to the direction of stress will depend strongly on matters such as the presence or absence of a backing strip and whether the weld is made from one or both sides. In that case it is clear that the design drawing must define the type of weld in some detail.

Whether the edge preparations are considered part of the design information will depend on the nature of the component and the design and manufacturing organisation. To some extent the method of edge preparation will influence the approach: it is convenient for parts to be machined to be fully detailed on the design drawings with edge preparations; parts which will be flame cut in the fabrication shop will probably be adequately described in the shop drawings and not the design drawings.

To obtain consistency a design office should include in its written operating procedures a full description of the system to be adopted in calling up welds on drawings. The document control system should also include an appropriate distribution system so that inputs are obtained from specialists as required. Chapters 4 and 5 show how this subject is handled by the fabricator.

WELD QUALITY STANDARDS

If weld quality is to mean anything it must have a rational basis; unfortunately, such is not the case in most industries. Many industries do not recognise that it is necessary to specify weld quality at all, and many specify an arbitrary set of standards borrowed from another industry. A few use levels of quality originally established as what could be expected from good workmanship, and which have been shown by experience to give products which do not fail under normal operating conditions. Such levels of quality are frequently higher than is strictly necessary for the product to perform satisfactorily, and represent levels to which the fabricator can control the welding processes. They do as a result lead to rejection and repair of welds which, for their duty, are perfectly satisfactory and in which the repair, made in less favourable conditions than the original weld, can actually be damaging to the integrity of the product.

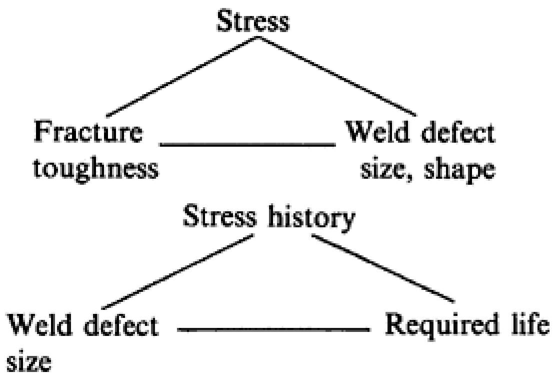
There is nothing wrong with producing welds to a higher quality than is necessary, provided that it is not excessively costly and that other characteristics are not thereby compromised. What is of concern is that failure to recognise the significance of weld quality by a designer may reflect a general ignorance about the performance of welded joints, which may in the extreme result in products incapable of being suited to their function. Many designers abdicate their responsibility by default to the fabricators, to whom they attribute wisdom capable of being applied beyond their contractual responsibility.

In the interests of product quality it behoves every chief designer to review his products in the light of the effects of weld quality and set out, with the help of external assistance if necessary, a policy on weld quality standards. This might only be a one off exercise, but it would demonstrate how the designer could respond in a situation where product liability was under test.

In the more sophisticated industries an approach under the title of Fitness for Purpose has been pursued for a number of years, in which the aim is to define rational requirements for design based on the actual needs rather than achievable targets. In this approach, weld quality standards are derived on the basis of a procedure known as Engineering Critical Assessment, in which weld quality requirements reflect the material properties and the service requirements.

One application of this type of analysis is in deriving fracture toughness requirements for weld metals and heat affected zones, to avoid the occurrence of a brittle fracture. For a brittle fracture to occur there needs to be a value of the local stress field, called the stress intensity, greater than a critical value which is a function of the fracture toughness of the material. This stress intensity is itself a function of the size and shape of a stress-concentrating feature such as a crack and the level of stress applied across this crack. In essence, then, there are three parameters involved, and the knowledge of any two permits the derivation of the third. This can be illustrated in a simple diagram of inter-related criteria:

This approach requires reliable information on the three parameters, and is therefore capable of being applied at various levels of detail.



An analogous approach is used for the assessment of the fatigue life of welds with defects such as cracks. Again, stress intensity is a parameter, and the other two are the stress history and the life in terms of the number of stress cycles:

SPECIFICATIONS

A specification is a written description of a product, accompanied by drawings as necessary, in as much detail as is considered essential to its proper definition. The specification may be prepared by the customer or the supplier; it may be one especially prepared for the particular product or it may be a standard specification from an industry, national or international series. Specifications may be written separately for the design and manufacturing phases.

Once accepted as part of the contract, the specification is a prime, legally enforceable, document which defines the product and is therefore the basis of all quality requirements. Any omission or ambiguity in the specification can have serious effects at any stage in design and manufacture, and so it is necessary that it be carefully studied during the contract review referred to in Chapter 1. For welded products, the following type of information should appear in a specification:

A specification of the materials or a basis for their selection.

The basis of welded joint performance, e.g. fatigue.

Properties required of welded joints.

The manner in which these properties are to be demonstrated.

Weld and material defect acceptance standards.

Type and extent of non-destructive testing.

Any restriction on the choice of fabrication methods, including welding processes, post-weld heat treatment, control of distortion, consumables and repair techniques.

Dimensional tolerances.

Standard Specifications

A number of standard specifications and codes of practice exist for products made by welding, and there are supporting detailed specifications encompassing welding procedures, consumables and non-destructive testing. The following is a list of some of the more commonly used documents published in the English language:

British Standards

BS 5400	Steel, concrete and composite bridges
BS 5950	Structural use of steelwork in building
BS 2573	Rules for the design of cranes
BS 5500	Unfired fusion welded pressure vessels
BS 2654	Vertical steel welded storage tanks with butt welded shells for the petroleum industry
BS4741	Vertical cylindrical storage tanks for low temperature service
CP 118	Structural use of aluminium
BS 5135	Arc welding of carbon and carbon-manganese steels
BS 4360	Weldable structural steels
BS 1501–6	Steels for fired and unfired pressure vessels
BS 4449	Hot rolled steel bars for the reinforcement of concrete
BS 4461	Cold worked steel bars for the reinforcement of concrete

U.S. Standards

AWS D1.1	Structural welding code
API RP 2A	Planning designing and constructing fixed offshore structures
ASME	Boiler and pressure vessel code
ASTM	Annual book of standards (materials)

There are also national standards in most other industrial countries.

FEEDBACK FROM SERVICE EXPERIENCE

The real test of the quality of a product is whether it performs its duty properly for the required length of time. Service records ought to be a valuable contribution to product quality. Unfortunately, this is very difficult to achieve in practice and is successful in only a few industries, usually those in which their customers operate the product to controlled procedures in verifiable conditions and who keep records of performance. An example of this is the air transport industry.

Most customers do not do that, and the effort to analyse the cause of failure when the operating conditions are unknown is unlikely to be justifiable. The occurrence of a substantial proportion of failures under unknown conditions must, however, be recognised as a signal that the product is either unsuited to the market or is being sold in the wrong market.

Some years ago, a multi-national company making earthmoving equipment found that its UK company had significantly more structural failures in the same models than the USA company, although product quality was the same. A review of the usage suggested that in the UK the customers tended to buy the model whose performance matched what they saw to be their needs, whilst U.S. customers tended to buy models which were larger than necessary. What are the solutions to this? Perhaps the UK sales force should have pushed the heavier models or maybe the performance in the brochure should have been derated. That would then have put them at a disadvantage with their competitors. There is really no simple answer to that problem, but it does show the importance of assessing the real market as opposed to the supposed one, and that the matter of quality is more than a matter of engineering.

Most manufacturers have experience of the 'idiot fringe' of users who abuse anything they buy. Now, if the designers take account of these few failures they will in effect be selling a product which is of an unnecessarily high quality, which will make the product more expensive than the competition but of no more value to the great majority of users. In welded construction this may mean the difference between partial and full penetration butt welds or the use of butt welds instead of fillet welds. Common sense says ignore the few idiots, but the pressure of the worst type of 'consumerism', supported by strict product liability legislation, makes them less easy to ignore with the result that most individuals or companies may end up having to pay more than is necessary for their goods.

THE DESIGNER'S RESPONSIBILITY FOR QUALITY

The Manufacturer

In the situation in which a company both designs and makes the product, the quality requirements will be set by the design office but the achievement and control of the quality will usually be the task of the production departments. The company as an entity takes the contractual and legal responsibility for the product. The designer's responsibility rests in setting the proper quality levels to be achieved and, within the company, he carries the can if a correctly made product fails under normal usage.

The Engineer

Where the designer is a commercial entity which specifies and purchases products to be made by others, sometimes called vendors, or where the designer, in this case the engineer, has contracted with his client to provide the product which is made by construction contractors under his supervision, as is common in civil engineering, then the designer may well be responsible for the quality of the product. In that case he has to establish from the outset that the manufacturer, usually called a fabricator in welded construction, is both capable of and can demonstrate work of the specified quality. This is done in one or more stages. The first stage would be to assess whether the fabricator has the capability of undertaking the work at all; if not, that fabricator would not be invited to bid for the work. The next stage might be for the designer to carry out an audit of the fabricator's quality system, as described in Chapter 1.

Once work was under way the designer would review the fabricator's execution of his quality programme by means of a surveillance programme, which would vary in the level of attention to detail depending on the nature of that activity. In practice this means that basic, one off, activities such as welding procedure tests would be under 100% surveillance, whilst activities such as production radiography might receive only a limited examination. This is because this type of activity should be performed to an agreed procedure, and the results of this activity itself contain evidence of adherence to the procedure in the radiographs, which can be examined by the designer if he so wishes. Although the word ‘designer’ is used here, the actual surveillance might well be performed by a specialist firm that would be acting on his behalf.

In some circumstances, activities such as welding procedure tests may be witnessed by an inspection organisation acting as an independent body. This is called third party surveillance or inspection, and has an advantage to the fabricator that the welding procedures may be offered for several different customers; this, if accepted by them, will save the cost of repeating basically similar procedures. The costs of the surveillance will be met by one of the parties to a contract. It must be understood very clearly that, in the case of a designer accepting a previous third party witness, the stamp or signature of the third party confirms only that the test has been carried out in accordance with the specification indicated on the test record. It does not approve the procedure for any particular job; the designer still has to take that step himself. It should also be recognised that third party witnessing is not always perfect and its value may not then be as high as is necessary.

Checking of Designs

An essential task for any design office is the control of quality of the work being turned out, either as drawings, calculations or reports. In the case of welded construction this activity is no different in principle from that in any product, but there are some matters of detail which should be attended to. The conventional check is conducted by a person in a more senior position, or at least with more experience, than the originator. How the check is conducted will depend on the nature of the work; in particularly complex calculations a superficial check of the work may be insufficient and a re-run of the calculations may be necessary. Before this an initial check will be made to ensure that the basis of the work is sound, namely that assumptions are rational and the methods and data bases are valid for the circumstances. Beyond this it is important to ensure that the realisation of the design in practice is feasible.

From these points it is perhaps apparent that as well as this ‘single discipline’ type of checking there is a case to be made for a specialist check by someone versed in the subjects of materials and welding. The approach exercised by such a person has to recognise all the constraints surrounding the design and to reject details where they are likely to compromise the successful fabrication or performance of the item.

Any failure to observe the design office procedures should become apparent during quality system audits conducted in the office on a regular basis. Such audits should appear in the office or project quality plan, depending on the size of individual projects. It is unrealistic to try to impose an audit during the execution of a small project, unless it is of a type unusual to the office, and it is better to audit whatever is going on at the time of the audit.

QUALITY IN DESIGN

The basis of quality management for design is the same as for any other industrial activity. It may be summed up in the following sentence:

> ‘Achievement of quality is facilitated by working in a systematic manner to formalised procedures designed to minimise the occurrence of errors and to detect and correct any which do occur.’

REFERENCE

1. UK Offshore Steels Research Project—phase II. Final Summary Report, Offshore Technology Report OTH-87265, HMSO, 1987.

3

Designing Reliable Welded Products

J.G.HICKS

Consultant, Cambridge, UK

INTRODUCTION

The previous chapter set out the steps which should be taken to provide a design office with the capability of designing welded products which fulfil their purpose. This chapter looks at what might be called the methodology of design, in other words the sequence of operations which when employed with the appropriate knowledge and data will arrive at a reliable welded product.

BASIS OF DESIGN

The function of the product must be clearly and comprehensively described, and attached to this must be the performance requirements. These two areas might be thought of simply as ‘What does it do?’ and ‘How much does it do for how long?’ The environmental conditions will also be described either by association with the function or as part of the performance requirement. The basis of design will also incorporate some reference to the conceptual means by which the performance will be measured and achieved. For example, in a structure it would be necessary to postulate whether a simple elastic design were to be employed or whether a limit state approach was to be adopted. For fatigue in a structural member or a machine part one might consider whether safe life or failsafe philosophy was to be observed. The cost of the product cannot be ignored and it will be necessary to decide whether first cost or cost of ownership is to be considered as controlling the design. For some products some of these subjects will appear as mandatory or advisory instructions in regulations imposed by legislation; in others it will be the responsibility of the designer to identify and take account of the matters included in the basis of design.

Conceptual Design

Once the basis of design is agreed between the interested parties, it is possible to proceed with the conceptual design which will reflect the required function and performance criteria in the light of the conditions imposed by the basis of design. It may be necessary to prepare several conceptual designs and assess each against the basis of design in relation to other factors such as ease of manufacture, availability of materials, transportation and installation, etc. The conceptual design stage offers an opportunity for the customer or other interested parties to offer inputs to the design process in the light of their own operating practices and any constraints imposed by legislation; for example, the appearance of a building or a bridge, the operability with existing plant or vehicles, requirements for training of operators, etc.

Detail Design

Once the conceptual design is agreed the detail design work can be commenced. This will attend to the individual parts of the product, methods of joining components and manufacturing methods. Simultaneously, proprietory items will be identified and ordered.

For structures, a detailed structural analysis will be performed and for this it will be necessary to specify material strengths. In parallel, attention to properties such as fracture toughness or corrosion resistance will be pursued. It is in this area that the influence of welding as a fabrication method will be very significant. In a welded construction it is essential to seek materials which, when welded, will give to the structure the required properties of resistance to brittle fracture and the various types of corrosion which can occur, depending on the environmental conditions. It is important to recognise that, particularly in process plant, the designer has to be concerned with the environment, both internal and external to the items. Specialist advice is needed in this area, as in others, and the solutions are not often those which occur to the layman. High temperatures require attention to creep properties and low temperatures require attention to fracture toughness.

All the foregoing matters will have influenced the manner of fabrication and to a degree the details of the welded joints. At that point an assessment has to be made of the effect of any fluctuating loads which may cause fatigue cracks to be developed during the life of the construction.

It will be apparent from all of this that there are several routes of activity which have to be pursued simultaneously but at the end of the design all the requirements, some conflicting, will have to be satisfied before construction can be started with confidence. It will be seen that there are a number of sub-disciplines to be employed, and each will require its own data base together with designers capable of employing them to full effect.

A particular attribute of a good designer is to be able to understand the uncertainties which are inherent in much of the data used in everyday engineering. Such activities as sensitivity analyses may be needed to identify those quantities the variability of which would have most effect on the integrity of the design. A further refinement might then be a total design review on the basis of data uncertainty and sensitivity so as to arrive at a design which is most tolerant of the uncertainties.

PARAMETERS IN WELDED DESIGN

The following are some of the parameters which have to be recognised in many types of construction.

Materials

Strength of material and of welded metal: yield (or proof), tensile, as

welded or stress relieved

Strength at working temperature

Fracture toughness of parent and weld metal: as-welded, stress relieved

Corrosion resistance: as-welded, stress relieved

Member Shape and Size

Strength under axial and bending loads, stability in compression

Attracted loads due to aerodynamic or hydrodynamic effects

Loads due to resonance (dynamic magnification)

Loads imposed during transport and installation

Rolled or fabricated sections

Connections

Weld details—distortion, fatigue and access for welding and inspection. The latter is particularly important if non-destructive testing methods are to be used (see Chapter 8).

Shop or site conditions may affect the welding position which may restrict the choice of welding process.

Required weld properties must be reflected in the welding procedure specification and tested if necessary (see Chapter 4).

DESIGN REVIEW

A team which includes others than the design team can conduct a valuable exercise which can be performed at any stage in the design process. The object of such a review is to examine the approach to the design, with particular attention to a successful solution of the original requirement. The review will address the basic engineering approach and can identify any areas which have not been attended to by the designer.

A separate review called a value analysis can be pursued to ensure that the solution is the most cost effective one; more often than not this is aimed at the design as it affects the manufacturing costs rather than the operating costs of the finished product.

These activities are not within the scope of a quality system audit and are sometimes included in what is called a technical audit. The use of the word ‘audit’ here is frowned upon in some quarters because it is rather open ended; auditing is properly restricted to an activity which can be assessed against a procedure.

EXAMPLE OF A WELDED DESIGN

It is helpful to follow the stages in the design of a fairly common type of welded construction such as a crane rail beam. The following are the design requirements taken from the specification:

Span	15 m
Maximum load	50 t
Number of operations	20 per day for 25 years
Minimum service temperature	−5°C

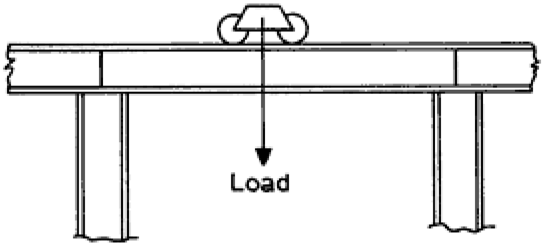


FIG. 1. Crane girder assembly.

Detail Design

A fairly early decision will be whether to use a continuous girder or whether to have simply supported sections between columns. The latter will make erection rather easier, avoiding the need for site welding or friction grip bolts to join the lengths. The penalty will be in the size of the girder section, which will have to be larger for the simply supported design because the maximum bending moment will be greater.

The selection of a girder size can be made from stock sizes or a special fabricated girder can be designed for this crane. The conventional matters involved in design must of course be dealt with (strength and stability) and it must be recognised that there is a moving load which will induce fluctuating stresses in the girder. It should also be recognised that the load from the crane gantry is carried on concentrated points—at the gantry wheels. This is an important point to recognise because it means that not only does the overall girder design have to allow for the fluctuating loading but the local details under the wheels at any time have to suffer a localised load fluctuation which can induce extremely high local stress ranges. In addition to these points, the designer needs to look at the possible need for specifying minimum notch toughness in the steel and the welded joints to resist brittle fracture. Failure to recognise this can result in the type of collapse shown in Fig. 1 of Chapter 5. However, provided that the design configuration is such as to minimise stress concentrations by minimising eccentricities, avoiding sharp changes of section or direction of load-carrying parts, the selection of steel properties can conveniently be confirmed once the design concept is complete. Attention may be required earlier if there are very high thicknesses, in which case there may be restraints on the delivery time for steel to some specifications.

Reverting to the basic outline of the girder, the required properties can be achieved by a welded beam with twin fillet welds attaching web to flanges (Fig. 2). These welds can be sized on the maximum shear in the web, but attention must be paid to the effect of the crane gantry wheel loads which may induce high local loads transmitted through the rail. At this point it is important that the designer pays attention to the fatigue strength of this welded joint. The fluctuating loads will be from the same sources as the static loads, that is from overall shear in the web and from the local load under the wheels. Failure to understand this situation led to the cracking of literally miles of crane girders in steelworks in the 1950s [1]. The stress which determines the fatigue life of fillet weld is the weld throat stress, and this must be calculated realistically and the weld size called up accordingly. Now, in practice there comes a size of fillet weld for which the amount of weld metal and the distortion is more than would be in a full penetration butt weld between the web and flange. The small trade-off in cost of edge preparation for a T-butt weld (Fig. 3) may well give a benefit of large proportions because the butt welded joint will have an immensely long fatigue life under a compressive load cycle and will have the same performance against the web shear loads as the parent metal.

The webs will still need some stabilisation as in the conventional girder, but the upper flange carrying the rail loads will also need stabilisation to resist lateral rail loads and any off-centre loads. The two functions

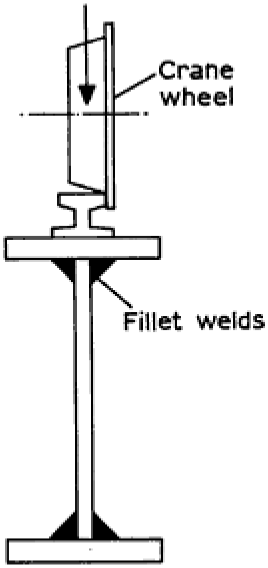


FIG. 2. Fillet welded girder.

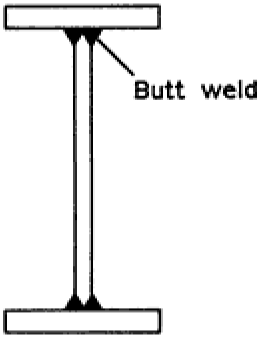


FIG. 3. Butt welded girder.

can of course be combined in one type of stiffener, except that not all the stiffeners, if any at all, may need to be attached to the bottom flange (Fig. 4).

The significance of this will become apparent when the fatigue design of the lower flange is being considered.

Fatigue cracks are caused by fluctuating stresses and they tend to start, if at all, at welded joints, not only because these joints cause a concentration of stress by their shape but also because welds give rise to minute cracks, usually at the weld toes. Not all types of welded joints have the same fatigue life and the weld itself does not need to carry a load for it to give rise to fatigue cracks in the member on which it is made. Therefore, the stiffener welded to the lower flange on the crane girder can make it liable to fatigue cracking; there is then a good case for not welding onto the flange if it can be avoided.

The occurrence of fatigue cracks is more likely if the stress fluctuations are tensile rather than compressive. It is necessary, therefore, to look at the calculated stresses in the flanges to see where the tensile stresses are for any position of the gantry. It will be clear that for the simply supported beam the

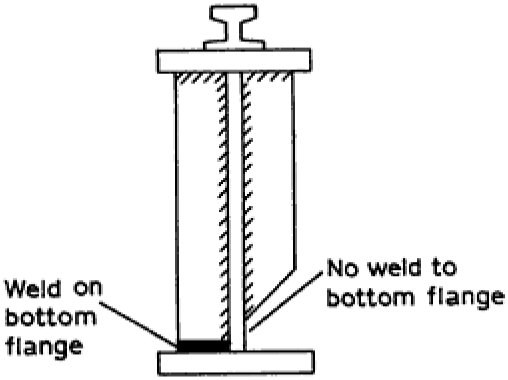


FIG. 4. Web stiffeners.

tensile stresses occur only in the lower flange, but in the continuous girder design there can be tensile stresses in the upper flange in the bay adjacent to the bay occupied by the gantry. This means that greater care has to be taken in designing this continuous upper flange with the attachment of the stiffeners necessary for its support, as described earlier.

For crane structures, information for designing against fatigue cracking is given in BS 2573 and a few calculations done with its assistance will illustrate the implications. For other types of structure there is similar information and reference should be made to the documents listed in Chapter 2. A wider understanding of the subject of fatigue will be gained from Refs 2 and 3.

Other details of a fabricated girder have to be taken into account when fatigue loading is present. Otherwise innocuous items such as cope holes in the web in the way of flange butt welds become important because the start and finish of the longitudinal weld represent a potential fatigue cracking site; the designer then has to ensure that the flange stresses allow for this effect. Whether or not the stiffeners should be allowed to overhang the edge of the flange makes a difference to the fatigue behaviour. The designers of bridges have recognised the need for clarifying the significance of details to fatigue life, and the British Standard Code of Practice for Bridge Design, BS 5400: Part 10, contains a set of charts to assist the designer in coming to a decision.

THE KEY TO RELIABLE DESIGN

The key to well designed products is attention to detail. This is not just in the sense of physical detailing but in the acquisition, appreciation and assimilation of all the technical data, and in a thorough understanding of the basis of its derivation.

REFERENCES

1. Senior, A.G. and Gurney, T.R., The design and service life of the upper part of welded crane griders. *The Structural Engineer* (The Institution of Structural Engineers), October 1963.
2. Gurney, T.R., Fatigue of Welded Structures. 2nd. Edn. Cambridge University Press, 1979.
3. Hicks, J.G., Welded Joint Design. BSP Professional Books, 1987.

4
The Control of Quality During Shop Operations

A.F.GIFFORD

NEI International Combustion Ltd, Derby, UK

INTRODUCTION

Over the past few decades demand for reliability of engineering systems has increased significantly. This has been a direct result of the ever-increasing cost of 'down time' of major capital plant, where loss of revenue can often exceed £30k per day. In the recent past there has also been a number of major failures of welded structural components and pressure parts which have become headline news, sometimes resulting in loss of life. Such failures include Flixborough Chemical Plant, Milford Haven Bridge, the Alexander Kieland offshore accommodation rig; their cost runs into millions of pounds. Such failures may occur as a result of workmanship or material deficiencies but, equally, are often due to inadequate design. Fortunately, the number of such multi-million pound disasters is limited, but every year equally large sums of money are lost in fabrication workshops due to welding problems. Welds or parent materials crack due to a variety of reasons; porosity and slag makes seams unacceptable; distortion renders components unusable without major rework; unsuitable welding consumables are used or specified properties are not achieved. Problems such as these are encountered every day in industry and result in loss of profit to the fabricator, loss of reputation and often associated delay to major projects. Many of these problems can be avoided if the fabricator follows a systematic course of quality assurance at all stages of his operation.

Primarily companies are in business to satisfy their customers, to make profits in order to satisfy their shareholders and to ensure the continuity of the company. It is however essential in achieving a profit that the correct balance is obtained between the cost of actually manufacturing the products, delivery to a predetermined programme, and ensuring that the quality is as specified. The important feature is to control the balance between these key functions.

This chapter will consider the inter-relationship which must exist between the various parties associated with fabrication. This may be very complex in the case of major projects involving the ultimate client, consultants, insurers, and major sub-contractors, as well as the fabricator himself and his sub-contractors. A simplified route illustrating the basic relationship from client to operation is shown in Fig. 1.

DESIGN CONSIDERATIONS

The importance of design in respect of production costs is paramount. The designer must specify clearly and precisely what shape he is seeking to be fabricated, what materials are to be used, and what levels of dimensional control and weld quality he is seeking. Far too frequently the designer backs off from defining the limits applicable to fabrication, preferring to leave this to the shop floor, since he often does not understand *what* can be achieved economically.

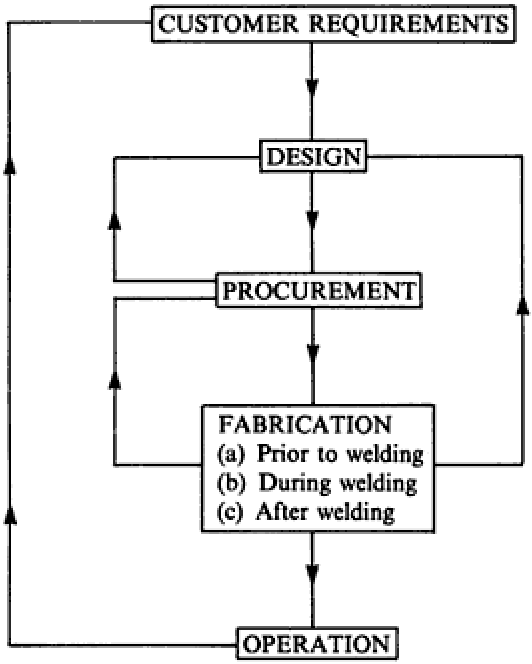


FIG. 1. A simplified outline of the QA route to be followed in welded fabrications.

To enable a weldment to have its required reliability throughout its working life it must incorporate, as a minimum, the correct level of quality—quality being defined in this instance as ‘fit for the intended purpose’. There is no bonus for over-design or excessive quality being provided, and adequacy should be seen as the minimum requirement to be achieved, even though in certain cases that adequacy may constitute near perfection.

The role of the designer with respect to welded components can be defined as:

(a) Determine the functional and material requirements, observing any requirements of relevant codes.
(b) Translate these into working drawings and specifications which incorporate value engineering, production and quality engineering, reliability and research and development, as appropriate.
(c) Establish tolerances and acceptance criteria.
(d) Design the joints such that access for welding and testing is available.
(e) Operate within economic and programme constraints.

The part played by the designer in the success of a fabrication is most important and, to ensure his conformity, a ‘design review’ is desirable in many cases. Such reviews should be held at three stages:

(a) product definition,
(b) basic conceptual design,
(c) detailed design.

The meetings should be attended by representatives, as appropriate, of sales, quality, production, welding, procurement and other involved departments. It is also desirable that a non-involved designer is present to ensure a detached viewpoint. The objective of such design reviews should be to:

(a) ensure specified customer requirements are met;
(b) relate to previous experience;
(c) review welding, inspection and testing requirements;
(d) design details suitable for fabrication;
(e) identify requirements for new processes;
(f) identify any procedure testing requirements;
(g) establish acceptance criteria for specified non-destructive testing;
(h) record the decisions and reasons.

There is little doubt that such actions will reduce overall costs and manufacturing time, and increase the conformity to design. Costs are relatively low at the design stage and become progressively higher as the contract proceeds.

In considering the economic and programme aspects of a fabrication, it is important to remember that there is no clearly defined procedure to be followed. A decision taken to reduce the manufacturing time span may involve higher production costs, depending on a variety of factors, including numbers to be made, availability of plant and materials, capital investment, supply of labour, etc. Some of these issues are directly influenced by the designer who must therefore take every care to ensure he makes the optimum decision in respect of function, production time scale and overall economics of the fabrication.

There must therefore be close co-operation between the designer and the welding engineer to ensure that the foregoing requirements are met. The welding engineer should keep the designer informed of developments in welding equipment and techniques which may affect the industry and he himself must be able to take the full advantages of new materials which may improve the effectiveness or economics of a particular design. He must determine the production route to be followed for the various welds and must reach a compromise between welding and weld preparation costs (i.e. large tolerances on preparation may reduce the cost of that activity but significantly enhance welding cost).

It is important that the simplest and most ductile base material is chosen which will fulfil the design requirements [1,2]. The choice of sophisticated materials may appear to reduce the estimated cost of a fabrication, but associated production problems and maintenance of very critical fabrication specifications may well override, if the workshop has not been correctly equipped to handle the new material. The selection, for example, of carbon steel will invariably prove satisfactory, since it has good weldability, often coupled with adequate mechanical properties. The use of alloy steels may be essential in some applications due, for example, to creep or stress corrosion environments, but the use of such steels increases the risk of weld metal or heat affected zone cracking, or of the wrong material being used either in the product or weld metal. The weldability of the materials of construction is of prime importance and should be carefully assessed before any material not previously welded by the manufacturer is introduced into a design. The designer must specify the minimum strength of weld metal required for each joint, since only he knows the load it has to carry. In general he should choose the lowest strength the design will allow, but the higher the strength of the material and the greater the applied loads, the more the design must be refined. Abrupt changes in section, which may be acceptable in low strength fabrications, cannot be tolerated in high strength steels (550–700 N mm^2) (Fig. 2) and butt joints carrying tensile or pulsating strength stresses must be full penetration with the weld reinforcement blending smoothly to avoid notches [3].

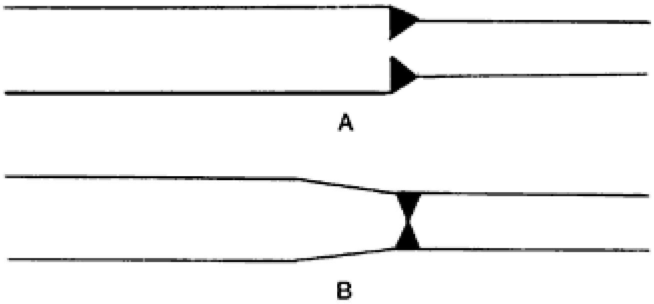


FIG. 2. Abrupt section changes should be avoided in stressed joints. Type A is not acceptable due to lack of penetration of weld and the high stress concentration at the toe of the weld. A satisfactory design is shown as Type B.

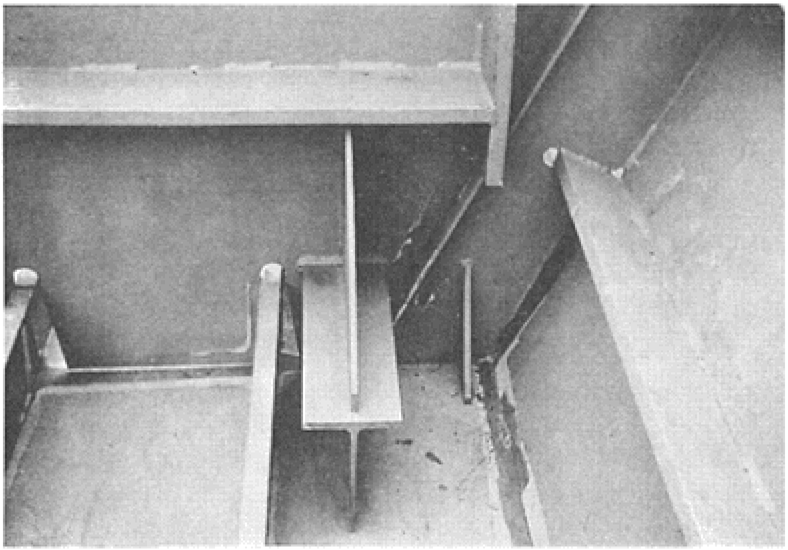


FIG. 3. Inadequate welding access in a large fabricated bridge structure arising from lack of interfacing between the draughtsmen responsible for different sections.

Good fabrication practice cannot rectify a basic design fault!

Access for Welding and Testing

Insufficient attention is often given at the design stage to the question of access for welding. Poor access (Fig. 3) will lead to defective welding and, in such cases, the welding process or the welder is often blamed for the deficiency. In many cases models or, better still, full scale replicas (Fig. 4) are essential to ensure access exists [4]. Access is not well defined but will include [5]:

(a) *Operator*—this means there must be physical space into which the operator can fit in order to adequately make the weld.

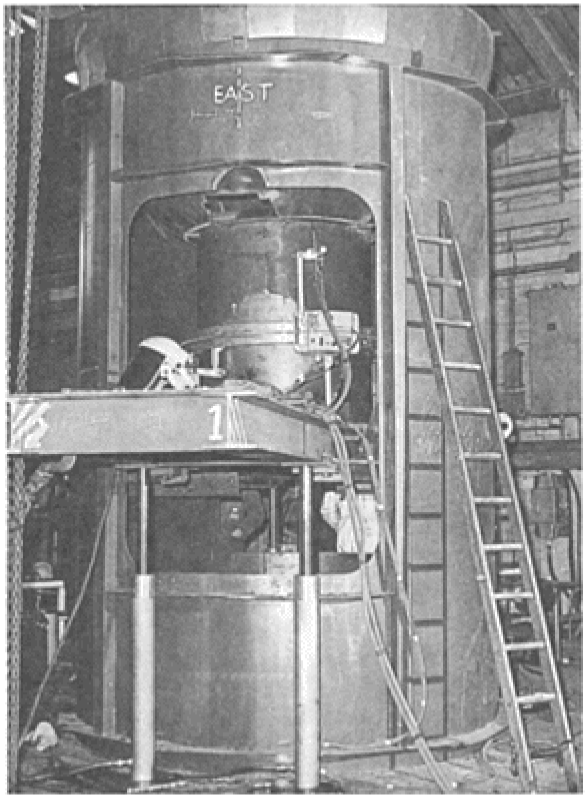


FIG. 4. Full scale model of lower end of ammonia converter. This rig was built to provide access for welding, cutting, testing and heat treatment to facilitate replacement of inlet forging.

(b) *Visual*—for all welds made by a manual process, the operator must be able to see all of the weld. In the case of automated welds this is desirable but not so essential.
(c) *Technique*—to ensure that the chosen technique can be correctly performed, e.g. two-handed processes such as 'TIG+filler' have different space requirements to manual electrode welds.
(d) *Equipment*—in some cases, e.g. MIG, the size of the equipment may limit its application in confined spaces.

For most manual purposes the operator's head and screen can be assumed to be 300 mm diameter with the eyes at least 100 mm from the top of such a sphere. Welding should not be, in general, more than about 600 mm from the eyes of the welder, whose body should be assumed to be 450 mm diameter. Automated welds, for example in piping systems of nuclear power plant, may be made by orbital welding processes. In such cases the facility now exists for remote viewing of the weld pool by TV, or by fibre optical systems.

When the weld is completed, access for testing is required and for dye penetrant and magnetic particle testing this does not usually present problems. X-ray testing may be impossible due to the size of the equipment and stand-off required, whilst gamma radiography can present health hazards in confined spaces. Unless joints have been designed with ultrasonic testing in view [6] this can be impractical, or take

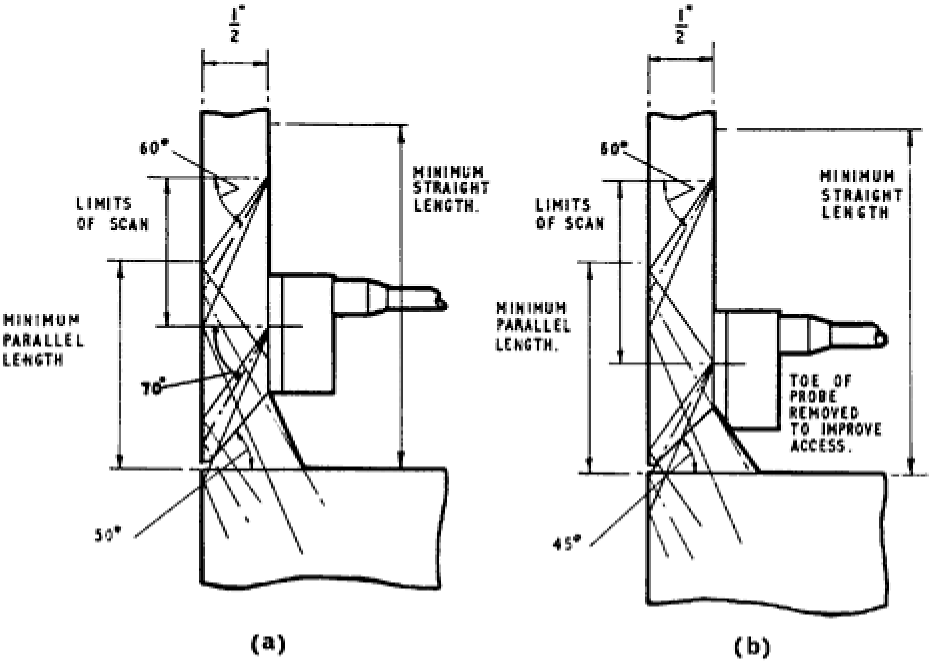


FIG. 5. An example showing how the choice of weld preparation angle can increase ultrasonic testing time by about one-third. (a) Two scans required, one at 70° for root and one at 60° for remainder. (b) One scan required at 60°. Time to test reduced by about one-third.

more time, not only due to space considerations but also to insufficient planar surface from which to scan the joint with probes, or the weld preparation angle itself (Fig. 5).

Care and time spent at the design stage will significantly influence the economics and quality of fabrication. Errors made at this stage may be repeated many times before they are detected, and subsequent inspection stages may well be incapable of detecting some design errors.

CONTRACTING AND ESTIMATING

The most important aspect of any contract is to determine exactly what the fabricator is undertaking to manufacture. If this is not clearly defined and understood by all parties no amount of effort in the workshops can make the activity a success. The requirement for reliability, previously referred to, together with the need to operate in a profitable manner, make the specification of the work to be undertaken of paramount importance. Words such as ‘water-tight welds’, ‘good fusion’, ‘good clean metal’, ‘free from slag’, ‘free from undercut’, or one-sided clauses such as ‘shall satisfy the engineer’ or, again, ‘all welds shall be radiographed’ cannot form the basis of an effective contract. The standards defined by such terminology are impossible to cost and the fabricator cannot hope to operate efficiently if they remain in his client’s order.

The estimating department of the fabricator’s works, in the quest for assured quality and profitability, must therefore closely review the enquiry document, isolate clauses such as those illustrated above, and tell the prospective purchaser what he will be offered, in clear, unambiguous wording, and then price his operation to suit. When non-destructive testing is specified it is essential that the acceptance criteria be

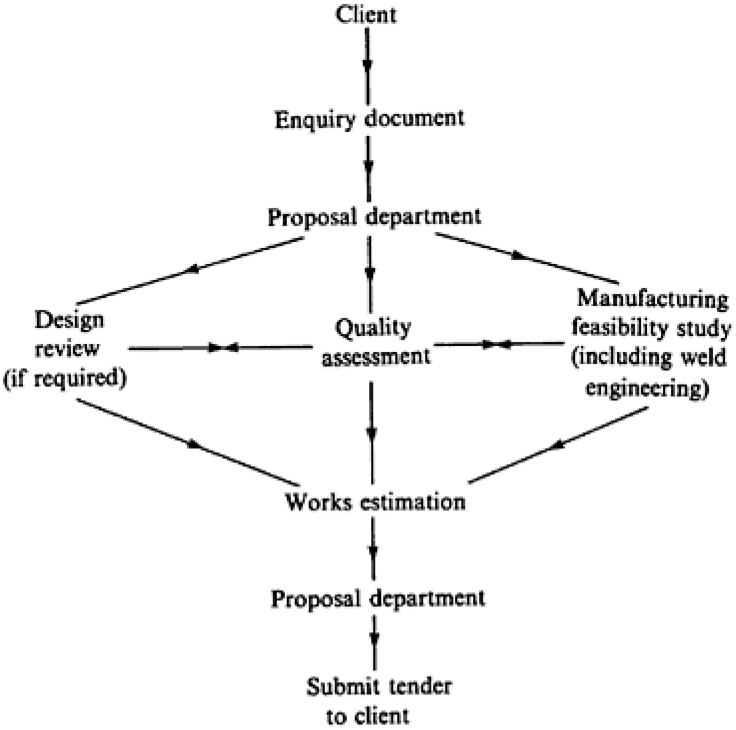


FIG. 6. The sequence of operations in producing an estimate for fabrications adopted by a large manufacturer.

established. This can often be achieved by reference to relevant British Standards. For example, acceptance levels for ultrasonic testing are contained in BS 1113. Unless the offer is made in such terms the purchaser can take a position whereby the work produced is never acceptable to him because he has been clever enough not to specify his requirement in detail! The route followed in handling an enquiry by a large fabricator is shown in Fig. 6.

In supporting the estimating department, the welding engineer must provide data on the processes to be used, the joint forms to be adopted, and the tolerances that must be achieved. He must also identify what risks are being taken; for example, is a particular joint configuration likely to cause lamellar tearing and what are the alternatives that could be followed? In some cases his alternative proposals may be adopted at the expense of a higher basic cost, but on other occasions calculated risks may be taken by management when being faced with a depleted shop forward load.

An essential role of the welding engineer is to ensure that the design offered to him does not present insurmountable problems to execute. A common example of this is in the inaccessibility of certain welds whereby, due to technical limitations of most welding processes, no amount of work on his part can economically produce a sound weld in the nominated location (see Figs 3 and 7).

In arriving at the welding costs to build into an overall estimate, most organisations use their own standard data as a basis. This is then modified, as advised by the welding engineer, depending on the complexity of the component to be fabricated, and any difficulties, e.g. distortion, which are envisaged. Data on welding deposition rates for various processes is available from a number of sources [7, 8].

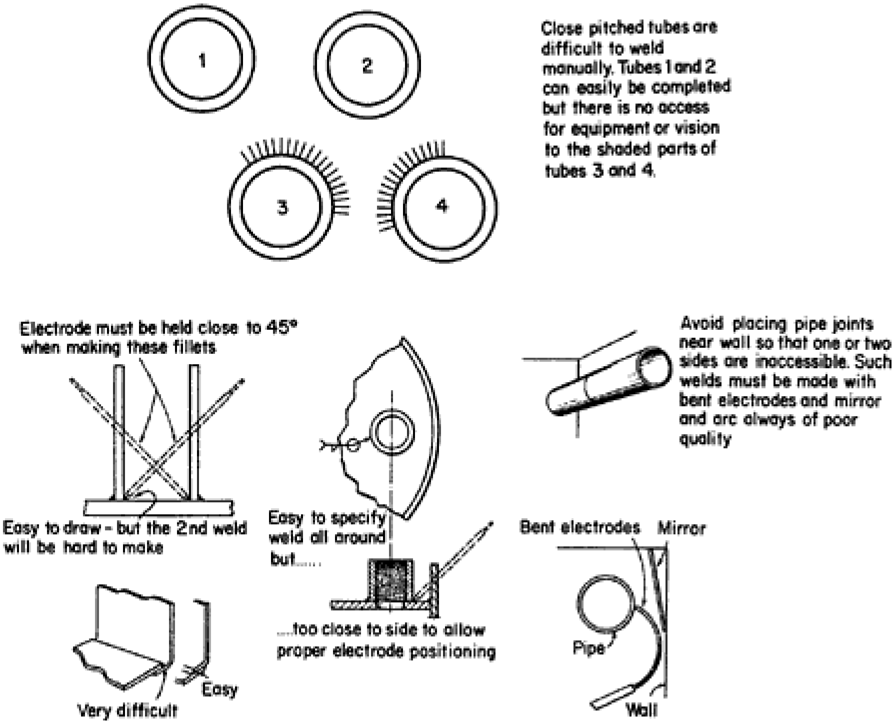


FIG. 7. Some examples of poor access for manual welding resulting from design requirements. (After Lincoln Electric Co. Ltd, Welding Handbook.)

It is a general rule that the better the design and estimate, the greater is the chance of a successful fabrication being made.

PROCUREMENT AND MATERIAL CONTROL

Obtaining the materials and welding consumables specified by the designer or engineer at the most advantageous price and at the correct time is the role of the procurement department. They should receive clear and unambiguous requisitions defining exactly what is wanted, and must not deviate from that requirement unless a concession has been approved by the originator of the requisition. Unless any options are clearly defined, the supplier is at liberty to provide what he will—and it may not be what the purchaser requires. Problems were encountered some years ago when submerged arc welds were found to be low in tensile properties. Subsequent investigations showed that whilst there was a maximum carbon content of 0·12% in the specification of the *wire,* there was no minimum requirement, and when 0·03% carbon was supplied the required strength just could not be achieved. Submerged arc welding consumables are now controlled by national standards such as BS4165, and similar problems should not now occur. To identify the options possible in the purchase of plate the British Steel Corporation has issued a check list (Table 1) defining everything required for complete specification of plates.

Many companies operate an ‘approved vendor’ register and all suppliers are assessed [9, 10] prior to inclusion. Manufacturers of welding consumables and equipment may now also be approved by third party assessment bodies, such as Lloyds Register Quality Assurance (LRQA), to the criteria set by BS 5750. Such approvals help to ensure that the products meet the client's specifications on delivery to his plant. Depending on the rating of the supplier, inspection of materials may be either at the supplier's works or on receipt by the manufacturer. It is normal, however, as a minimum, to check base materials on receipt for dimensional conformity, surface quality, pitting and flatness. It is also

TABLE 1
PLATE ENQUIRY CHECK LIST[a] (Courtesy of British Steel Corporation Plates)

	Check	*Notes*
(1)	Project/application	Useful in confirming the specification or suggesting an alternative, particularly important when fabricators intend to carry out cold spinning or hot forming processes
(2)	Steel specification	Including grades within a specification
(3)	Modification to mechanical properties	(a) Yield stress
(b) Tensile strength		
(c) Elongation		
(d) High temperature properties		
(e) Charpy V-notch (or other); impact properties—indicate longitudinal or transverse (for thin plate, confirm that subsidiary test pieces and their associated impact strengths are acceptable)		
(f) Hardness		
(g) Others		
(4)	Chemical composition	Indicate product or ladle analysis and any additional elements not covered by the specification. Modifications to existing specification (e.g. carbon equivalent maximum)
(5)	Heat treatment	
(6)	Plate dimensions/tonneage Plate size Plate tonneage/numbers of plates Tolerances	Gauge, flatness, length, width—confirm whether the tolerances associated with the specification stated in (2) apply; if not, give full details of tolerances
(7)	Special surface standards and treatment	(a) Surface standard?
(b) Primer to be used?		
(8)	Testing and inspection heat treatment of coupons	For stress relieving heat treatments, state whether these are to be shop or site and indicate soaking times and

		temperatures. State whether mechanical properties are to be met in the stress relieved condition,
	frequency of testing	Batch test, individual test, 'as rolled' or in the 'as-heat-treated' condition?
	special mechanical tests	(a) Which test?
(b) Number of tests per plate?		
(c) Test positions?		
	ultrasonic standards required private inspection	(d) Specify acceptable results
Levels and stages of inspection—witness tests only, or witness tests and surface inspection? State whether inspection will be by one or more inspection authorities. Please indicate which authorities. Is a quality assurance agreement to be operated? Is a quality plan required?		
(9)	Marking and documentation marking documentation	Any special stamping, stencilling or colour or other coding
Any special requirements		
(10)	Order/delivery closing date for receipt of quotation date order will be placed required delivery date priority sequence of deliveries	

[a] These principles are applicable for many other purchase situations.

essential that any test certificates are verified for correctness and completeness and also compared to the material identification.

Control of Consumables

Welding consumables are normally purchased against national standards, e.g. BS 639 or ASME IX, and are not checked at the fabricator's works. In critical applications, e.g. high strength low alloy composition, creep conditions, etc., pads of metal are often deposited and checked on a direct reading spectrograph. Welding wires can readily be fused under argon to produce a small ingot suitable for processing on these instruments [11]. Manufacturers of welding consumables are, however, concerned at the increased demand for them to supply comprehensive test certificates for all types of consumable. This demand has developed with the expansion of formal QA systems, and the use or value of such certificates has been questioned.

One manufacturer has reported the following increase in demand:

1975:	350 certificates per month
1980:	750 certificates per month
1983:	1500 certificates per month
1984:	2000 certificates per month
1985:	*c.* 4000 certificates per month

In 1975 only critical clients required certificates for key products, but in 1987 everyone asks for a certificate—'just in case'. Such requests are additional to national standards requirements, and in future may incur additional charges.

Many problems in fabricated plant arise from the use of incorrect base material or electrodes [12]. Such problems can be just inconvenient and costly or sometimes dangerous to life and limb.

The storage and control of welding consumables requires special attention. The problems associated with the presence of hydrogen in welds and its almost inevitable cracking tendencies are well documented [13]. BS 5135 gives guidance on the calculation of carbon and carbon manganese, and requires that the weld diffusible hydrogen content of arc welding processes be established in order to arrive at the preheat temperature. The standard provides details of how to measure the hydrogen content and allocates a scale to the result (Table 2). The AWS Structural Welding Code D.1.1. 1986 gives tables of recommended preheats, but in Appendix O also provides information enabling preheat to be calculated, based on either HAZ hardness control or on hydrogen control.

TABLE 2
HYDROGEN SCALES

Diffusible hydrogen content (ml/100 g of deposited metal)		
Over	Up to and including	*Scale*
15	—	A
10	15	B
5	10	C
—	5	D

TABLE 3
SHELF LIFE FOR COATED ELECTRODES

Type of package	*Heated room*	*Non-heated room*
Unsealed and damaged	—	Not stored
Sealed[a]	1 year maximum	Should preferably not be stored but in any case not to exceed 6 months
Hermetically sealed[b]	3 years maximum	1 year maximum

[a] Sealed describes containers which, after opening, are used again after closing by staples, adhesive tape, etc., or cardboard type boxes; [b] hermetically sealed containers are cardboard boxes coated with plastic film, soldered tins, sealed plastic boxes, etc.

The avoidance of problems calls for close control and discipline in respect of both storage and use of most welding consumables [11]. Fabricators use electrodes and other consumables from various suppliers, of differing composition and requiring different treatments prior to use. These may range from very precise baking at 450°C followed by storage at about 150°C, to others requiring little or no protection other than that offered by the maker's packaging.

On receipt in a factory all previously nominated consumables (possibly excepting simple rutile carbon steel electrodes) are placed in a bonded area until sampled and tested. Once accepted they can then be stored, preferably in heated insulated rooms with a maximum relative humidity of 55% at a temperature of 16–25°C. Shelf life for coated electrodes is not well defined, but Table 3 forms a good basis for guidance.

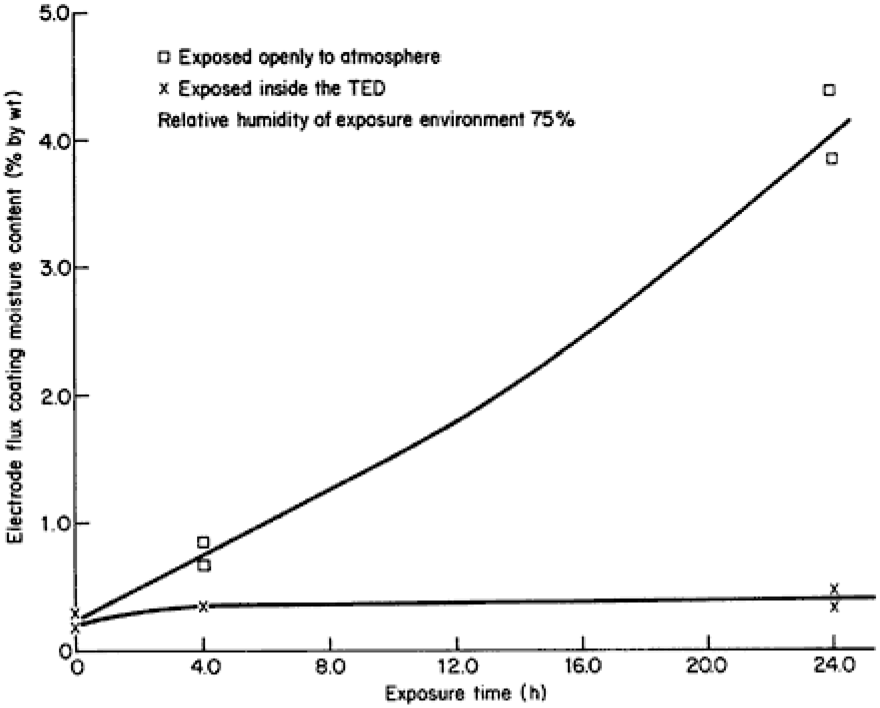


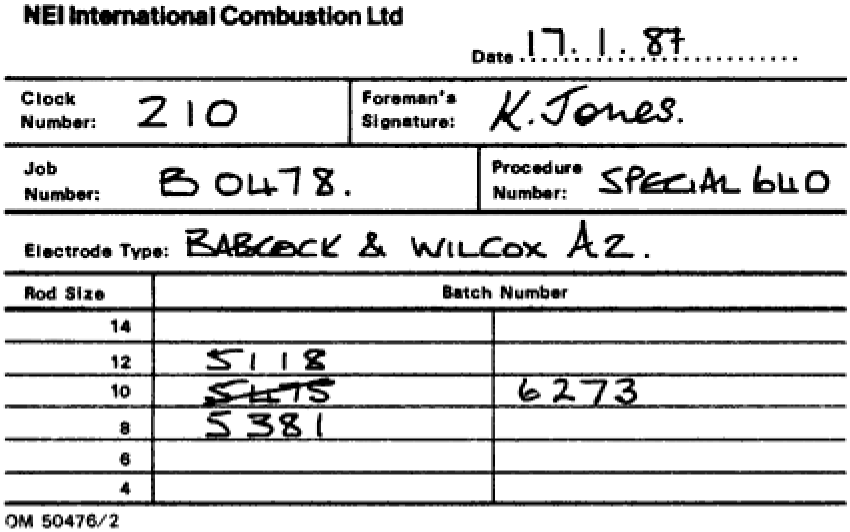
FIG. 8. Comparison of moisture pick-up E7016 consumables inside the TED (thermal electrode dispenser) and exposed to the atmosphere.

In many cases electrodes, particularly basic coated electrodes, are stored in holding ovens at about 130–50°C immediately prior to use and issued into heated quivers, labelled to indicate the batch number concerned, in quantities not exceeding 4 h normal supply.

A recently marketed electrode container does not involve any electrical supply at the point of use. Electrodes are placed in a plastic sealed container, incorporating an opening flap and ejector mechanism, directly from the holding oven. The object of the system is to prevent moisture coming into contact with the already dried electrode. Independent trials have shown (Fig. 8) that moisture ingress at 75% relative humidity is not significant and the device is considered to be viable for at least 8 hours use [13].

Recently, electrode manufacturers have devoted considerable attention to the production of electrodes which do not require to be baked by the fabricator in order to meet BS 5135 Scale C or D hydrogen levels (Table 2). In addition, claims are made that the electrodes do not pick up moisture during an eight-hour shift and, hence, do not invalidate the hydrogen scale. Tests are currently in hand by a number of fabricators to substantiate these claims.

The storekeeper should maintain records of all issues of welding consumables (Fig. 9) and unused electrodes must be returned to store at the end of each work period, for drying. It is a dangerous and often costly practice to permit electrodes and other consumables to be littered around the workshop since they are then available to be used on critical applications in an uncontrolled manner, i.e. use of damp low hydrogen electrodes causing cracking [14] or use of the wrong consumables in a particular application.



NEI International Combustion Ltd

Date 17. 1. 87

Clock Number:	210	Foreman's Signature:	K. Jones.
Job Number:	B 0478.	Procedure Number:	SPECIAL 640

Electrode Type: BABCOCK & WILCOX A2.

Rod Size	Batch Number	
14		
12	5118	
10	~~5475~~	6273
8	5381	
6		
4		

OM 50476/2

FIG. 9. Control card issued to a welder to authorise withdrawal of electrodes from the welding stores. The batch number is completed by the storeman and changed as the batch changes.

QUALITY PLANS

The concept of planning to ensure that quality is achieved is not new. Various methods have been used in the past including inspection schedules, inspection route cards and quality control sheets. These tended to indicate what inspection and testing should be carried out on a given fabrication but, in general, they all failed to integrate manufacturing, internal inspection and external visiting inspection activities.

Quality plans are a requirement of many of the quality assurance standards, e.g. ASME III, BS 5750 Part 1, and they are designed to provide not only a schedule of operations to be carried out by process and inspection personnel, but also to serve as documentary proof that the operations have been performed. It is normal to require the operator, either as a direct worker or an inspector, to sign a control document indicating completion of a stage of the quality plan. 'Hold points' are established in conjunction with visiting inspectors beyond which work must not proceed without the signature of the authorised inspector; these normally apply to inspection, test and documentation stages and are not usually applied to process operations.

Various definitions of a quality plan exist, and confusion between quality plans and quality programmes often occurs. In the writer's opinion, the definition given in BS 5882 (Clause O.4.11) best meets the requirements of the fabrication industry, viz. '*Quality Plan*. A document describing or identifying specific practices and procedures relevant to particular items, processes or services'.

The essential feature of a quality plan is that it should describe (Fig. 10) the manufacturing route, reference to relevant procedures and any acceptance criteria, the associated in-house inspection stages, and the hold points agreed with the authorised inspector. For most contracts the quality plan, as agreed with the purchaser or his representative, becomes part of the contractual documentation. The amount of detail to be included in a quality plan by a fabricator is not well defined [15]. The more the fabricator includes as in-house checking the more the authorised inspector may wish to become involved with mandatory hold points, thus potentially delaying production.

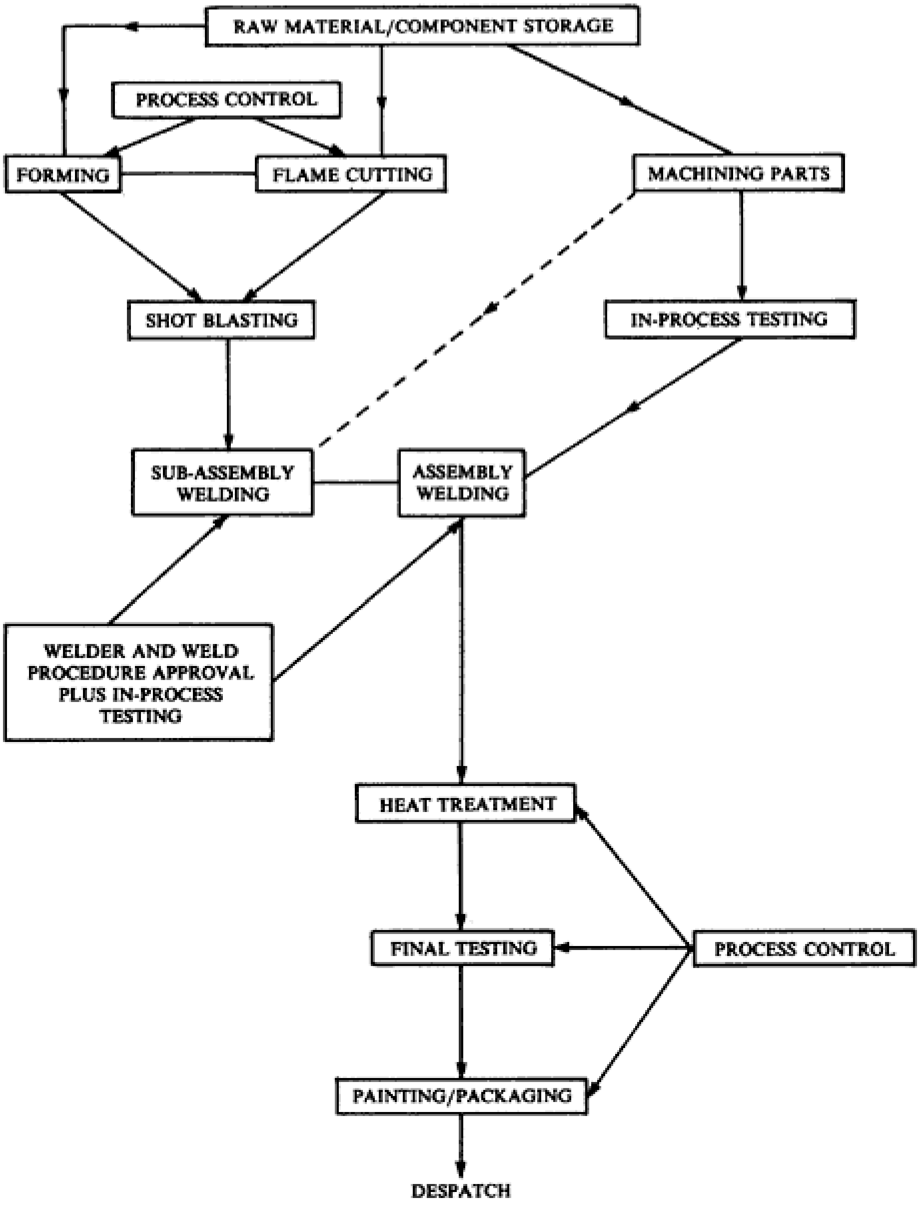
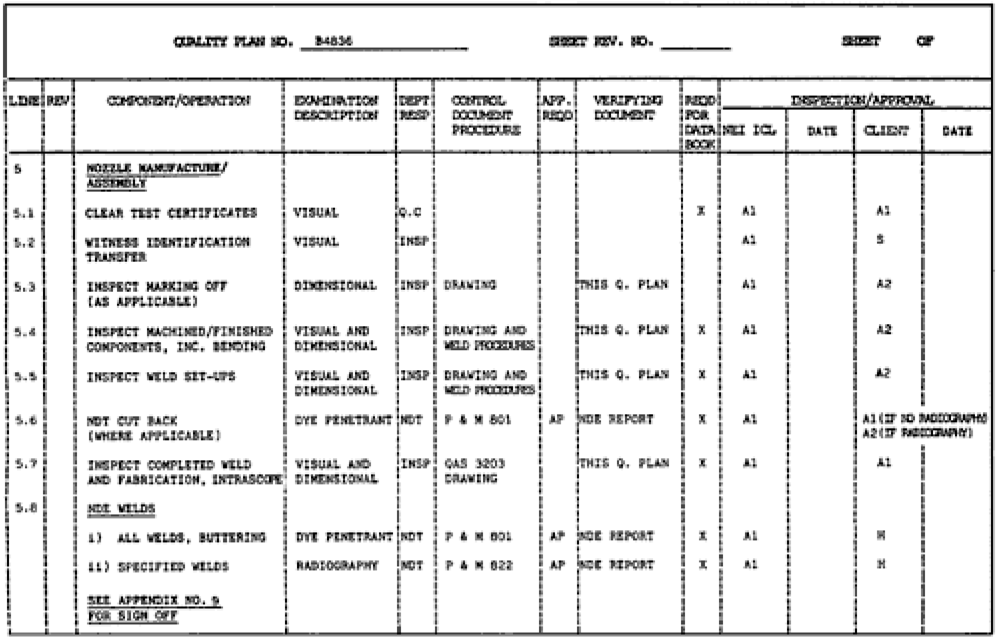


FIG. 10. An outline manufacturing sequence for a steel fabrication showing some elements to be covered by a quality plan.

There is no standard layout for a quality plan, each fabricator designing a system to meet his own needs. A typical format as used by a pressure vessel fabricator is shown in Fig. 11. The approach adopted in preparing quality plans must not be too system orientated. Excessive paperwork and unnecessary duplication of activities such as auditing and inspection must be avoided. Quality plans should not be



QUALITY PLAN NO. B4836 SHEET REV. NO. ________ SHEET OF

LINE	REV	COMPONENT/OPERATION	EXAMINATION DESCRIPTION	DEPT RESP	CONTROL DOCUMENT PROCEDURE	APP. REQD	VERIFYING DOCUMENT	REQD FOR DATA BOOK	INSPECTION/APPROVAL			
									NEI ICL	DATE	CLIENT	DATE
5		NOZZLE MANUFACTURE/ ASSEMBLY										
5.1		CLEAR TEST CERTIFICATES	VISUAL	Q.C				X	A1		A1	
5.2		WITNESS IDENTIFICATION TRANSFER	VISUAL	INSP					A1		S	
5.3		INSPECT MARKING OFF (AS APPLICABLE)	DIMENSIONAL	INSP	DRAWING		THIS Q. PLAN		A1		A2	
5.4		INSPECT MACHINED/FINISHED COMPONENTS, INC. BENDING	VISUAL AND DIMENSIONAL	INSP	DRAWING AND WELD PROCEDURES		THIS Q. PLAN	X	A1		A2	
5.5		INSPECT WELD SET-UPS	VISUAL AND DIMENSIONAL	INSP	DRAWING AND WELD PROCEDURES		THIS Q. PLAN	X	A1		A2	
5.6		NDT CUT BACK (WHERE APPLICABLE)	DYE PENETRANT	NDT	P & M 801	AP	NDE REPORT	X	A1		A1 (IF NO RADIOGRAPHY) A2 (IF RADIOGRAPHY)	
5.7		INSPECT COMPLETED WELD AND FABRICATION, INTRASCOPE	VISUAL AND DIMENSIONAL	INSP	QAS 3203 DRAWING		THIS Q. PLAN	X	A1		A1	
5.8		NDE WELDS										
		i) ALL WELDS, BUTTERING	DYE PENETRANT	NDT	P & M 801	AP	NDE REPORT	X	A1		H	
		ii) SPECIFIED WELDS	RADIOGRAPHY	NDT	P & M 822	AP	NDE REPORT	X	A1		H	
		SEE APPENDIX NO. 9 FOR SIGN OFF										

regarded as being sacrosanct and flexibility is required at all times, especially if the fabrication is of a one-off or of a non-standard nature.

Quality plans are now in common use in the pressure vessel, nuclear, and heavy structural welding fields, and their use is increasing in many other industries.

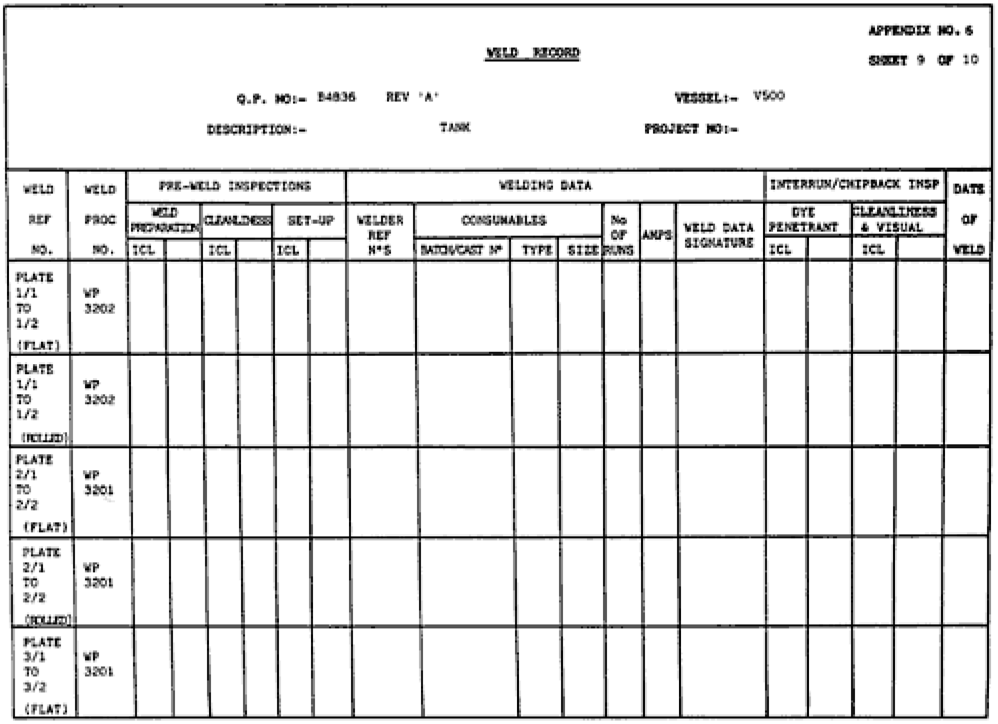
WELDING PROCEDURE AND WELDER APPROVALS

The requirement for approval of the competence of welders and determination of the suitability of welding procedures goes back to the earliest days of the welding process. At that time the emphasis was on welder testing, usually by mechanical means together with macro-etched sections, and certificates of competence were issued, often by the inspection bodies. Manufacture at that time often included welding test plates, the successful testing of which determined the acceptance of the fabrication. Whilst this was probably satisfactory up to about the 1950s, the increasing number of welding processes and materials to be joined has dictated a different approach.

The current welding codes, AWS, ASME, BS 5500, etc., all require the welding procedure to be proven *before* any work is commenced [16, 17], and that the work itself is then carried out by welders who have demonstrated their competence in the skills needed to make joints conforming to that procedure. The following is a comparison of the approval systems for welding.

Previous

Current



APPENDIX NO. 6

WELD RECORD

SHEET 9 OF 10

Q.P. NO:- B4836 REV 'A'

VESSEL:- V500

DESCRIPTION:- TANK

PROJECT NO:-

WELD REF NO.	WELD PROC NO.	PRE-WELD INSPECTIONS						WELDING DATA							INTERRUN/CHIPBACK INSP				DATE OF WELD
		WELD PREPARATION		CLEANLINESS		SET-UP		WELDER REF N°S	CONSUMABLES			No OF RUNS	AMPS	WELD DATA SIGNATURE	DYE PENETRANT		CLEANLINESS & VISUAL		
		ICL		ICL		ICL			BATCH/CAST N°	TYPE	SIZE				ICL		ICL		
PLATE 1/1 TO 1/2 (FLAT)	WP 3202																		
PLATE 1/1 TO 1/2 (ROLLED)	WP 3202																		
PLATE 2/1 TO 2/2 (FLAT)	WP 3201																		
PLATE 2/1 TO 2/2 (ROLLED)	WP 3201																		
PLATE 3/1 TO 3/2 (FLAT)	WP 3201																		

FIG. 11. Part of a quality plan and associated weld record for a high quality stainless steel storage tank. Inspection/surveillance codes: A1 100% inspection or test; A2, sample inspection or test (10% minimum); Wl, 100% witness of inspection or test; W2, sample witness inspection or test (10% minimum); S, surveillance; H, hold point. Documentation codes: AP, control documents required to be approved; R, review of verifying documents; V, verifying documents required to be submitted; X, documents required for master record data dossier.

(b) Approval of welding procedure → Competent operator → Production work → Optional test plate

The older systems of welding control, being very dependent on approved welders and test plates, meant that the fabricator did not know if the work he was producing was acceptable until the final test plate was examined, and large amounts of work could then be in question. By utilising approved weld procedures, qualified welders and systematic control of manufacturing operations, dependence on test plates is now reduced to optional, special circumstances, e.g. to act as a bench mark to measure for irradiation damage in nuclear plant.

The concept of approved procedures is straightforward; however, in practice it is not quite so simple due to the large number of variables involved. Thickness and diameter of pipes and tubes, thickness and joint form in plates, nozzles, base materials, welding consumables and weld processes are just a few of the factors to be considered. Clearly, many procedures are similar and do not require individual proving, and there is therefore an incentive to group or range materials/processes/sizes to provide acceptable results from a single test. A complex test is expensive, for example a $\frac{1}{2}$Cr $\frac{1}{2}$MO $\frac{1}{4}$V pipe test weld can easily cost in excess of £2300 to weld and test to BS 4870, so no one wishes to make more tests than are required.

TABLE 4
OUTLINE COMPARISON OF PROCEDURAL VARIABLES FOR SUBMERGED ARC WELDING AS DEFINED BY ASME IX AND BS 4870

		ASME IX			*BS 4870*	
Procedural variables		*Essential*	*Non-essential*	*Supplementary*	*Essential*	*Non-essential*
Joints:	type of groove		x			x
change in backing		x		x		
root gap		x		x		
Base material:	thickness	x		x	x	
material group	x		x	x		
Filler material:	F-number	x			x	
flux classification	x					
flux additions	x				by agreement	
filler specification			x			
additonal filler	x					
Position:	change of position		x		x	
Preheat:	decrease >56°C	x			x	
post-weld heating		x		x		
interpass temperature			x	x		
PWSHT:	change	x		x	x	
Electrical:	current		x	x	x	
Technique:	deposit size			x	x	
stringer/weave		x		x		
cleaning		x			x	
back grooving		x		x		
oscillation		x	x		x	
stick-out		x			x	
number of passes		x	x		x	
number of wires		x	x	x		
non-metallic backing		x		x		
automation		x			x	
	peening		x			x

Note: Cosult ASME IX or BS 4870 for precise requirements.

TABLE 5
SOME EXAMPLES OF COMMON *P* NUMBERS FOR STEELS AS USED IN ASME IX

P *number and Group*[a]	*Type of material and typical compositions covered*[b]	*Inclusive Range of specified minimum tensile strength* (ksi)	*Some specific examples*
*P*1			
Group 1	Carbon, e.g. C–Mn, C–Si, C–Mn–Si	Up to 65	SA 285 Gr.C SA 516 Gr.60

P *number and Group*[a]	*Type of material and typical compositions covered*[b]	*Inclusive Range of specified minimum tensile strength* (ksi)	*Some specific examples*
Group 2	Carbon, e.g. C–Mn, C–Si, C–Mn–Si	70–75	SA 515 Gr.70 SA 738 Gr.B
Group 3	Carbon, e.g. C–Mn, C–Mn–V–N	80–95	SA 737 Gr.C
*P*3			
Group 1	Low Alloy, e.g. C1/2Mo, 1/2Cr 1/2Mo	70–65	SA 213 Gr.T.2
Group. 2	Low Alloy, e.g. Mn 1/2Mo, 1/2Cr 1/2Mo, C 1/2Mo	55–75	SA 387 GR.2
Group 3	Low Alloy, e.g. Mn 1/2Mo, Mn 1/2Mo 3/4Ni, 1/2Mo V	80–90	SA 302 Gr.B.
*P*4			
Group 1	Low Alloy, up to 2Cr I Mo	55–85	SA 213 T11
*P*5			
Group 1	Low Alloy, up to 3Cr 1Mo	60–75	SA 336 F21
Group 2	Low Alloy, up to 9CR 1Mo	60–90	SA 213 T9
*P*6			
Group 1	Ferritic stainless, up to 13Cr including 11Cr Ti	60–70	SA 240–410
Group 2	Ferritic stainless, up to 15Cr	60–65	SA 240–429
Group 3	Ferritic stainless, 13Cr	85–110	SA 182-Gr.F6b
Group 4	Ferritic stainless, 13Cr 4Ni	110–115	SA 182-F6NM
*P*7			
Groups 1-2-3	Ferritic stainless, up to 18CR 2Mo Ti	60–70	SA 268 TP430
*P*8			
Group 1	Austenitic stainless, 19Cr maximum	65–80	SA 213-TP347
Group 2	Austenitic stainless, 25Cr maximum	65–87	SA 312-TP310
Group 3	Higher tensile austenitic stainless	75–120	SA 249-TPXM19
P9A	Ni steels, 2 1/2Ni	63–70	SA 334 Gr.7
*P*9B	Ni steels, 3 1/2Ni	65–70	SA 203 Gr.D

[a] Specific impact test requirements are associated in Group numbers, within the *P* numbers.

[b] Consult ASME IX for the precise permitted compositions.

TABLE 6
GROUPING SYSTEM FOR STEELS—BS 4870 PART 1

Group	*Type of steel*	*Material grade in BS 5500 (for information)*
A1	C/C-Mn steel with minimum tensile strength in the specification up to and including 430 N/mm^2	M0 and M1

Group	*Type of steel*	*Material grade in BS 5500 (for information)*
A2	C/C-Mn steel with minimum tensile strength in the specification over 430 N/mm^2	M1
B	C-Mo steel	M2
C	Mo-B steel and Mn-(Ni)-Cr-Mo-V steel	M3 and M4
D	1/1 1/4Cr1/4Mo steel	M7
E1	2–3Cr 1Mo steel normalised and tempered	M9
E2	2–3Cr 1Mo steel quenched and tempered	M9
F	1/2Cr 1/2 Mo 1/4V steel	M8
G	5Cr 1/2Mo steel	M10
H	9Cr 1Mo steel	M11
J	12Cr Mo V steel	M12
K	3 1/2Ni steel	M5
L	9Ni steel	M6
M	13Cr ferritic stainless steel	—
N	17/20Cr ferritic stainless steel	—
P–Q	Reserved for future allocation of other steel groups	—
R	304 type austenitic stainless steel	—
S	310 type austenitic stainless steel	—
T	316 type austenitic stainless steel	—
U	321/347 type austenitic stainless steel	—
V–Z	Reserved for future allocation of other steel groups	—

The code writers of ASME and British Standards have tackled this problem by developing the concept of essential, supplementary variables and non-essential variables, changes which determine if requalification of procedures is required. In ASME IX variables the welding procedures are classified as essential, non-essential and supplementary essential. Essential variables define limits within which the variables can be changed without requalification, but the changes must be recorded by a revision of the welding procedure. Similarly, changes to non-essential variables must be recorded on the welding procedure. The supplementary essential variables define restrictive limits for cases when the base material has guaranteed impact properties. An example of how these principles operate is shown in Table 4 for submerged arc welds, made both to ASME IX and BS 4870.

Material groupings applicable to both codes are shown in Tables 5 and 6. It will be seen that there is a close similarity between the two codes, although sub-grouping within the ASME system is more specifically

TABLE 7
GROUPING FOR JOINTS BETWEEN SIMILAR STEELS (X=APPLICABILITY)—BS 4870

Steel group of originally approved procedures	*Steel group also approved*				
A1	A2	B	E1	R	
A2	X	X	—	—	—
B	X	X	X	—	—

Steel group of originally approved procedures	*Steel group also approved*				
A1	A2	B	E1	R	
D	—	—	X	—	—
F	—	—	—	X	—
K	X	X	—	—	—
T	—	—	—	—	X

TABLE 8
COMPARISON OF MECHANICAL TEST.REQUIREMENTS OF ASME IX AND BS 4870 FOR PLATE BUTT WELDS AND BRANCH ATTACHMENTS

		Weld butt		*Branch attachment weld*	
Number of samples		*BS 4870*	*ASME IX*	*BS 4870*	*ASME IX*
Macro-examination		1	—	4	Not required by code
Hardness survey		1	—	1	
Transverse tensile		1	2	—	
All-weld tensile		1	—	—	
Root bend	<10 mm BS 4870 <9 mm ASME IX	2	2	—	
Face bend	<18 mm ASME IX <10 mm BS 4870	1	2	—	
Side bend	>10 mm BS 4870 >9 mm ASME IX	2	4	—	

designed to accommodate materials having nominated impact values. The groups represent a best endeavour to associate base materials having similar weldability composition and mechanical properties (Table 7). If used intelligently, this reduces the number of qualification tests required.

All the procedure parameters must be accurately recorded at the time of testing and, once documented, the procedure remains valid provided none of the essential variables are changed. The mechanical test requirements of ASME IX and BS 4870 for butt and branch welds are summarised and compared in Table 8.

Planning of weld procedure testing is essential if the minimum number of tests is to be carried out and qualified prior to production welding commencing. The sequence of events would be:

(a) List all welds involved in the contract.
(b) Determine date when they must be first used in production.
(c) Decide the type of welding procedures to be used.
(d) Classify (a) into groups which can be qualified by a single test.
(e) Set the conditions of the test such that all essential and supplementary essential variables for all welds are covered.
(f) Establish schedule of operations to meet required date (b).

A different approach is however adopted by the American Welding Society's Structural Welding Code AWS D.1.1, where qualification by individual fabricators of certain common joints and consumables used

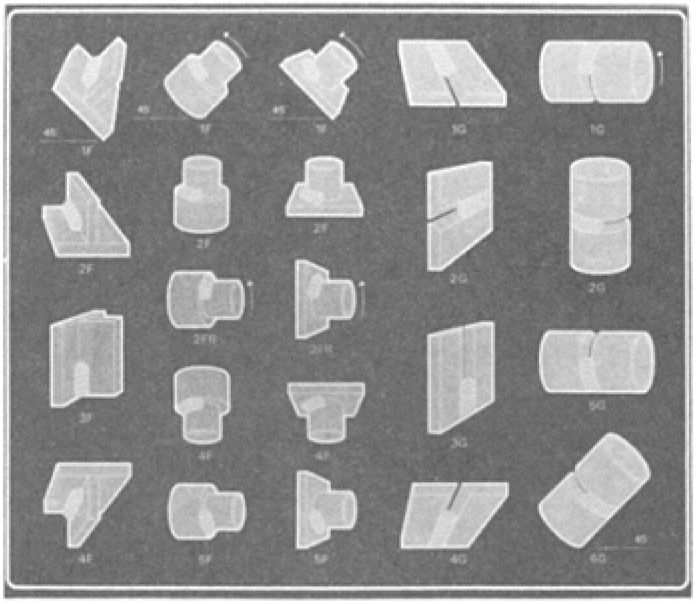


FIG. 12. The basic test positions for fillet and groove welds, as defined by ASME IX.

with any listed steels is not required provided nominated requirements are met. Such welds are designated as 'prequalified' and the code defines the joint configurations, with tolerances, which may be used with manual metal arc, submerged arc, gas metal arc (except dip transfer process), or flux cored arc welding, as appropriate.

Welder approval is based on the operator producing a test piece using

TABLE 9
ASME IX PERFORMANCE QUALIFICATION AND ASSOCIATED LIMITING POSITIONS

Qualification test	*Position and weld type qualified by test*	
Butt weld	*Butt welds*	
Plate position	*Plate*	*Pipe*
1G	1G	1G
2G	1G, 2G	1G, 2G
3G	1G, 3G	1G
4G	1G, 4G	1G
3G, 4G	1G, 3G , 4G	1G
Pipe position		
1G	1G	1G
2G	1G, 2G	1G, 2G
5G	1G, 3G , 4G	1G, 5G
6G	All	All
2G, 5G	All	All

Qualification test	*Position and weld type qualified by test*	
Butt weld	*Fillet welds*	
Plate position	*Plate*	*Pipe*
1G	1F	1F
2G	1F, 2F	1F, 2F, 2FR
3G	1F, 2F, 3F	1F, 2F, 2FR
4G	1F, 2F, 4F	1F, 2F, 2FR, 4F
3G, 4G	All	All
Pipe position		
1G	1F	1F
2G	1F, 2F	1F, 2F, 2FR
5G	1F, 2F, 3F, 4F	All
6G	All	All
2G, 5G	All	All
Fillet weld	*Fillet welds*	
Plate position	*Plate*	*Pipe*
1F	1F	1F
2F	1F, 2F	1F, 2F, 2FR
3F	1F, 2F, 3F	1F, 2F, 2FR
4F	1F, 2F, 4F	1F, 2F, 2FR 4F
3F, 4F	All	All
Pipe position		
1F	1F	1F
2F	1F, 2F	1F, 2F, 2FR
2FR		1F, 2FR
4F	1F, 2F, 4F	1F, 2F, 2FR, 4F
5F	All	All

parameters determined during the procedure test, but the test is now aimed at demonstrating the welder's *skill* in performing the operation—his ability to produce a sound weld, *not* to reapprove the procedure by a full testing schedule. Variations to the welder qualification procedure are acceptable which would be considered vital in welding procedure qualification. For example, steels and electrode types are grouped together and proof of the welder's skill with one steel or electrode will be acceptable for many others. The basic test positions recognised by the ASME Code are illustrated in Fig. 12 whilst Table 9 shows how the increasing difficulty of certain positions qualifies the welder for other positions which are considered easier to weld. A similar system of qualification positions is given in BS 4871.

Certification of welder approval is valid for a nominated period, three months, six months or one year, but at these intervals checks are made, normally by the employer, to confirm the continued skill of the operator. If any serious deterioration of capability occurs as shown for example by poor non-destructive testing performance, the operator will be advised and subjected to retraining and/or recertification. If the record is satisfactory, the certificate is endorsed and is valid for a further period. Normally a certificate lapses if no work of the type covered by the certificate has been performed in the preceding period.

CALIBRATION OF WELDING EQUIPMENT

Quality Management systems normally require fabricators to provide control and maintain inspection, measuring and test equipment to demonstrate conformance to specified requirements. Such systems, as part of manufacturing management control, require that the fabricator conducts his operations under controlled conditions, including provision of suitable manufacturing equipment. When taken together these requirements can place extreme demands on the fabricator to provide, calibrate and maintain calibration of a great variety of welding equipments. In some cases auditors have made extreme demands such that, for example, a.c. transformers, which are not normally provided with meters, are fitted with a meter in order to calibrate the equipment!

Whilst national standards exist which describe the calibration of new meters etc., no standards are available which describe requirements for the calibration of various welding equipments, the accuracy of which may or may not influence the resultant weld.

In order to meet this potential impasse one major fabricator, with over twenty manufacturing plants in the UK, has prepared a Calibration Policy for Welding Equipment. This is implemented as a minimum in all his plants, but may be exceeded in certain locations, depending on particular circumstances.

This policy identifies three categories of welding plant, the main features of which are as follows:

Category 1

'Welding equipment where the quality of welding is primarily dependent upon and controlled by the welding operator without reference to instrumentation. Calibration is not normally required for the correct execution of welds in this category.' Included in this category are:

(a) oxy/fuel gas welding;
(b) manual metal arc welding;
(c) manual TIG welding;
(d) manual MIG/MAG welding, including bare wire and flux cored wire welding;
(e) self-shielded wire welding.

Category 2

'Welding equipment where the quality of welding is primarily dependent upon and controlled by the welding operator through reference to instrumentation.'

This category of equipment shall be provided with meters. Such meters shall comply with the requirements of BS 638 (latest edition), 'Arc Welding Plant, Equipment and Accessories', and shall be calibrated to the levels prescribed in that standard. Speed will normally be checked by rule and stopwatch. The speed of associated equipment, e.g. rotation speed, may also be checked by rules and stopwatch.

Where travel speed meters are fitted, these shall be for guidance only, unless subject to calibration control.

Included in Category 2 are all mechanised welding processes where the welding parameters are set and adjusted by the welding operator. (A mechanised welding process is defined as one in which the welding torch is mechanically supported rather than hand-held.) Examples are submerged arc welding and unprogrammed, mechanised MIG/MAG/TIG equipments.

Category 3

'Welding equipment where the quality of welding is primarily dependent upon and controlled by a pre-programmed welding sequencer.'

The equipment in this category may be controlled by electronic means and may not necessarily involve the use of meters. Where meters are provided they shall be regarded as for guidance only.

All instrumentation used for setting up such equipment for production and maintenance or adjustment shall be calibrated. This calibration may be carried out by the manufacturer, in accordance with in-house procedures, or by services offered by external organisations.

Included in this category are:

(a) all robot welding;
(b) all pre-programmed TIG and MIG/MAG welding machines;
(c) all high energy and solid phase welding equipments, including flash butt welding.

Except in very demanding circumstances, calibration of gas flow and gas bottle meters is not required since the amount of variation encountered does not normally influence weld quality.

The frequency of calibration is determined by the requirements of particular plants, but does not exceed approximately 12 monthly intervals.

The need for a definite policy for the calibration of welding equipment has been referred to the British Standards Institution for consideration.

Problems are often encountered with drying and baking ovens for electrodes, particularly at higher temperatures, above 300°C, when the temperature may be shown on the recorder but not achieved in electrodes. Failure to achieve the required temperature may also be a function of the way the electrodes are loaded into the oven (Fig. 13) since, if the layers of electrodes are too thick, heat may not reach to the centre of the bundle in the nominated time [18].

Preheating and post-weld heat treatment of welds is critical to the success of the welding operation. Preheat is often measured by temperature-sensitive crayons which, whilst generally accurate in themselves, do not provide a continuous reading of temperature. Portable and permanent devices for measuring preheat, including pyrometers, digital devices, etc., should be subjected to regular (not exceeding three months) calibration against a known standard, and should be marked with a label showing the date of the next calibration, in addition to the normal book records. Furnaces used for heat treatment normally contain permanent thermocouples recording the furnace atmosphere temperature, whilst portable thermocouples are often attached to measure the actual *metal* temperature on a multi-channel recorder. Both these systems require regular checking and certification for conformity.

WELDING OPERATIONS

There is a series of distinctive actions which are required to be performed prior to, during, and subsequent to the welding operaton, apart from systematic activities described elsewhere in this chapter, e.g. consumable control. Not every action is required for every construction, but a conscious decision should be taken when omitting any activity, e.g. not providing local environmental protection. The major requirement is to ensure that the qualified weld procedure is followed as accurately as possible.

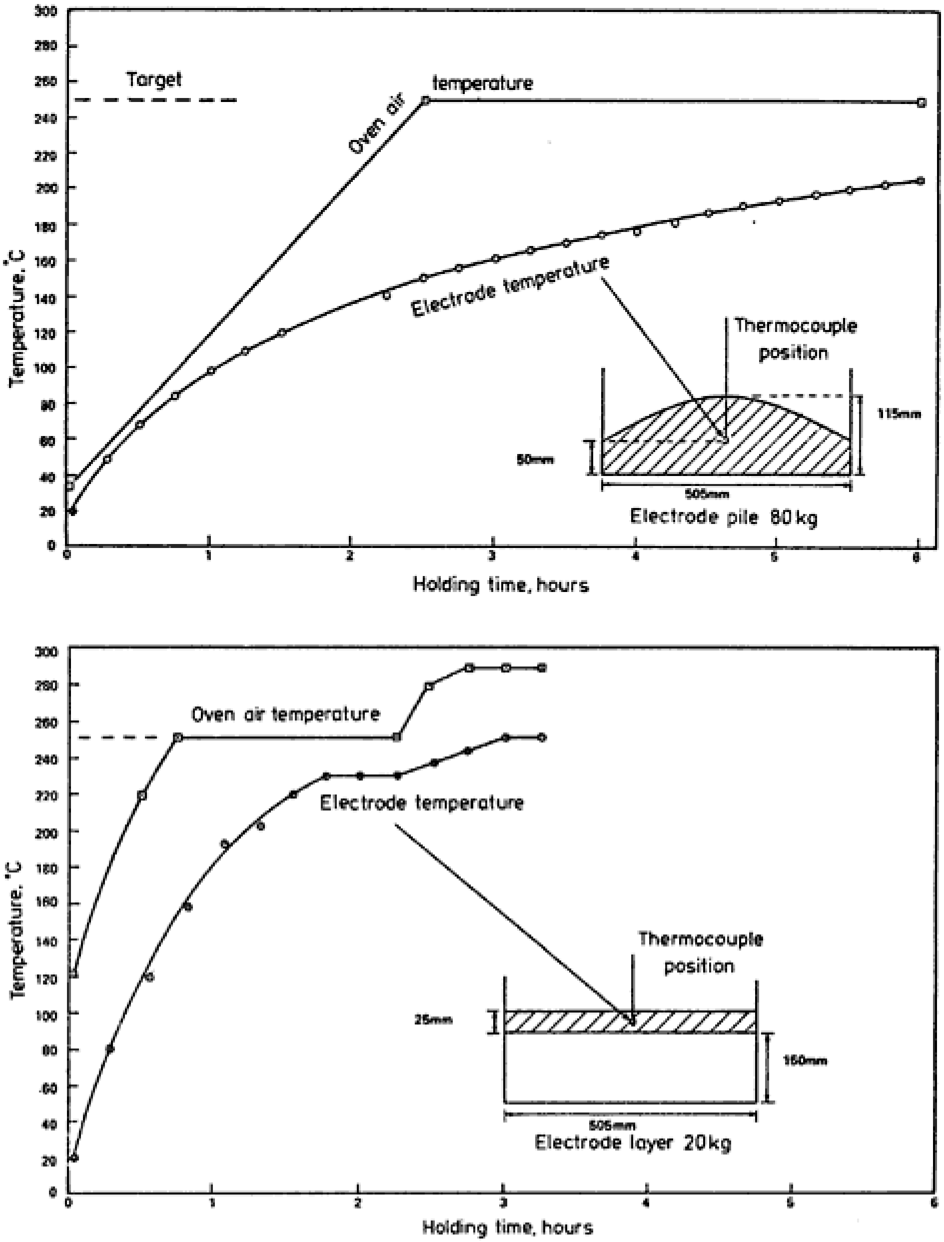


FIG. 13. The effect of loading electrodes into a drying oven in piles or bundles rather than thin layers of *c.* 25 mm showing how readily electrodes can be inadequately dried. Top—temperature rise after loading 80 kg of electrodes into a hot oven at 250°C original temperature. Bottom—temperature rise after loading 20 kg of electrodes into a hot oven at 250°C original temperature. (After Boniszewski and Pavely, reference 18.)

Prior to Welding

(1) *Protection* of the welder from the elements such that the adopted welding process is not adversely

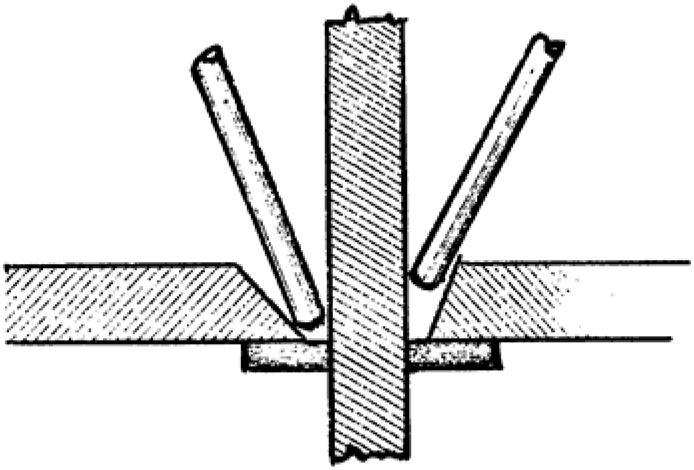


FIG. 14. How the joint weld preparation angle on the root gap can limit access for welding. On the left hand side a 45° angle is adequate to reach the root area but on the right hand side with 22 1/2° the weld metal will bridge without fusing into the root, unless the root gap is increased.

affected. In some cases it may be essential to erect a temporary sheeted cover over the workpiece to prevent the effect of draught or wind when using gas shielded processes such as MIG or TIG, even in a shop environment, apart from the need for protection from the elements when working outdoors.

(2) Data is not readily available as to the effect of *wind,* at various speeds, on gas-shielded processes. BS 5135 suggests that air currents as low as 8 km/h can remove shielding gas. The normal conservative practice is to provide temporary protection. Self-shielded flux-cored electrodes do not use gaseous protection and can be used in exposed locations. Care must also be taken in siting automatic gas-shielded machines relative to shop doors, etc., or porosity may occur intermittently as these are opened and closed.

(3) Care must be taken to ensure *cleanliness* of the work. This may be achieved by wire brushing, grinding, solvents, etc., depending on the nature of the contaminant. Clean materials should not be assembled for long periods prior to welding or dirt or grease may enter into joints and affect weld quality. Care is required to ensure that dirt and rust are not trapped in joints involving fillet constructions or porosity may result. BS 4870 requires the method of cleaning to be indicated on the Procedure Qualification Record (PQR).

(4) *Weld preparation* dimensions and *fit-up* should be carefully checked and rejected if not conforming to the welding procedure requirements. Accidental reduction of the size of the weld preparation may give insufficient access to deposit weld metal in the required sequence or by the nominated process (Fig. 14). On the other hand, if the weld preparation is too large, distortion may occur together with excessive shrinkage, apart from incurring additional costs due to the increased volume of weld metal. Similarly, the fit-up of joints requires close attention. Misalignment, mismatch or incorrectly sized gaps can, again, make the joint unacceptable. Fit-up for non-arc processes such as electron beam or laser welds are critical and often require machined edges.

(5) *Preheat* metal temperatures should be determined and welds should not be made if the required temperature has not been achieved within about 75 mm of the welding point. Preheat is sometimes applied

by placing the component in a furnace—in such cases the metal temperature of the workpiece must be measured—*not* that of the furnace.

For carbon and carbon manganese steels, guidance on the calculation of preheat is given. This takes into account the joint geometry and thickness and the hydrogen content of the weld metal. Reference is made to tables to determine the relevant preheat. The Welding Institute, and others, now offer this data as a programme to be used on a microcomputer.

For other alloy steels, application standards, e.g. BS 5500 and BS 1113, give guidance but do not normally relate to the potential hydrogen content of the weld.

During Welding

(1) *Tack welds* should be examined during welding to ensure they are sound and have not broken. Failure to do this can result in distortion or incorrectly dimensioned fabrications.

(2) *Welding parameters* should be checked, including welding current, polarity, electrode or wire sizes, travel speed and gas flow rates, when applicable.

(3) The *deposition sequence* of weld runs should be confirmed to ensure that no pockets are formed and that deslagging is effective (when required). Control of distortion techniques must be observed [19].

(4) *Preheat* and *interpass* temperatures should be constantly monitored. In some cases the work must not fall below specified temperatures and in others must not exceed a given temperature prior to deposition and subsequent run of weld metal.

(5) In-process *non-destructive testing* should be applied at any initial stages of welding, e.g. magnetic particle testing of root passes, as required by the weld procedure or quality plan.

(6) When required by the contract, control of the *weld consumables* should be maintained to each welder concerned in the work and joints or parts of joints should be identified as being the work of specific welders. This requires careful control of the welders to ensure that they continue to operate in their designated zone.

After Welding

(1) The final *geometry* of the weld should be examined for size and shape, undercut, porosity and cracks.

(2) Welds which are ground should be examined for excessive removal of metal which may reduce the effective thickness of the component.

(3) Particular attention should be paid to the removal of spatter and temporary assembly cleats.

(4) Non-destructive testing should be carried out by competent operators. Care should be taken in certain cases, e.g. high strength low alloy steels, that the prescribed period (normally about 48 h) has elapsed before testing is permitted to commence, since delayed hydrogen cracking may occur.

(5) Repairs to any defective areas should be made to approved procedures, the workpiece having been clearly marked in an unambiguous manner to prevent the repair being carried out at the wrong location.

(6) Heat treatment, when required, should be confirmed as conforming to the procedure in respect of temperature gradients, heating and cooling rates, location of thermocouples, etc.

WELD RECORDS AND FEEDBACK OF INFORMATION

In a number of cases the fabricator is required by the code of practice to maintain records of some aspects of welded constructions. These records are normally provided to the purchaser and may even form part of the contractual agreement. Such records commonly include [20]:

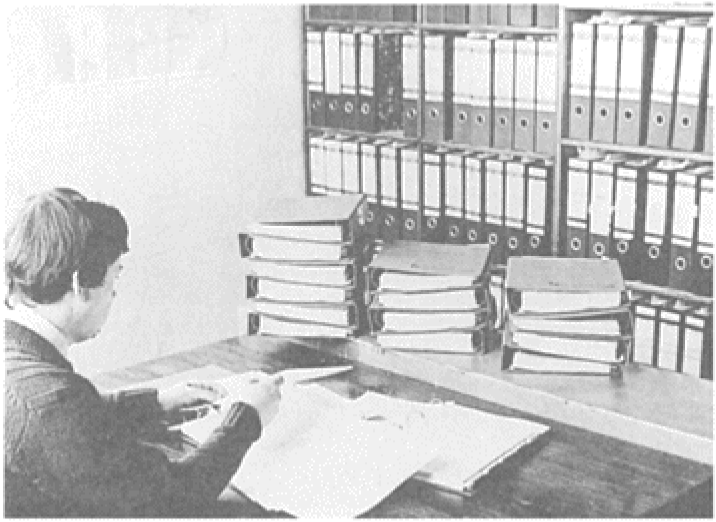


FIG. 15. Compilation of data books for the fabrication of a high quality steam drum.

(a) material test certificates;
(b) weld procedure test records;
(c) welder performance certificates;
(d) heat treatment charts;
(e) reports on non-destructive testing;
(f) hydraulic test certificates.

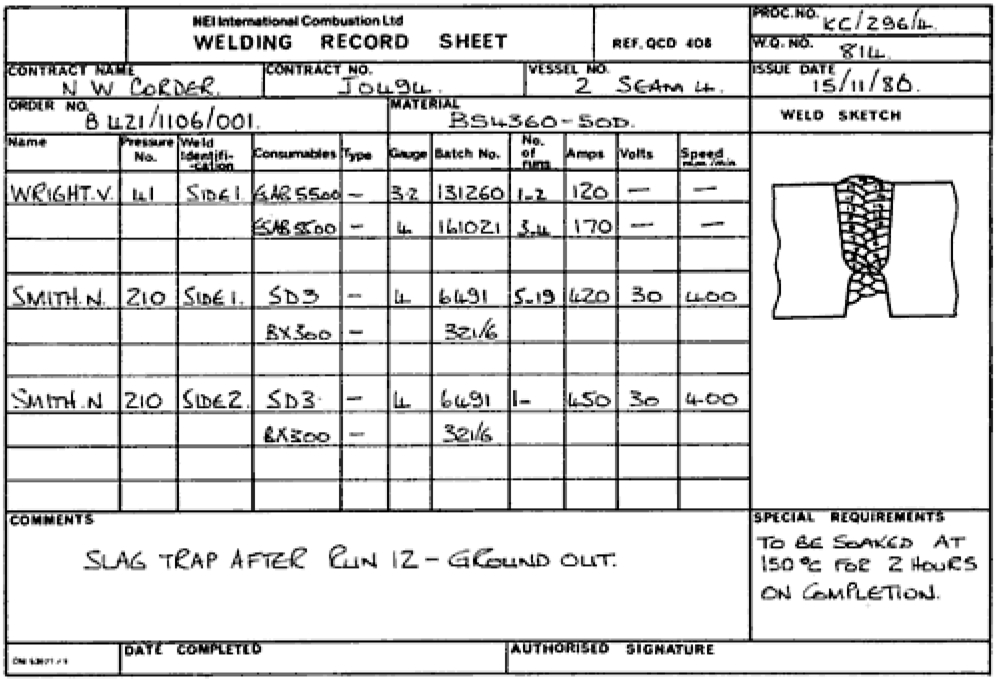
In the case of complex or very large projects, the compilation of the required data can require a significant effort on the part of the fabricator, and a systematic approach, based on the quality plan, is required to ensure all data is input to a central source from all individual activities engaged on the project, for example, metallurgy, inspection, NDT, etc. The use of in-house, pro-forma documents is to be commended to ensure that all the required information is provided. The amount of paperwork required can be significant and Fig. 15 shows the manual compilation of data books for a large steam drum. The use of microfilming of data is now common and it would be of great value in many cases if purchases would accept microfiche in lieu of the paperwork.

There are few cases where the codes or specifications require records of the actual use of welding consumables, although many fabricators find it beneficial to be able to identify which consumables have been used in which seams. Welders can be issued with seam record cards (Fig. 16) when they are given the instruction on weld procedures, and the completed cards controlled by the welding engineer.

Records of weld quality are often maintained by fabricators in order to be able to measure the effectiveness of their workshops and welders (Fig. 17). Such data is normally compiled by the inspection and non-destructive testing departments and is provided at regular intervals of, say, a week or a month, to senior production management.

There are a number of ways in which the information can be supplied in terms of weld seam length, sub-components welded or items completed,

TABLE 10



NEI International Combustion Ltd
WELDING RECORD SHEET
REF. QCD 408
PROC. NO. KC/296/4.
W.O. NO. 814.
CONTRACT NAME N W CORDER.
CONTRACT NO. J0494.
VESSEL NO. 2 SEAM 4.
ISSUE DATE 15/11/86.
ORDER NO. B 421/1106/001.
MATERIAL BS4360-50D.
WELD SKETCH

Name	Pressure No.	Weld identifi-cation	Consumables	Type	Gauge	Batch No.	No. of runs	Amps	Volts	Speed mm/min
WRIGHT.V.	41	SIDE 1	ESAB5500	—	3.2	131260	1-2	120	—	—
			ESAB5500	—	4	161021	3-4	170	—	—
SMITH.N.	210	SIDE 1.	SD3	—	4	6491	5-19	420	30	400
			BX300	—		321/6				
SMITH.N	210	SIDE2.	SD3	—	4	6491	1-	450	30	4-00
			BX300	—		321/6				

COMMENTS
SLAG TRAP AFTER RUN 12 – GROUND OUT.

SPECIAL REQUIREMENTS
TO BE SOAKED AT
150 °C FOR 2 HOURS
ON COMPLETION.

DATE COMPLETED
AUTHORISED SIGNATURE

FIG. 16. A partially completed weld seam record card for a submerged arc weld.

EXAMPLE OF A REWORK CAUSE CODE RELEVANT TO WELDED FABRICATION

Code	*Cause*	*Notes*
0031	Drawing errors, route cards, documentation	Incorrect drawings, revised drawings, issued after job has started resulting in scrap or rework; incorrect documentation
0032	Defective, incorrect or lost material	For any reason whether due to internal errors or incorrectly furnished by suppliers
0033	Layout	Material laid out incorrectly, wrong patterns used, etc., marking out; jigging
0034	Material preparation	Burning, grinding operations
0035	Tube manipulation and tube preparations	Unsatisfactory bending, incorrect weld preparations
0036	Defective castings	All causes
0037	Forming and pressing operations	Defective press tools, incomplete bending, incorrect material temperatures
0038	Machining errors due to operator mistakes	
0039	Defective machines	Machining errors caused by inadequacies of the machine
0040	Fitting errors	Including erection fitting, electrical fitting, etc.
0041	Fit up/clean up	Butt welds, nozzles, stubs, lugs, etc., not attached correctly (out of position etc.); scale, slag, spatter, burns and sharp edges not removed
0042	Manual welding (MMA)	Undersize or oversize welds, undercut defective welds, welds not to drawing, incorrect rods, etc.

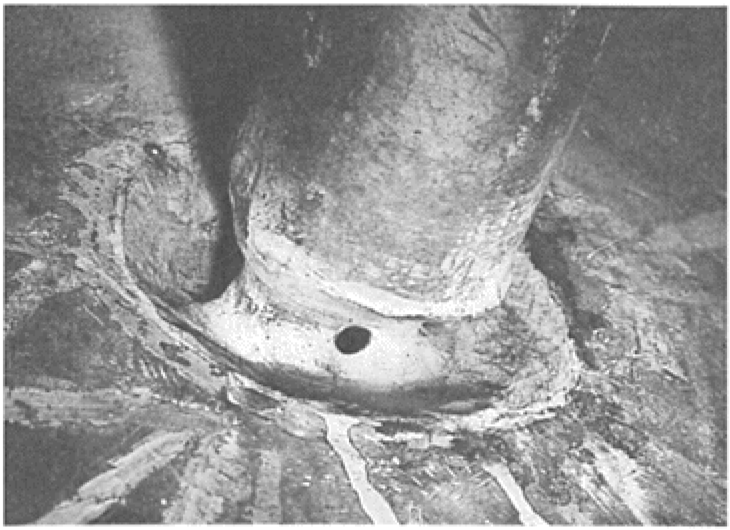


FIG. 17. An extreme example of excavation of a 75 mm diameter stub weld to remove slag, detected by ultrasonic testing and trapped above the argon arc root pass.

Code	*Cause*	*Notes*
0043	Welding	All methods except MMA
0044	Heat treatment errors	Including incorrect pre- or post-heat
0045	Handling, packaging, storage	Machine surface damages, damage caused during internal transport, deterioration due to incorrect or poor storage, damage to packaging etc.
0046	First time weld repairs	
0047	Quality control errors	Incorrect NDT sentencing, incorrect inspection leading to rework, incorrect heat treatment instruction, incorrect quality literature
0048	Miscellaneous	Includes all reasons not listed above; a full explanation should be made in the rejection notice
0049	Site damage/losses	All work connected with site

the amount of satisfactory work being measured against that found to be defective [21], i.e.,

$$\text{rework (\%)} = \frac{\text{defective weld (mm)}}{\text{total weld (mm)}} \times 100.$$

This form of measurement gives a quick overall reading of how an individual welder or workshop is performing; the shop manager or welding engineer soon learns if he normally operates at, say, ‘3% defective’ and can take prompt action to deal with any situation if a drift is noted. It also enables a measure to be made of the effectiveness of changes, i.e. introduction of a new welding process.

Data can also be kept, normally using a computer based system, of the rework causes and costs which are then segregated by a cause code for subsequent analysis. Such data can be of great use in pinpointing problems to a particular shop, office, machine or process, and enable effective corrective action to be taken.

Some examples of the cause codes used by one fabricator are given in Table 10. Given such data and its cost, associated with the overall costs of quality, it is possible to provide senior management with information which enables the efficiency of quality operations to be measured [22].

The feedback of information to the welding engineer and designer from the shop floor, erection staff and operating personnel, is essential if reliable, economic fabrications are to be produced. It should never be too much trouble to report difficulties since, unless reported, they will repeat themselves in other circumstances and inevitably cost money to correct.

THE IMPACT OF MODERN TECHNOLOGY ON WELDING

Like many other industries, welding is now being significantly influenced by modern technologies in the fields of microcomputers for QA data processing and controlling the welding process. It is premature to consider how the effects of these changes will modify existing concepts of quality assurance for welding, but it is certain that facilities are becoming available which make the control of the welding operation much more positive than previously. Some examples are therefore given of how they are making an impact on the industry.

Welding Information

Microcomputer programmes are now available which facilitate the job of the welding engineer in the preparation and subsequent recording and filing of weld procedure data. 'Floppy disk' programmes are commercially available which enable, for example:

(a) calculation of preheat (to BS 5135);
(b) documentation of volume of weld metal (for estimating purposes);
(c) establishing the cost of depositing weld metal (again, for estimating purposes);
(d) development of weld procedure data (to meet, for example, specific heat input requirements);
(e) storage and retrieval of weld procedure data.

All these programmes have a common objective in that they permit the engineer to perform necessary, often routine, tasks quickly and with the maximum precision.

Controls are necessary to ensure that any changes to the programmes are made only by authorised persons, and that records of such changes are maintained.

Inspection of Welding

Welded components are now being increasingly examined for conformity to dimensional specifications by automatic multi-axis measuring machines. Such equipment has been used with great success in measuring small welded components for nuclear power plants, and for the checking of welded car body shells.

New horizons may appear with the advent of portable laser operated bar code readers. These units are the size of a small torch and will store data throughout an eight-hour shift; this data is then transferred to the factory computer for analysis and storage. The system has found increasing use in recording the visual quality of welds, for example in tubes in boiler plant, and may be extended to embody data from nondestructive testing. The resultant information is clear, legible and suitable for contract records [23].

FIG. 18. Microprocessor controlled robot, with built-in seam tracking facility, welding on earthmoving equipment.

Welding Equipment

Welding equipments are increasingly controlled by microchips and processors. Standard MIG equipment is now available in which predetermined weld parameters can be obtained by the welder simply by turning a knob to a nominated setting. This then gives optimum settings for a given wire diameter, composition and shielding gas. The welder is only able to 'tune' the weld parameters very slightly; this advance is leading to much more regular utilisation of correct weld settings by welders and can therefore only lead to more consistent weld quality. The welding engineer can now specify, for example, 'downhand welds—setting 3', 'vertical welds—setting 5', and will know that the welder will be very close to his optimised settings.

Microprocessor control of real time welding operation is now available, and is used for automatic applications of TIG in both tube to tubeplate and orbital tube and pipe welding. Changes to the amperage and voltage can be readily programmed to occur at predetermined points in the weld cycle. The consistency of weld quality in such welds is considerably enhanced by the process control now employed.

Presetting of welding parameters and associated control of movement of the welding arc, for example in robotic operations, is now available for the MIG/MAG process (Figs 18 and 19). Welding parameters can be readily preset and varied at will, for a variety of materials, wire and gas combinations. Programmes are often controlled through a closed loop feedback system from the arc itself, and may embody seam tracking through the arc. Once programmed into the equipment the control console can be locked leaving the welder to simply 'trim' the settings. Once again, consistency of the operation, and quality, can be assured over large numbers of components, with little intervention required either by the engineer or the welder. Attention should, however, be paid to ensuring that an adequate system to ensure correct calibration of equipment is established, especially if a number of identified equipments are performing similar tasks.

EXAMPLES OF PROBLEMS ASSOCIATED WITH WELDING

The earlier part of this chapter described a sequence of actions which, if correctly followed through the manufacturing cycle of a fabrication, will largely guarantee a successful product. We do not however live in

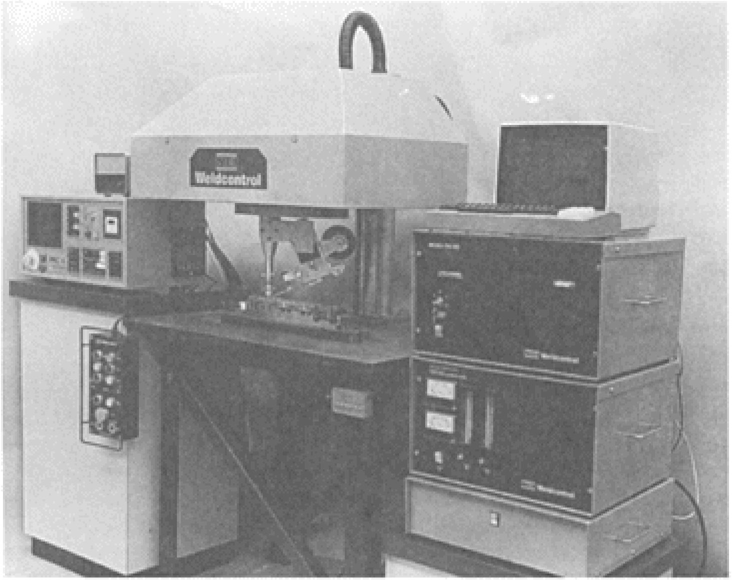


FIG. 19. TIG plus filler blade tipping system incorporating weld control, microprocessor controlled transistorised power source and PNC four-axis controller.

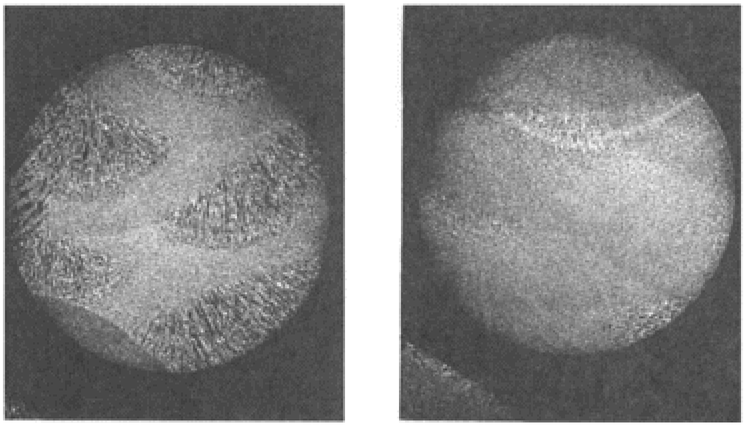


FIG. 20. The carbon-manganese submerged arc weld on the left hand side with clear, alternate refined and unrefined ferrite, gave 512 N/mm^2 UTS whilst the essentially refined weld metal on the right hand side from the same weld gave only 457 N/mm^2 UTS.

a perfect world and a number of cases are now given which illustrate the consequences of failure to observe these quality principles.

Test Plate Failure

The test plate for a steam drum was welded in 102 mm thick BS 1501– 223–32B, by submerged arc welding using SD3 wire and BX 200 flux. The plate was examined by X-ray and subsequently heat treated in accordance with BS 1113 at 600°C. The minimum tensile strength of the joint was required to be 494 N/mm^2, and all weld test pieces were taken from the top and bottom sides of the test plate. The results obtained were —top of the weld, 457 (UTS) N/mm^2; bottom of the weld, 512 (UTS) N/mm^2;—representing a shortfall of 37 N/mm^2 for the top tensile test piece.

Comprehensive examination of records of consumables used showed no identifiable problems and analysis of the tensile test pieces gave the following results:

	C%	Si%	Mn%	P%	S%	Cr%	Mo%	Ni%	Cu%
Top:	0·07	0·26	1·61	0·017	0·007	0·05	0·01	0·04	0·27
Bottom:	0·06	0·28	1·62	0·014	0·010	0·04	0·01	0·04	0·30

These figures clearly indicate that there was no error in the consumables used. Hardness tests on the tensile samples showed average values of 206 Hv_{10} at the top and 215 Hv_{10} at the bottom. Macro- and micro-examinations indicated that, whilst the lower sample consisted of alternate unrefined acicular ferrite and refined zones of fine-grained polygon-ferrite, the latter being caused by the normalising and tempering action of successive weld passes, the upper sample contained a disproportionate amount of refined zone (see Fig. 20). This would account for the lower tensile strength recorded and probably arose from the weld bead deposition sequence, which differed from top to bottom of the weld, coupled with an excessive interpass temperature.

The Lesson

Eyen in a well executed weld, using proven consumables, the weld sequence and/or the interpass temperature can result in unsatisfactory mechanical properties.

Yoke Failure on Bending Press

A large, 2000 ton, vertical plate bending machine was closed by a 400 mm thick carbon steel hinge, after the plate was inserted between the joining rolls. During initial trials of the machine one winter's morning the yoke piece broke clean through in a brittle manner. Examination showed that the failure originated from an 8 mm intermittent fillet weld, attaching a guide member on the inside of the yoke (see Fig. 21). The weld had been made using rutile electrodes, with no preheat, onto a flame cut surface, and was not subjected to heat treatment.

The Lesson

Small welds on highly stressed members are very prone to cracking, ifinadequate welding procedures are used, thus initiating failure. Such welds should be avoided as far as possible. In this particular case, on the replacement unit, the guide member was attached by setscrews!

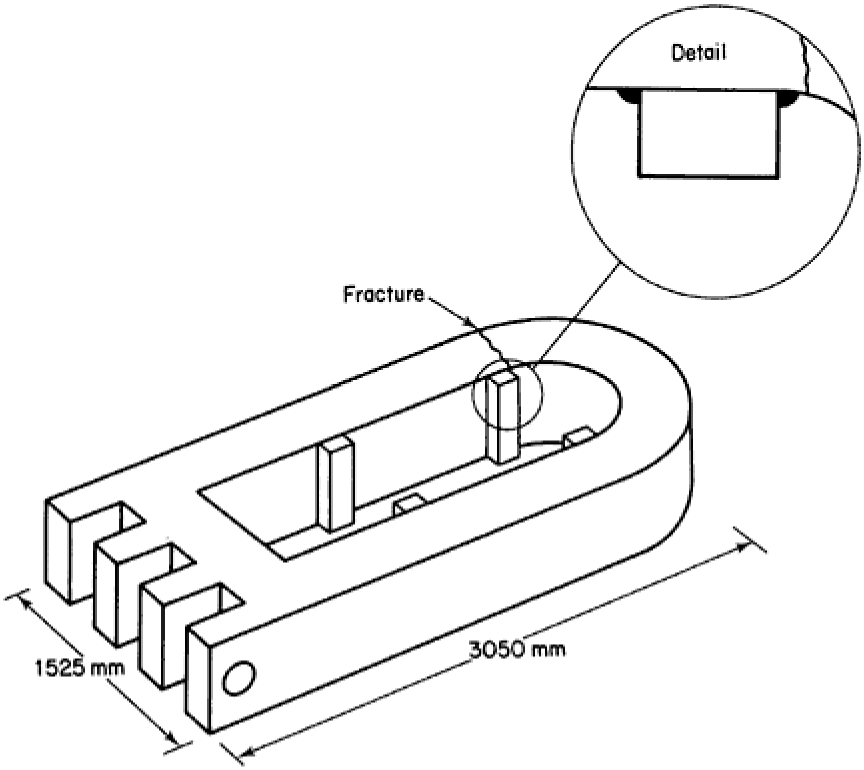


FIG. 21. Failure of yoke piece from a 200 ton vertical plate bender. The origin of the fracture was from an intermittent fillet weld attaching a guide bar.

Furnace Heat Treatment of Waste Heat Boiler

A medium sized waste heat boiler measuring about 4400 mm long and 2290 mm diameter, was made from 56 mm carbon steel to BS 1501–151– 28A. The unit had flat ends, 45 mm thick, through which 500 carbon steel tubes, 44·5 mm×5 SWG, were expanded and seal welded, and into which 14 large diameter stay bars were welded (Fig. 22). On completion of fabrication the unit was furnace stress relieved, as required by the code, at 600°C. The metal temperatures were measured on the end plates and on the shell, with the axis of the vessel horizontal. When the vessel had cooled it was found that the outer ring of tubes had bowed by as much as half-diameter, and others to a lesser extent, due to permanent elongation of the tubes.

Subsequent investigations showed that the tubes in the centre of the bundle must have been up to 100°C colder than the shell and outer tubes during the heating cycle, leading to significant residual stress and resulting in the deformation of the tubes.

The Lesson

Codes do *not* cover all circumstances and intelligent application, together with experience, is required by the welding engineer and designer. In this instance the fabricator failed to recognise the mass effect of the bundle of tubes and the consequential lag in temperature of the tube bundle behind the shell. The solution here was to retube and reheat-treat with the vessel vertical, using thermocouples inside the tube bundle

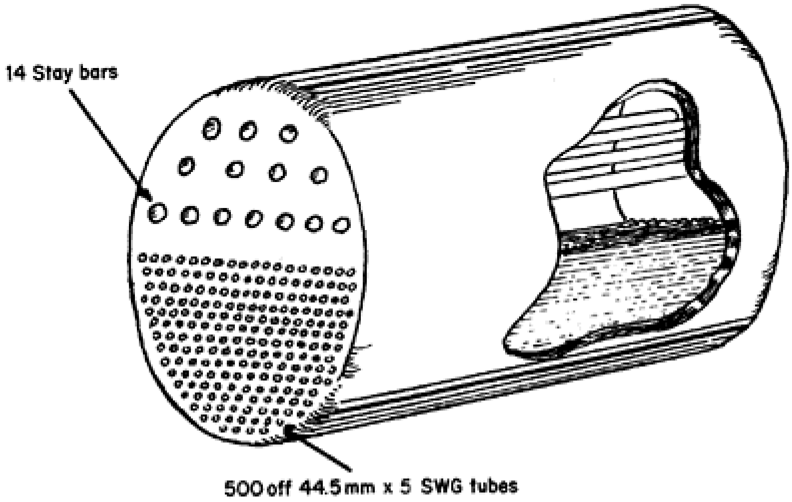


FIG. 22. Cut-away view of a waste heat boiler showing tube bundle and stay bars.

to control the heating and cooling rates, having established that a further stress relief treatment would not lower the properties of the shell plate below the design minimum [24].

Stainless Steel Tube Failure

It is sometimes a requirement for butt welds in stainless steel tubing to be locally solution treated after non-destructive testing has been carried out. In a power station a number of SA 213 TP 316 tubes, 27·5 mm OD×12 SWG, were required to be heat treated at 1030 to 1060°C for 30 min, followed by rapid removal of insulation and the electric heater. The temperature of each weld was measured using a thermocouple attached by capacitor discharge welding, the leg of which was bound with wire to the tube, to avoid damage to the thermocouple.

When cold a number of tubes broke transversely, just clear of the weld, in a brittle manner, and displayed an oxidised crack face. A light tan coloured deposit was noticed on the fracture face, and analysis revealed that this contained large quantities of zinc. Detailed investigations showed that the failure was due to hot shortness (of the material in the presence of molten zinc) and arose directly from binding of the thermocouple to the tube with galvanised wire, when heated at 800 to 950°C, and under a stress of 3000 to 6000 psi.

The Lesson

Great care must be taken at all times to ensure that incompatible materials do not come into contact with susceptible welded fabrications. A further example, commonly encountered, is when the copper alloy contact tips on submerged arc welding heads are accidentally in contact with the weld pool—cracking will inevitably result.

Mechanical Properties of a Submerged Arc Weld

An SD3 1/2Mo wire used with an acid flux had satisfied all requirements for the welding of a low alloy steel (Mn, Cr, Mo, V) with tensile strength of 560 N/mm^2 (min) and a yield strength of 385 N/mm^2 (min). During a routine examination of a test plate the following all weld tensiles were recorded.

	Specimen 1	Specimen 2
Yield stress (N/mm^2)	388	404
UTS (N/mm^2)	492	532

The UTS values do not meet the minimum specified requirement, and a full investigation ensued. The wire, weld deposit, and the wire used for the initial tests were analysed, with the following results:

	C %	Mn %	Cr %	Mo %
Original wire	0·154	1·91	0·10	0.621
Production wire	0·11	1·78	0·10	0·47
Weld deposit	0·04	1·11	0·15	0·50
Wire specification	0·16 maximum	1·60/2·20–0·40/070		

The inferior properties are clearly due to the lean analysis of the weld deposit, with carbon and manganese being particularly low. The carbon loss of 0·07% was considered to be particularly significant and was ascribed to the use of the acidic flux. The short term solution to the problem was to control the wire to 0·15% C minimum, 1·8% Mn minimum, and 0·50% Mo minimum, whilst in the longer term a different combination of wire and flux (basic) was adopted.

The Lesson

Welding consumables are supplied within a range of compositions and care must be taken to ensure that procedure test results are not obtained from wire at the upper end of the range, or unsatisfactory mechanical test values may be obtained during production from materials at the lower end of the specification. The fact that the wire specification had a maximum carbon value but no minimum was significant, particularly when used with an oxidising flux.

Brittle Failure of Large Water Turbine Spiral Casing

A turbine spiral casing, some 2–4 m diameter, was fabricated in a 'lobster back' manner from 42 mm high-tensile carbon steel conforming to the now obsolete BS 968:1962. The specified composition was (all maximum values):

C %	Si %	Mn %	S %	P %	Cr %	Ni %	Cu %
0·23	0·35	1·8	0·060	0·060	0·35	0·50	0·60

A branch pipe, some 1000 mm diameter, was attached at an angle of about 45°C to the axis of the spiral, compensation being provided for the opening by a large reinforcing ring. Welding was by manual metallic arc using low hydrogen electrodes and with a nominal preheat of 100°C. Non-destructive testing was by radiography of main seams, and magnetic particle inspection of fillet welds. Cracking problems were

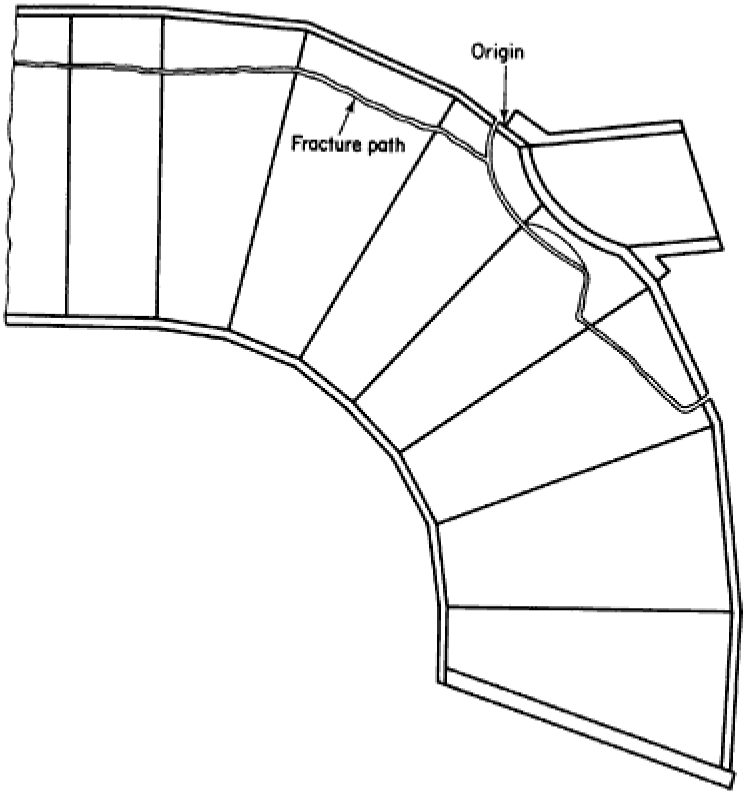


FIG. 23. Sectional plan view of failure of water turbine spiral casing showing path of crack.

encountered during fabrication in a number of welds and the unit was given an intermediate stress relief at 625°C. The cause of this cracking was not determined.

The unit was undergoing hydraulic testing at 10°C (50°F) to achieve a design pressure of 53 bar, when the spiral burst in a brittle manner at 52 bar. The fracture ran from the edge of the compensating ring in both directions and was some 8 m in length (see Fig. 23). Examination showed the plate to posses very poor impact strength, although this property had not been specified when the plate was ordered. There was a large, almost through-thickness, repair weld, some 1·3 m long, in the spiral plate adjacent to the compensating ring fillet weld, in which extensive heat affected zone cracking had occurred, and which acted as the origin of the crack. The particular plate was severely segregated, a factor which probably contributed to the cracking.

The Lesson

Although this particular failure occurred some 20 years ago it illustrates some of the difficulties which can be encountered during fabrication work. These include:

(a) When structural components which, even locally, reach yield point stress, whether stress relieved or not, they should be made of notch ductile steel.

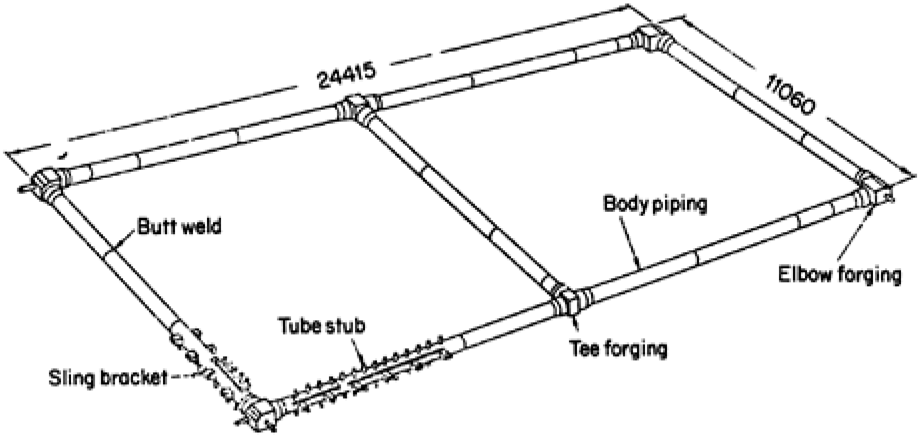


FIG. 24. Typical header assembly for high pressure steam generators.

(b) When assessing the properties required in steel plates for a particular application, due consideration should be paid to possible deterioration of these properties, particularly impact, when the steel is to be subject to cold forming, with or without subsequent stress relief. The casualty plate exhibited Charpy values of less than 10 ft/lb at the temperature of test.

(c) Joints in all highly stressed welds should be designed to lend themselves to meaningful NDT. This was not possible at the junction of the reinforcing ring to the shell plate, and fillet welds are extremely difficult to examine, other than by surface microprobe inspection.

(d) The preheating requirements for large complex fabrications may be difficult to achieve without careful planning. In this case local gas heating was probably totally inadequate, both in temperature reached and in its distribution.

(e) All major repairs to welds, or fabrication difficulties, should be reported to a central authority, by shop management, to determine any additional precautions to be taken. The incidence of cracking during manufacture of the spiral was possibly due to the severe segregation which contributed to the eventual failure.

(f) Weld repairs should be rigorously controlled to conform to approved weld procedures and should be subject to NDT at least as thorough as required on original welds. In the case in question the weld repair was not made to an agreed procedure and no records of NDT of the repair were available.

Effect of Base Material Manufacturing Route

Manufacture of collector and distributor headers for power stations, in a carbon-manganese steel, with a tensile strength of 32 tons/in^2, had proceeded without difficulty for a number of years [25]. The main header body was about 380 mm diameter and 50 to 70 mm thick, and consisted of an assembly of forged ‘T’ pieces and elbows, joined by wrought pipe, made by full penetration butt welds, and to which were added many tube stubs, 50 mm outer diameter×8 mm wall thickness (Fig. 24).

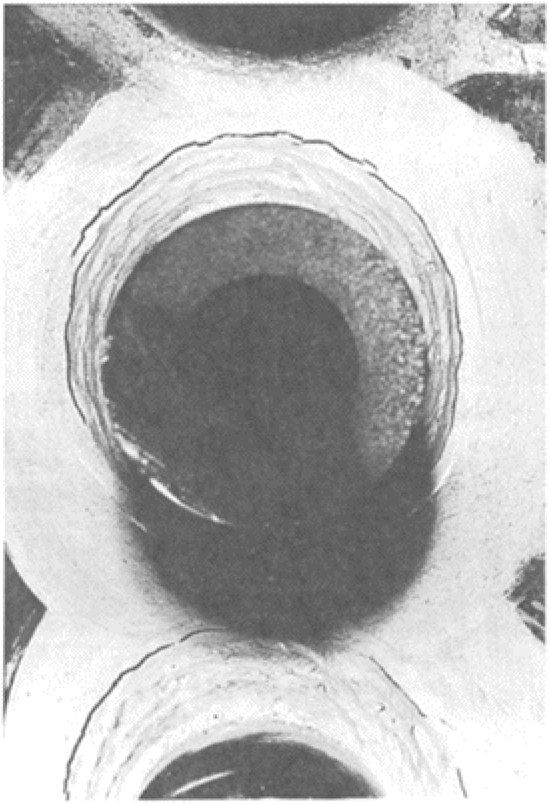


FIG. 25. Typical weld toe cracking as shown by magnetic crack detection techniques, on a low sulphur, carbon-manganese steel forging.

The basic manufacturing procedure involved a preheat of 100°C, the use of low hydrogen electrodes, together wth radiography of butt welds, and 10% magnetic particle testing of stub welds, before and after stress relief.

There had been no incidence of cracking when, without warning, cracks were found at the toes of an unprecedented number of stub welds (see Fig. 25) on forged elbows and ‘T’ pieces. After much heart searching and a process of elimination, it was concluded that the welding procedure was not at fault and the forging material was abnormally crack-sensitive. This conclusion was supported by the fact that components fabricated from material from another supplier were crack-free.

The cast analysis of the forgings was critically examined and no differences of significant consideration were noted. The analysis is as follows:

	Cracked forgings	Sound forgings
Carbon, %	0·22	0·23
Manganese, %	1·10	0·97
Sulphur, %	0·008	0·032
Phosphorus, %	0·041	0·024

Copper, %	0·19	0·07
Nickel, %	0·17	0·13
Tin, %	0·037	0·008
Nitrogen, %	0·011	0·012

There was no difference between the pearlite ferrite distribution, but it was noted that the steel of the cracked forgings was significantly cleaner.

It was established that the cracked material had been made by a basic electric arc, oxygen blown, vacuum cast route, whilst the sound forgings were made from acid open arc steel, the substitution having been made by the steelmaker without consultation with the fabricator. It was postulated at the time that the cracking was due to the cleanliness of the basic electric steel forging, and that the low volume of sulphide did not provide a sink into which hydrogen could be temporarily absorbed, thus avoiding incipient cracking. (A subsequent programme of work at The Welding Institute has suggested that with rolled plate the presence of inclusions helps to nucleate ferrite during cooling and that by reducing the number of inclusions this transformation is inhibited, resulting in a harder structure [26]. This investigation did not include forged products.)

Production was resumed using the same welding procedure but introducing a long post-weld hydrogen release treatment prior to stress relief, which proved effective in preventing cracking.

The Lessons

(1) Even a valid and well proven weld procedure can fail if the base metal is variable.
(2) Close liaison must be maintained between the user and the steelmaker, since changes in manufacturing routes of raw materials may have significant effects on fabrication.
(3) The user should indicate to the steelmaker the intended use of the material and any major working to be performed (e.g. cold spinning) since the latter can often advise on its probable effectiveness.
(4) The fact that the material was ‘better’ in respect of cleanliness was not so in respect of its weldability.

SUMMARY

The preceding sections of this chapter can be summarised into a number of key words which will prove useful aides-mémoires. The lists are by no means exhaustive, and certainly do not purport to indicate that the nominated activities must be performed by a single department, or indeed that they are the only actions to be performed. They do however give an overall view of major requirements to be completed in order to ensure a satisfactory fabrication.

Actions by the Client

(a) Specification of basic function and requirements.
(b) Design appraisal.
(c) Fabricator appraisal.
(d) Bid appraisal.
(e) Contract award.
(f) Approval of design, procedures and sub-contractors.
(g) Provide surveillance of manufacturing/inspection operations.

Design Responsibilities

(a) Determine function and material needs.
(b) Translate into working drawings and specifications. Incorporate value engineering, quality engineering, reliability and research and development.
(c) Establish tolerances and acceptance criteria.
(d) Design joints for welding access and testing.
(e) Observe economic and programme requirements.

Procurement Responsibilities

(a) Establish list of approved vendors and sub-contractors.
(b) Receive material requisitions.
(c) Issue purchase orders.
(d) Control incoming materials.

Manufacturing Responsibilities (including Quality Control)

Prior to Welding

(a) Review specification requirements.
(b) Prepare quality plans/inspection points/holds.
(c) Prepare work programme/instructions.
(d) Determine machines and equipment.
(e) Select processes—establish procedures.
(f) Receive and control material, including welding consumables.
(g) Prove welding, heat treatment and NDT procedures.
(h) Approve welders and procedures.
(j) Establish weld consumable control.
(k) Liaise with inspection agencies.

Note standing activities—documented system covering (i) calibration (ii) document change control (iii) work status and (iv) effective stores.

During Fabrication and Welding

(a) Control cutting, assembly, welding. (Measure, visual examination and NDT to specification.)
(b) Involve inspection agency.
(c) Control welding consumables.
(d) Repair unacceptable welds.
(e) Make test plates.

After Fabrication

(a) Involve inspection agency.
(b) Perform post-weld heat treatment.
(c) Perform post-weld heat treatment non-destructive testing.
(d) Carry out proof tests.
(e) Approve test plates.
(f) Measure, and final inspection.
(g) Document.
(h) Prepare for shipment.

CONCLUSIONS

There is no bonus for the purchaser or the fabricator if the quality of a welded fabrication exceeds the level required for satisfactory service. Conversely, a defective weld, requiring reworking, adds nothing but cost to the construction. The implementation of a formal quality system will do much to ensure that the required quality is obtained from a welding process, at the first attempt. The key to success of such a system is enthusiastic initiation with subsequent full support from management and a team work attitude by every employee engaged in the construction operation, on the shop floor and in associated activities.

ACKNOWLEDGEMENTS

The author wishes to thank the Directors of Northern Engineering Industries Limited for permission to use some of the data and illustrations. Thanks are also due to my colleagues for helpful discussions, especially to Mr N.Scrimgeour and Mr Dennis Smith. Assistance from various manufacturers of equipment and materials is also gratefully acknowledged.

REFERENCES

1. Lancaster, J.F. (July 1974). QA through optimum choice of materials. *Petroleum International,* 38–42.
2. Lamellar Tearing in Welded Steel Structures. The Welding Institute, London, 1972, 16 pp.
3. Ott, C.W. (April 1979). Fabricating the constructional steels. *Welding Design & Fab.,* 53–60.
4. Gifford, A.F. and Gorton, O.K., Total QA Makes for Successful Repair of Ammonia Converter—Fabrication and Reliability of Welded Process Plant. The Welding Institute, London, 1976.
5. Roberts, D.F. J. and Frazer, H.W., Report on Access for Welding. CEGB/ Boilermakers' Collaborative Committee, July 1967.
6. Abrahams, C.J. (1970). A Designer's Guide to Inspection Problems. *Metal Construction,* **2**(9), 365–8.
7. Standard Data for Arc Welding. The Welding Institute, London, 1969, 129 pp.
8. The Procedure Handbook of Arc Welding. 12th edn. Lincoln Electric Company, Cleveland, Ohio, USA, 1973.
9. Johnson, L.Marvin, Quality Assurance Programme Evaluation. Stockton Doty Trade Press Inc., California, USA, 1970.
10. Clark, R.L. (Oct. 1980). Investigate suppliers to maintain quality control. *Hydrocarbon Processing,* 171–86.
11. Gifford, A.F. and Orme, J.M., The Control of Welding Consumables for High Quality Products. The Welding Institute, London, 1974.
12. Clark, W.D. and Sutton, L.J. (1974). Avoidance of losses caused by confusion of materials in piping systems. *Welding & Metal Fabrication,* **42**(1), 21–5.
13. Welding Steel Without Hydrogen Cracking. The Welding Institute, London, 1973, 68 pp.

14. Colder, K., The TED Electrode Container. NEI Mechanical Engineering Ltd., Internal Report, October 1980.
15. Nicholson, S., Problems associated with the production and implementation of quality plans. *J. Brit. Nuclear Soc.,* **16**(3), 277–9.
16. Welding Approvals—A Testing Time for All. Sheffield & East Midlands Branches of the Welding Institute Seminar, April 1979.
17. Turnell, A.J. (1970). ASME welding procedure specifications and how to comply with them. *Weld Metal Fab* **38**, 355–9.
18. Boniszewski, T. and Pavely, D.A. (Nov. 1978). Timing at temperature when drying welding electrodes before use. *Metal Construction,* 530–1.
19. Control of Distortion in Welded Fabrications. The Welding Institute, London, 1976, 80 pp.
20. Anon, Construction of Littlebrook Power Station. *Metal Construction,* November 1980, 588–97.
21. Salter, G.R. and Gethin, J.W., An analysis of defects in pressure vessel main seams. *Pressure vessel standards—the impact of change.* The Welding Institute, London, 1972.
22. Gifford, A.F. and Blount, N.R., How should quality costs be measured in the pressure vessel industry? Paper presented at the International Conference on Pressure Vessels, London, 1980.
23. Weymueller, C.R. Organisation assures success in quality control. *Welding Design & Fab.,* 32–37, September 1986.
24. Lochhead, J.C. and Speirs, A., The Effects of Heat Treatment on PV steels. *West of Scotland Iron and Steel Institute* **80**, 1972–3.
25. Smith, N. and Bagnall, B.I. (Feb. 1968). The influence of sulphur on heat affected zone cracking of carbon manganese steel welds. *Brit. Welding J.* 63–9.
26. Hart, P.M., Low Sulphur Levels in C—Mn Steels and Their Effect on HAZ Hardenability and Hydrogen Cracking. Trends in Steels and Consumables for Welding, The Welding Institute Conference, London, 1978.

5

Quality Control of Site Welding

B.S.BUTLER

Viking-Ord Ltd, Leyburn, N.Yorks, UK

INTRODUCTION

In recent years the importance of quality management systems has been recognised on most major contracts involving welded fabrications and quality assurance has become a mandatory requirement in the majority of cases (see Chapter 1).

The reasons for this development are largely historical and followed a succession of expensive and potentially catastrophic failures [1, 2]. National standards are now in force and elaborate systems, with classical clearly defined lines of responsibility, authority and communication from conceptual design through completion of fabrication, have been prepared to meet the requirements. Individual company management and quality control systems are monitored by their own internal or corporate QA functions, which in turn may be approved or overseen by an independent or third party authority. The outcome of this activity has, on balance and particularly where there has been a genuine endeavour to improve performance rather than satisfy a specific contract requirement, had a major influence on the general improvement in the quality of welded fabrications we see today. In the context of overall project control, it has:

(1) generated an improvement in the standard of design and workmanship; and
(2) reduced the frequency of errors and other manufacturing problems, which protects the work from expensive and embarrassing delays.

The obvious benefits have been:

(1) to the fabricator—an immediate and positive effect on profitability and credibility; and
(2) to the client—improved quality, protected delivery and enhanced service reliability.

However, the construction industry in general has been slow to recognise the benefits which established fabrication shop systems can offer at the site construction phase. The advantages of systematic control are illustrated most convincingly after the event, when deficiencies are clearly the cause of the problem [3]. In such cases closing the stable door when the horse has bolted may have only limited potential benefit in a relatively short term site construction situation and, traditionally, the contingent cost may have been allowed for and tolerable. It takes enlightened management to recognise the benefits which accrue from a planned approach to QA which is built into the site procedure [4].

Many factors militate against acceptance of QA on the construction site and they are in the main based on established custom and practice. Excessive paperwork and unbridled authority without responsibility (the ‘worst face of QA’) are cited as strong evidence against its acceptance. Site management is by tradition autonomous with complete authority over many functions, which in factory situations would report through separate lines of responsibility. This situation has evolved historically because the penalties for delay either in the final construction stage of a project, or in an on-stream plant down for repair, can be severe and the work programme tends to be more sacrosanct than ever. In the preparatory phases of a contract from design through fabrication, some delays may be tolerable and even necessary, in order to avoid later problems. The inevitable consequence, however, is to compress the site construction phase, which itself does not have the luxury of a following phase against which delays may be cushioned. The pressure on site management to avoid delays from any source is considerable. There is, therefore, a reluctance to introduce any independent system which could prejudice the authority of site management and have a potential for causing what may be considered to be uncontrollable delays.

Generally, construction site management skills are based on hard won experience gained against a background of itinerant labour, frequently in remote areas with associated communications and access problems. This background tends to develop forceful, independent management which is particularly skilled in ensuring progress, whatever the means. This approach can be detrimental to effective independent technical and quality management, particularly in the area of welding and fabrication where the technology of design, materials and production has advanced so rapidly in recent years. Consequently, there is an ever-present threat that site construction management will take expedient measures based on limited and possibly out-dated knowledge and experience, which may appear to offer the least complicated and perhaps quicker solution, without recognising the potential risks. These factors, together with the contemporary reward systems which recognise the immediate benefits of a ‘job on time’ rather than a ‘job done well’, are among the factors which can place the technical and quality management on a construction site under considerable pressure.

It is therefore essential to ensure that the construction site QA/QC function is independent of the local site management organisation in quality and technical matters. It is also equally important to recognise that the level of technical supervision on a construction site, which operates through a system of discipline or area engineers in addition to QC inspectors, may be more intense than on the shop floor, and that some of the control systems which operate satisfactorily against a relatively comfortable background of that environment may not be necessary and could even be detrimental to both progress and quality on site. This is not to say that essential contols should be relaxed on site. On the contrary, there may even be a case for increased caution in an exposed or dirty site environment but, essentially, basic principles of technical control in welding should be the same on site as in the shop.

Modification and Maintenance of Operating Plant

It should be remembered that site conditions apply equally to the maintenance and modification of existing operating plant as to ‘green field’ construction. Pressure for completion of the work and the working environment can be equally, if not more hazardous and hostile. In the installation of new plant the work is usually on virgin materials and in a planned sequence to give optimum accessibility and working conditions. On the other hand, maintenance or modification of existing plant may entail working in cramped and dirty conditions on materials which may have become degraded by heat, corrosion or mechanical damage.

Where plant is used in high-temperature processes, such as in the iron and steel industry, the main source of failure of the fabricated equipment arises from thermal damage. This may be either direct fusion, arising from molten metal breakout, or distortion where over-heating occurs. In addition, particularly when heating is cyclical, local thermal fatigue cracking may occur. Where there are diiferential expansion coefficients between the containment vessel and the refractory lining, incremental growth of the vessel may occur due to lining expansion. This effect may expose the vessel to stresses sufficient to initiate brittle fracture when it cools to an ambient temperature for maintenance.

Chemical plant may suffer from similar damage depending on the operating environment but, generally, the failure mode would tend to be either mechanical or corrosive. Wherever damage arises from thermal degradation or corrosion, suitable precautions should be taken to ensure that the existing material is capable of responding successfully to the repair process and that all damaged material is removed as required. Generally, material suffering mechanical damage, either from direct physical abuse, brittle fracture or fatigue, does not suffer severe metallurgical damage. Provided that any physical defects, such as cracks or laps, are removed a satisfactory welding repair can be made. If the cause of the initial failure such as the surface profile or stress level and pattern, can be identified and corrected before return to service, a satisfactory and lasting repair is possible.

In emergency situations temporary repair may be essential to protect production and safety of the plant. Such work must be given comprehensive technical consideration to confirm the viability of the proposals, and the work carefully controlled to ensure that the procedures are properly executed. Inevitably, there will be calculated risks, and these must be taken responsibly in close consultation with appropriate specialists. All possible contributory and consequential factors must be fully considered in order to limit risk, particularly with regard to the cumulative ill effects arising from apparently acceptable individual measures.

Work on plant which has been operating will inevitably involve more risk than when dealing with new materials. The extent of that risk will depend on the actual operating conditions. Some materials will be severely damaged and the work will be fraught with risk from almost every conceivable welding problem requiring very close technical appraisal and control to ensure success.

Inevitably in such situations, there is enormous potential for conflict between the need for precise application of a procedure and a more practical approach. Technical considerations may favour very close control within the specified procedure but practical limitations may preclude strict observance of the requirements. To insist on close control may prejudice the immediate operation of the plant by prolonging the repair work, and a critical review of requirements may be necessary. Obviously, malpractice cannot be condoned under any circumstances, but there are instances when technical guidance or practical experience is all that is necessary to assure quality and the punitive imposition of standards can have a completely adverse effect.

SITE WORK CONDITIONS

The scale of site operations can vary enormously, for example:

> Large green field sites; the British Steel Corporation’s Redcar Development, extended over a total area of approximately 1000 acres and included 10 major construction developments together with ancillary plant.
>
> Congested city sites; the erection of the headquarters building of the Hong Kong and Shanghai Bank in Hong Kong, was restricted to the actual site area itself, some 5000 m^2 on 47 levels with remote lay-down areas for preassembly and preparation work.
>
> Offshore installation and hook-up operations, which epitomise the ultimate in remote and concentrated site environments. All installed items have to be shipped in from an onshore base, and a very high standard of quality assurance and control is a mandatory requirement.

> Refurbishment of operating plant involving repair to process vessels inevitably takes advantage of the opportunity to carry out some additional work.

Characteristically, site welding work tends to be dispersed, presenting supervision and inspection of work in progress with problems not normally encountered in a shop environment. A comparison of site and shop conditions can be most graphically demonstrated when shop personnel visit the site to find that the enormous fabrication which strained their shop's capacity is dwarfed into relative insignificance by the scale of the work on site.

Depending on the size, complexity and nature of the construction, the number of contractors can vary. On large complex developments where a number of major contractors and a proliferation of sub-contractors are involved, supervision of quality can be difficult. Quality control may be seen as a problem to be avoided rather than a system to be observed, and some lower grade contractors have yet to master the simplest inspection techniques (see Chapter 4).

Taking account of these differences between shop and site environments, the problems of quality management become obvious. Nevertheless, quality standards in the shop still have to be met on site; the means by which they are achieved may vary depending on the circumstances. Statutory requirements are most easy, if tedious, to enforce because of the influence of an outside authority, but all have to be monitored to ensure continuing compliance and to protect the quality of the work.

QUALITY CONTROL—WHAT THE CUSTOMER WANTS

Individual site operations can vary from a single small repair involving one welder, to large multi-contractor projects costing millions of pounds. Quality and reliability is equally important in both cases, as lapses in control can jeopardise the security of the whole plant. There are numerous examples of small apparently insignificant faults, arising from malpractice, causing major failures. For example, the crane gantry illustrated in Fig. 1 failed by brittle fracture which initiated from a poorly repaired drilled hole in the web of the gantry girder. No reason could be given for the drilled hole being in the web. It had probably arisen as an error during the fabrication stage and was repaired without any approval. It is doubtful whether any competent person was consulted regarding its significance. However, it was the prime factor in the collapse of the gantry with the loss of three overhead cranes and incalculable disruption to production. It is doubtful if any control system could completely eliminate such negligence. Clearly, the work must conform to the designer's requirements. If the design does not show a poorly repaired hole then it should not be there and, in the absence of authority from the designer, the very minimum requirement must be that an effective repair is confirmed by 100% inspection using either radiographic or ultrasonic techniques as appropriate.

A system for quality control is therefore of paramount importance and the customer should protect his interests, for which he has a statutory responsibility in certain high-risk areas such as offshore oil development. It is doubtful in the case of the collapsed crane gantry whether identification of the culprit and successful prosecution of claims for damages or insurance cover would recover the total costs of the damage, but for a fraction of that cost, properly invested in quality control at the manufacturing and construction stages, the problem may well have been avoided.

Most industrial enterprises which require welding services are sufficiently large to employ a supervisory engineer or some other engineering expertise, capable of making engineering judgements on the need for QC. Therefore even the smallest, most insignificant contracts can be controlled by the customer, who should assume responsibility for specifying his requirements and ensuring that they are achieved. The actual character of the system necessary to provide this assurance depends on the size and nature of the contract

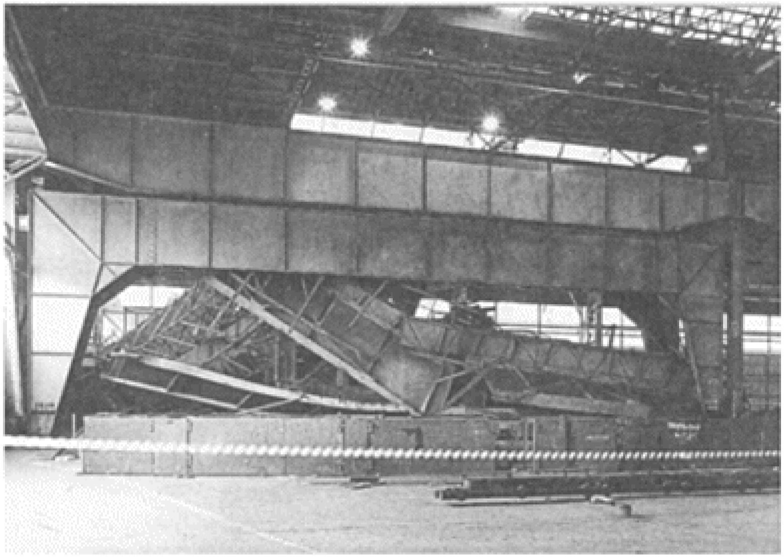


FIG. 1. Collapsed crane structures caused by a major fracture which can be seen in the main girder, emanating from a poorly repaired small hole in the girder web.

but, clearly, an important aspect is to ensure that those who do the work have a contractual responsibility for ensuring that the work is produced in accordance with the contract specification, and that any deviations are properly controlled and approved. The client should allocate responsibility for quality to a specific member of his project team. In the case of smaller projects this will inevitably involve a dual role. At the lower extreme, where only one man is looking after the project, he will have direct responsibility. On intermediate contracts responsibility may be given to a discipline engineer, and on large projects there will be a need for a dedicated engineer to have specific responsibility for quality. If there is a corporate QA strategy, then there will be a liaison between this function and the specific project. Where there is no corporate QA the basic principles should be applied, depending on the extent of control which the project requires. However, no matter what the size of the project, quality control must be planned and a firm policy formulated.

QC—SUB-CONTRACTOR'S OBLIGATION

The client, having established his requiremens for Quality Control, must ensure that the contractor addresses his responsibilities. Pre-contract award assessment will confirm the contractor's competence to deal with the work. This assessment must be made by experienced and capable personnel, who can recognise potential problem areas and have the power to make the necessary arrangements for corrective action.

On small jobs this requirement may be satisfied by inspection of the contractor's facility before approval to undertake the work. Larger, more complex projects will require detailed written procedure proposals, method statements or quality plans detailing the extent of control proposed for the work. These proposals should be scrutinised by the client, who may superimpose additional over-riding controls to check the effectiveness of the contractor's system. The use of such hold points will depend on the criticality and

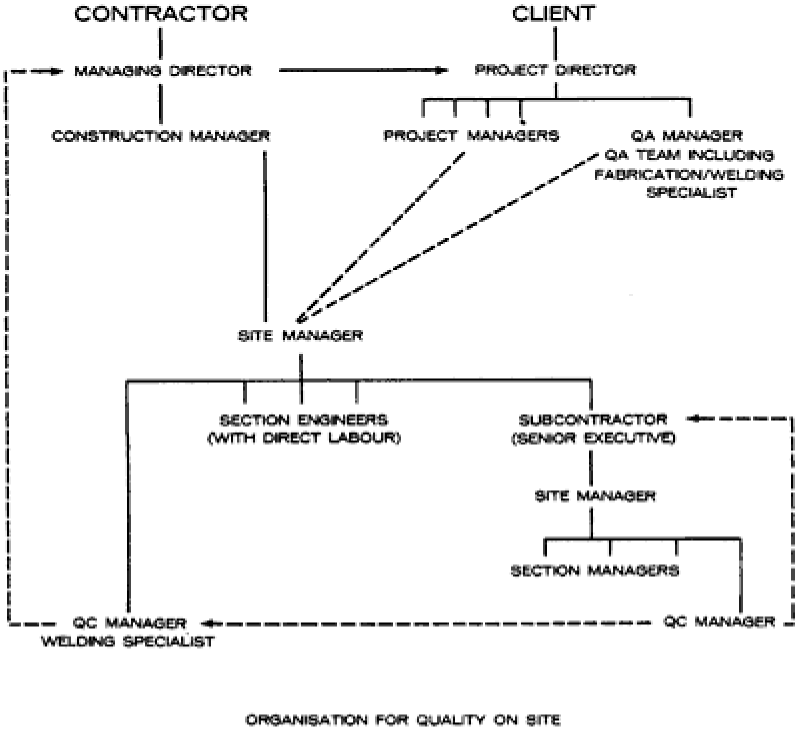


FIG. 2. Chart indicating the inter-relation between client and contractor in relation to quality requirements.

complexity of the work. In high-risk situations the client may feel obliged to recheck all of the work prior to acceptance, but the prime responsibility lies with the contractor to ensure that the work meets the specification requirements.

A significant feature of site construction work is the proliferation of sub-contractors, each feeding off a larger sub-contractor with increasing risk of degenerating control standards. Individual direct contracts placed with known small contractors with a high level of personal control probably represent the least need for independent supervision. Acceptable quality standards can be established and the supplier's reliable reputation will provide the necessary assurance that they will be achieved. It is comparable with the situation where an individual, doing a job for himself, will satisfy his own requirements and there will be no need to have his work checked. If, however, the work is sub-contracted then need for surveillance will increase progressively as the sub-contract chain lengthens. In the contracting industry it is not unusual to have a chain of five or six contractors.

On larger projects with a number of prime contractors employed directly by the client or management contractor, the need for systematic control increases. In this case, the overall system should be supervised by, or on behalf of, the client to ensure that his basic requirements are satisfied and to facilitate close intercontractor liaison at critical interfaces to avoid problems arising from variations in design or workmanship between contractors.

A typical organigram, shown in Fig. 2, illustrates the interrelation between the client and contractor's organisation and the QA chain.

DEVELOPMENT OF THE ORGANISATION

When the quality policy, scope of implementation and personnel responsible have been established, the associated support organisation should be developed. The size of this organisation will depend on the size and complexity of the project to be supervised.

Where the work involves modification to existing plant the established engineering functions are usually capable of dealing with quality aspects. However, the nature of the plant product will have some bearing on the expertise available. For example, personnel in metallurgically based industries may be more conversant with welding and fabrication than their counterparts in, say, consumer durables. However, the principles of QA should be familiar to all engineers, and the hallmark of a good engineer is his ability to recognise his limitations, and know when to seek help. It may not be essential for the responsible QA person to have detailed welding knowledge but it is always necessary and often essential, depending on the scope of the work, to have access to competent, practical welding/metallurgical expertise in order to retain credibility with the contractor, without which there will be a loss of confidence, followed by loss of control and poor quality. For example, it is better to have a sensible agreed procedure which is practicable, rather than specifying ridiculous demands which will only encourage the average contractor to take short-cuts with attendant risk to both himself and the client.

On larger projects the client may carry a comprehensive team of experts including a QA manager and full back-up service. In such cases a sound engineering background, including familiarity with engineering standards, and control-assurance systems insofar as they affect welding, are suitable qualifications for QA personnel. Detailed welding control will be in the hands of a specialist engineer. The manning levels will depend on the size and complexity of the project and the facilities available from the contractor and his sub-contractors, but the need for clerical staff to deal with documentation, which can often overburden technical staff, should not be overlooked.

SCOPE OF SITE QC

Having established the site QA/QC organisation, it is now necessary to establish a control policy and procedure.

Where a formal QA system is established, the controls will follow a pattern specified in the appropriate standard and will be audited periodically to ensure continuing efficiency. In other cases where QA is not fully implemented because of the size of the project or other governing policy, then precautions must be taken to ensure that the salient features of the operation, from conceptual design onwards, are in control.

Design

Proposals for the designs associated with the work, from basic concept to final detailed drawings, must be reviewed to ensure that all of the functional requirements are met, that it can be made, can be inspected and will work. This review may well be outside the scope of the site QA/QC organisation and may be undertaken by an engineering function. It is sufficient for the QA/QC team to ensure that it is done and that all aspects are covered and interface disciplines consulted.

Contractor Capability

A prime responsibility of the site QA/QC organisation is to ensure that appointed sub-contractors are capable of completing the work undertaken. This should involve a critical resource assessment and include:

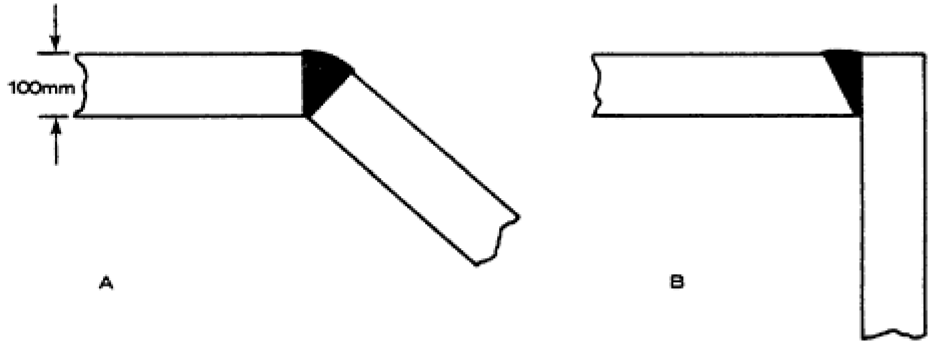


FIG. 3. Influence of a simple design change on potential welding problems. A, detail not susceptible to lamellar tearing; B, detail highly susceptible to lamellar tearing.

General capability

Equipment availability and control

Material control

Labour recruitment policy

Welding capability and qualification

Supervisory system

Sub-contractor control

Particular attention should be paid to general capability and resources. Site operations are in general serviced by reputable contracting organisations with recognised abilities and skills. However, from time to time they approach the boundary of their competence and expertise. It is in this area that they, together with the less reputable companies, represent the greatest risk to the project. It is therefore vitally important that claims of previous experience supporting their proposals are thoroughly checked. The extent of this check will depend on the nature and scope of the work, but must involve close examination to ensure that the claimed experience is compatible with the current work scope. The following are examples of questions which should be answered initially, in questionnaire form if necessary, but pursued for critical cases by direct discussion:

Have you completed a job of similar size and complexity?
    Supply drawings and specifications. State location and climatic conditions.
What materials were involved?
    State types, thickness and special qualities.
What fabrication techniques were used in erection?
    Supply examples of method statements.
What welding techniques were used?
    Supply details of procedures and non-destructive test requirements.
Do you propose any welding detail changes to facilitate erection?
    Supply proposals.

What special arrangements for labour recruitment, welding qualification and supervision do you consider necessary to guarantee quality?
What QA systems do you operate?
Supply details of approvals and audits.

Construction contractors often appear over-confident in their approach to the work and they may consider these questions an unnecessary intrusion. In some cases an innovative approach, with its attendant risk, may be justified and, indeed, without it many aspects of site construction work could not be contemplated. However, it is still very important to be sure that the experience claimed by the contractor has a sound technical base and that the current contract does not over-strain his capability. Such precautions should not be restricted to small contractors who may automatically arouse suspicion. Large international contractors can be very impressive with their articulate accounts of previous work in remote areas of the world. Experience has shown that in many cases they are unable to recognise the strains which an apparently minor difference in design, a material change or a size increase can place on their established technology. For example, when lamellar tearing in fabricated steel work was a major problem, it was difficult to persuade a large international contractor of the potential problems inherent in the proposed design for the attachment of the end plate on a ball mill. He insisted that he had produced many similar items without taking expensive and inconvenient precautions. It was not until the detail of previous and current designs were compared that the reasons for previous success were apparent. Figure 3(A) shows the previous weld detail which is immune from the risk of lamellar tearing, while the proposed detail (Fig. 3(B)) is an obvious candidate. The costs of modifying the welding procedure to give some protection against lamellar tearing were small compared with the potential costs of repair and the inevitable delay in completing the work.

The contractor should have a QC system capable of dealing with the work in hand. If the system is inadequate and incapable of improvement it is essential that the customer's QA/QC system has the capability and authority to deal with the contractor's QC from receipt and storage of materials to final acceptance of the finished work.

Equipment Availability

When specialised equipment is to be used, precautions must be taken to ensure that it is readily available with suitable support facilities for maintenance. The contractor should produce a comprehensive plant list for approval by the customer.

Goods Receipt and Storage

Material or equipment arriving on site should be examined before acceptance. Fabricated items are quite vulnerable to damage in transit and this will be revealed by site receipt inspection, which will also form a useful second check on the shop release inspection and enable any repairs to be made before the item becomes critical in the erection programme. Equipment received on site may be stored for unpredictably long periods, and precautions must be taken to avoid deterioration or damage in store. Sensitive items such as welding consumables and equipment must be stored in a controlled environment, as recommended by the manufacturer. Where goods do not require a controlled environment, suitable precautions must be taken to ensure that damage does not occur during storage. For example, structural fabrications designed for external use should include drain holes to avoid water entrapment in service. If the item is placed on its side during storage the drain holes are ineffective and quite severe corrosion may occur. Equipment designed for internal use which contains sensitive electrical equipment should also be given special attention. For example, overhead cranes which have control equipment within the structure may appear to be perfectly secure in an open environment and be generally weatherproof. They are seldom, if ever, completely air-tight, and exposure to extremes of hot and cold exposed conditions leads to moist air being drawn into the internal structure causing damage from condensation. Materials in general, and especially those to be welded, must be stored clear of the ground on suitable dunnage to avoid deterioration which may affect subsequent welding. Materials in store must be inspected regularly, preferably to a pre-arranged programme, and records maintained to ensure that the inspections are carried out.

Storage and Issue of Welding Material

The care of fabrication consumables, particularly those for welding, must be compatible with 'shop floor' practice unless the site welding procedures can tolerate a lower standard. Generally, shop and site welding procedures are the same and therefore materials should be treated equally. The extent of control will depend on the nature of the construction. In critical cases incoming material may be bonded pending release checks for conformance to specification but, generally, for structural welding this is not necessary and the supplier's quality assurance is considered adequate. The storage area must be enclosed, secure, dry and free from violent temperature fluctuations, preferably held at a minimum temperature of 20°C and a maximum relative humidity of 70%. In most cases, provided that these requirements are followed and baking of electrodes and fluxes is carried out in accordance with the manufacturer's recommendations or contract procedure specifications where more stringent, problems associated with hydrogen contamination can be avoided.

Cracking problems in site construction occurring in the weld and HAZ (heat affected zone) can usually be traced back to the presence of hydrogen resulting from lack of attention given to consumables during storage. Figure 4 illustrates a situation in which hydrogen-assisted cracking in the heavy weld between the nozzle and end plate of a heat exchanger initiated a brittle fracture in the end plate. In this instance the electrodes had been stored in an unheated corrugated sheet hut, with condensation streaming down the walls. Such abuse of electrodes is thankfully less common now than in the past, but vigilance must be exercised to avoid the problem. On small contracts it is frequently proposed that an accommodation office, often the foreman's office, is used as an electrode store. This can be equally unacceptable in critical cases since temperature and humidity may reach intolerable levels. Equally important are electrode baking and drying ovens and cabinets. They should have efficient temperature control, and allow free circulation of air. Damp electrodes held in an air-tight container may not reach the required maximum hydrogen potential levels, regardless of the holding time.

On a more general note, a neat, well managed store, using material rotationally, reduces the risk from deterioration or damage and ensures against waste from obsolescence when old stock has to be cleared and scrapped. Such good housekeeping also reduces the risk of electrode mixing. This itself can lead to serious problems from either welding defects, such as cracking when, say, using rutile rather than hydrogen controlled electrodes, or property deficiencies if an inferior electrode is used, such as using carbon-manganese steel on an alloyed base material, which could lead to premature plant failure, with all the associated consequences.

Quality Planning

An important feature of all efficient manufacturing and quality systems is forward planning, in which each element of the work is considered against time, resource and quality requirements. Areas of potential risk

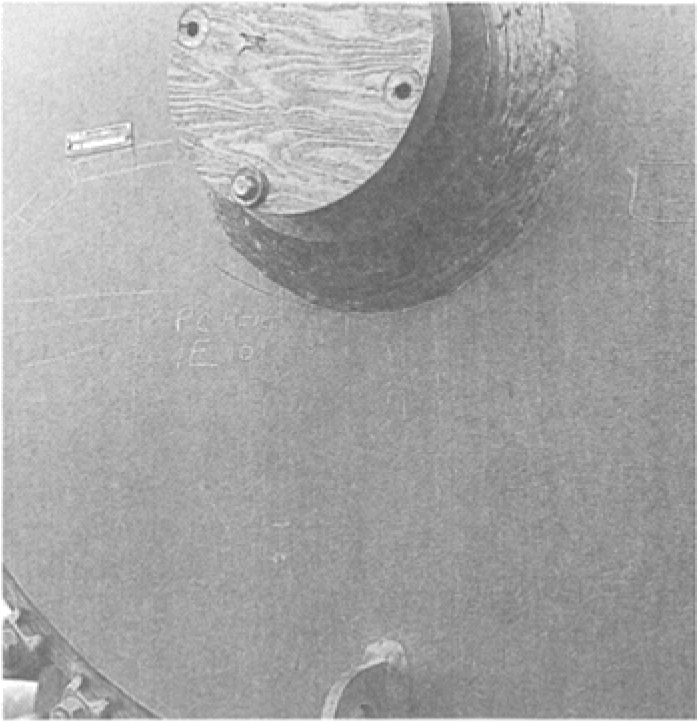
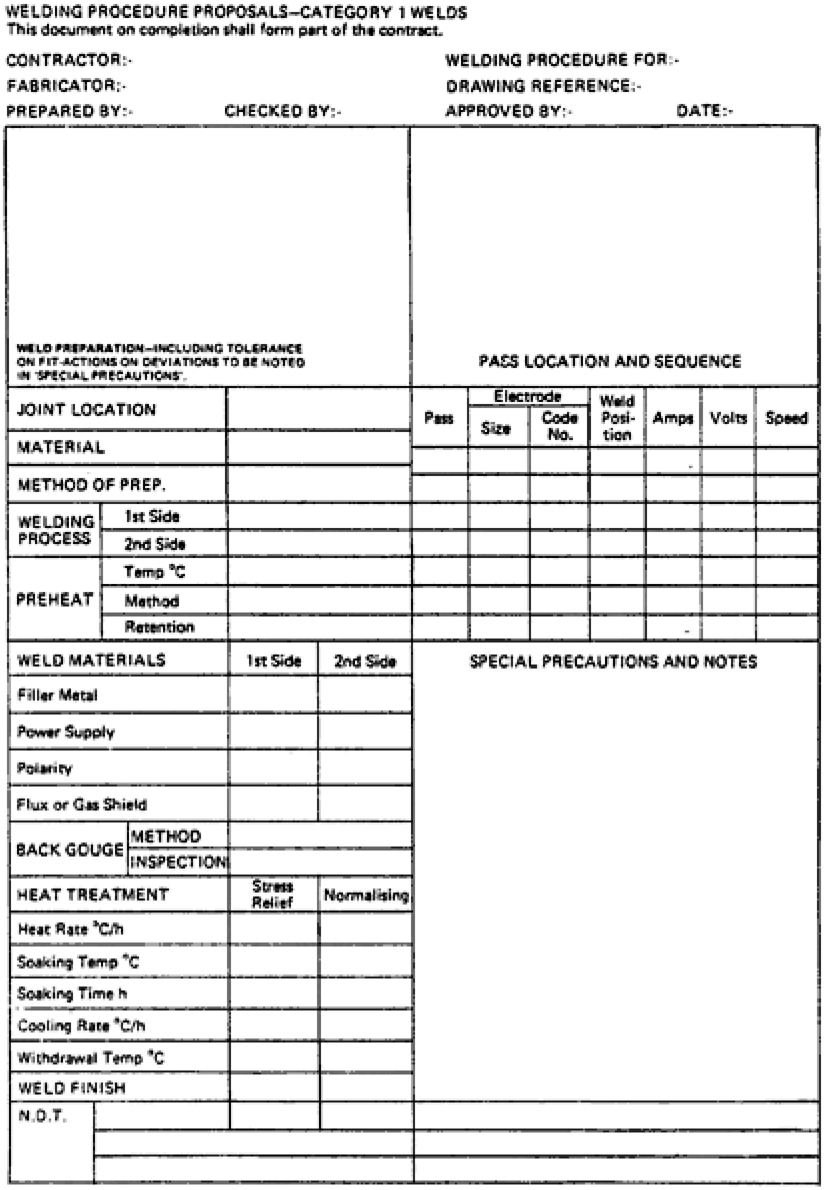


FIG. 4. Brittle fracture in end plate of low pressure heat exchanger initiating from arc strikes on plate surface.

are identified and the necessary avoiding action or enhanced surveillance is built into the planning schedules. The programme of work is backed up by procedures and method statements giving comprehensive detail of the sequence of operations required to complete the work. These procedures may require minor modification to accommodate revisions as work proceeds and problems emerge, but the basic principles of the work plan and quality control stages, which are set in the early stages before the pressures of progress demands come into force, must apply. Changes to planned QC schedules required to meet progress requirements must not be made without very serious consideration.

Welding procedure specifications should be presented in tabular format, such as that shown in Fig. 5, taken from the British Steel Corporation's in-house standard [5] which was discussed at the Welding Institute Autumn Conference in 1976 [6] and is now widely used throughout industry in various modified forms. The detail included is sufficiently comprehensive to complete the work and is much easier to assimilate than an essay presentation. This presentation may be used for specifying the requirements for the most simple details such as single run fillet welds, which may be adequately specified by simple notation in accordance with national codes such as BS 499 (Welding Terms and Symbols). It is, however, most useful and more appropriate for the presentation of information in complicated details such as heavy multi-run butt welds in high-strength materials. The proposed detail may then be submitted for acceptance by the appropriate approving authority before being transferred to the production phase.

In some cases the full procedure specification detail may be considered to be too involved for presentation to a welder. In such cases the concise salient details affecting the actual welding operation may be transposed onto a card to be held by the welder. These instruction cards may be mounted in plastic to



WELDING PROCEDURE PROPOSALS—CATEGORY 1 WELDS
This document on completion shall form part of the contract.

CONTRACTOR:-
WELDING PROCEDURE FOR:-
FABRICATOR:-
DRAWING REFERENCE:-
PREPARED BY:-
CHECKED BY:-
APPROVED BY:-
DATE:-

WELD PREPARATION—INCLUDING TOLERANCE ON FIT-ACTIONS ON DEVIATIONS TO BE NOTED IN 'SPECIAL PRECAUTIONS'.	PASS LOCATION AND SEQUENCE

JOINT LOCATION		
MATERIAL		
METHOD OF PREP.		
WELDING PROCESS	1st Side	
	2nd Side	
PREHEAT	Temp °C	
	Method	
	Retention	

Pass	Electrode		Weld Position	Amps	Volts	Speed
	Size	Code No.				

WELD MATERIALS	1st Side	2nd Side
Filler Metal		
Power Supply		
Polarity		
Flux or Gas Shield		

BACK GOUGE	METHOD	
	INSPECTION	

HEAT TREATMENT	Stress Relief	Normalising
Heat Rate °C/h		
Soaking Temp °C		
Soaking Time h		
Cooling Rate °C/h		
Withdrawal Temp °C		
WELD FINISH		
N.D.T.		

SPECIAL PRECAUTIONS AND NOTES

FIG. 5. Procedure proposal document (from BSC CES 22 [5]).

improve durability and include other basic guidance notes to the welder. A major problem in the control of welders, which applies particularly to site work, is ensuring that acknowledged details of good practice are followed. From many aspects, the quality of the work is ultimately in the hands of the welder and lapses in attention to detail can have serious consequences. A welder issued formally with an instruction card can hardly claim that he has not been informed of the job requirements, and this creates the necessary stimulus to do the job properly. In addition, such a system is easily auditable when checking the efficiency of information transfer to the welder.

Welding Approvals

Both procedure and operator qualification should be considered against the contract requirements. In most cases there are specified requirements for qualification which have to be satisfied. This approach to qualification requirements is generally accepted throughout industry, with some modification of requirements to meet the particular demands imposed and the criticality of the work.

Testing can be extremely expensive and in some cases may not be particularly relevant to the work in hand. Some doubts have been expressed in the industry over the justification of periodic or specific retesting of welders, and the pointless repetition of procedure qualification tests at numerous sites which are doing exactly the same work under similar conditions. However, care should be taken to ensure that the prevailing situations on the work site are considered when deciding the scope of qualification for site work. Exposed, dirty or confined conditions can make an otherwise adequate procedure impossible to operate, and late changes necessary at the welding stage can themselves be expensive and wreck the planned work programme, with attendant financial consequences.

It is prudent to review the procedure testing and pre-production trial requirements critically in the early stages of the project. There is often pressure to automate welding in order to improve productivity. In some cases environmental conditions and the accuracy of assembly achievable on site militate against automation, and pre-production viability trials must reflect such conditions accurately. For example, the feasibility of girth welding large cylindrical components in the horizontal-vertical position cannot be demonstrated effectively in simple small plate shop floor tests. In order to generate the necessary confidence a large full scale mockup should be used to confirm suitability of both the welding and mechanical characteristics of the equipment under simulated site conditions. There are many instances where the introduction of sophisticated procedures to the site environment without recognising these considerations has had disastrous consequences.

Whatever qualification or pre-production trial programme is decided upon, tests should be witnessed by the Site Welding Engineer, who must be satisfied that all potential problems arising from the site environment can be accommodated.

Having stressed the necessity for formalised acceptance of procedure qualification, there are inevitable emergency cases where time will not allow this ideal route. In such cases the details of proposals must be assessed by a competent experienced person, preferably independent from the site team, before work is allowed to proceed, and any testing work deemed necessary to prove the procedure put in hand immediately. Any emergency short term repair should only be undertaken on the authority of a competent person, and arrangements for a permanent repair, compatible with the design and service requirements, put in hand immediately.

Control of Work in Progress

The welding procedure specification and the method statement, which reflect the contract specification requirements, form the basis for quality surveillance against which workmanship is assessed. Generally, on site, a system of discipline or area engineers overseeing the work in general ensures that procedures are operated effectively by the welding supervision. This feature tends to compensate for deficiencies arising from other environmental problems of supervision and quality control which are peculiar to site working.

However, the control of welding technology should be directly through a specialist welding engineer who will liaise with area engineers and inspectors. Any decisions on welding. particularly changes to procedure or resolution of problems, must be channelled through this specialist, who should have absolute authority for control of welding technology on site. In case of disagreement, questions regarding quality should be resolved by recourse to higher corporate authority, as indicated in the organigram in Fig. 2.

INSPECTION AND TESTING

Aspects of inspection and testing, insofar as they are affected by site construction, will be discussed later. Weld testing on site should meet the same criteria set for shop construction, and operatives should be qualified to standards appropriate to the tests being carried out, e.g. CSWIP (Certification Scheme for Weldment Inspection Personnel) or equivalent.

Usually, because of congestion or problems in controlling personnel isolation of areas necessary for radiographic inspection, ultrasonic testing has become the preferred inspection technique. Equipment and suitably qualified personnel are now available so that a very high degree of confidence can be achieved with ultrasonics.

STRESS RELIEF ON SITE WORK

Stress relief at site usually involves local partial heat treatment of a major component, although complete structures can be stress relieved if necessary. Depending on the size, complexity and the number of components to be treated, a special furnace may be erected on site or, alternatively, the structure itself may

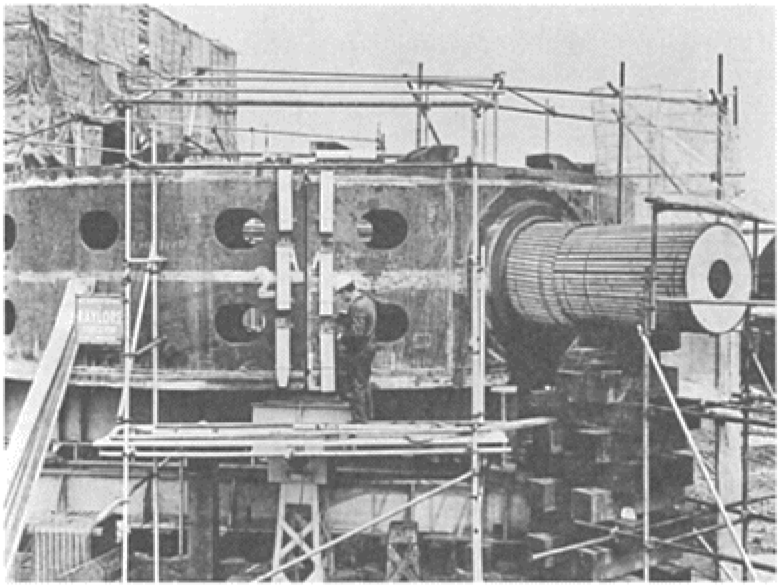


FIG. 6. Site welding of the closing seam in the trunnion ring for a large basic oxygen steel-making furnace. The figure shows the seam being prepared for preheat and subsequent stress relief.

be clad with insulation and heated from within. Gas or electrical heating may be used depending on availability, site conditions and the nature of the structure.

Local heat treatment is usually carried out with electrical heaters placed close to the weld seam, but gas may be used. In special cases, such as standard pipe work, joints are heated by specially prepared exothermic pads, which are placed round the weld and ignited. The heat generated during combustion is calculated to heat the joint to the required stress relief temperature without any possibility for control once the operation has been initiated. Generally, local heat treatment of structural items is covered by the requirements of BS 5500 1976, 'Specification of Unfired Fusion Welded Pressure Vessels', which details the procedure necessary to ensure satisfactory stress relief. Figure 6 shows the closing seam of a trunnion ring for a large basic oxygen steel-making furnace being prepared for site stress relief. The heating elements which were attached to the weld seams to control the preheat cycle were also used for the subsequent stress relief. Local weather protection was erected over the weld area.

Vibratory stress relief has been shown to be beneficial in certain cases, particularly when stability after machining is required. However, caution should be exercised where the structure is subject to fatigue loading conditions in service, since vibratory stress relief, which itself induces fluctuating stresses, can reduce the fatigue life of the structure.

HAZARDS TO WELDING ON SITE

Most modern welding techniques used on site are similar to those used widely in shop manufacture. The main difficulties are in the conditions under which they operate. Modification or repair to existing plant in heavy industry can involve working in very dirty and cramped conditions, often exposed to the elements, and quite often it is not possible to make any significant improvement to the situation. On new plant the location and accessibility of site welds should be considered at the design stage. Occasionally, however, due either to oversight or force of circumstances, access for welding is poor, which together with the presence of site debris, exposure to the elements, and remoteness of the welding. power source (with questionable electrical continuity, particularly in the earth system) can have a significant and detrimental effect on the quality of the weld.

Dirty Conditions

Cleanliness is a major factor which can have a significant effect on weld quality, both from the psychological point of view and also from the potential risk of contaminating the weld. Obviously, every attempt should be made to produce a clean working environment in the general area, but in the actual welding area the requirements for cleanliness must be mandatory. Welding should not start if the weld joint is contaminated or likely to be contaminated with potentially harmful extraneous material. Oil or grease must be removed thoroughly and any potential source of grease eliminated. Repair of mechanical components often leads to grease in bearings or crevices melting and running into the weld area as the work piece is heated by the welding in progress. Thorough removal by solvent flushing is essential to ensure the quality of the completed weld. Where, even after the most stringent precautions, such problems cannot be eliminated, the welding procedure must be reviewed and revised to reduce the risk involved. For example, the use of a 'low hydrogen' procedure under such circumstances is pointless, since no matter how carefully consumables are handled the process will be deluged with hydrogen from the contamination! In such circumstances a more secure route to avoid the effects of hydrogen would be to increase the preheat level and institute a post-weld hydrogen diffusion procedure, or use an austenitic welding consumable capable of accommodating hydrogen contamination.

Accessibility

Whether a problem of accessibility arises from poor design in a new structure or from the premature failure of plant in service, every effort should be made to improve the condition to the satisfaction of the welder to ensure his comfort and confidence to make the weld. If the welder feels neither comfortable nor confident then there is a high risk of defects arising in the weld, and it follows that any repair will be more difficult, resulting in a progressively deteriorating situation. Caution should also be exercised when assessing the risk on the basis of the confidence expressed by itinerant site welders who tend to be self-confident by nature and who may understate the risks involved. In critical situations, practice on a mock-up, simulating the actual conditions, is recommended and the welder's capability should be confirmed before any production welding is attempted. It is worthwhile to remember the maxim 'lf a weld is difficult to make then it will be difficult to inspect—and if it is difficult to inspect the quality will be questionable'. In some cases quality may have to be assured solely on the basis of successful mock-up welds, together with the skill and competence of the welder. Figure 7 illustrates a typical situation of poor accessibility in boiler manufacture, where a very high standard of quality is demanded, notwithstanding the practical problems.

Exposed Conditions

In common with many human activities, the final operation in a sequence of events tends to be given the least consideration. Welding often suffers the sins of preparatory operations and cumulative errors in planning. Joints which ought to be carefully prepared and assembled under controlled conditions are presented for

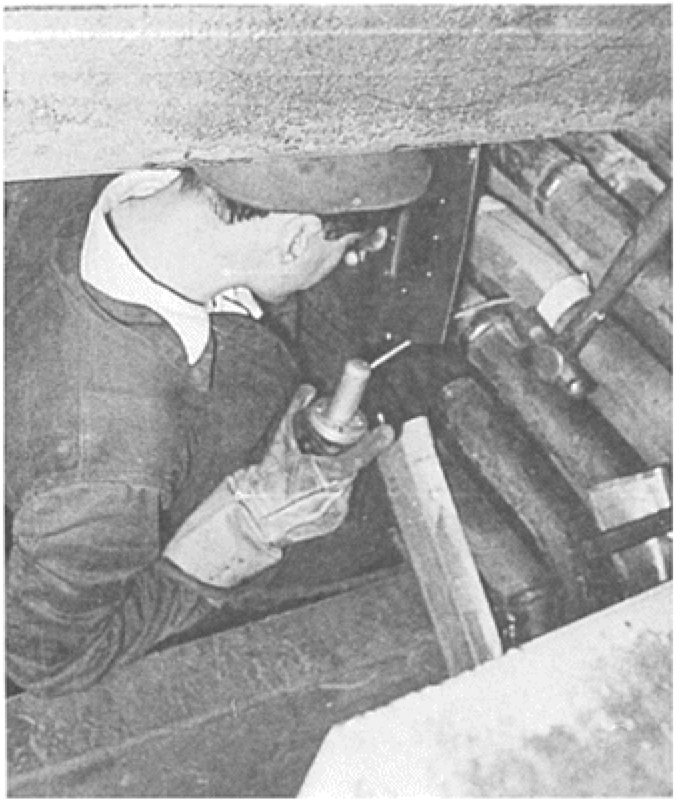


FIG. 7. Illustration of restricted access for welding, typical of the site situation.

welding as ‘best achievable’ set-up without any protection against the elements. In ideal weather conditions this may be acceptable, but in a changeable climate provision must be made for both overhead and side wall protection. Quite often, the sequence of structural erection involves leaving out side walls of buildings to allow access for installation of equipment. In such cases provision must be made to sheet the area with tarpaulins if any significant welding work is to be undertaken. Figure 8 shows the local protection erected around a blast furnace during erection, and Figure 9 shows the complete encapsulation of a 12 m diameter sphere, both of which were necessary to create a suitable environment for welding.

Security of Equipment

A major problem on construction sites is ensuring the security of equipment. Preheating equipment, welding cables, torches, earth clamps, lights and other ancillary equipment, which are necessary to ensure the safe and efficient completion of the work, are often abused or mislaid and not always replaced. This leads to a ‘make do and mend’ attitude, with all the attendant risks to quality, which should be recognised in the early stages when planning the work.

The risks arising from inadequate equipment include the following:

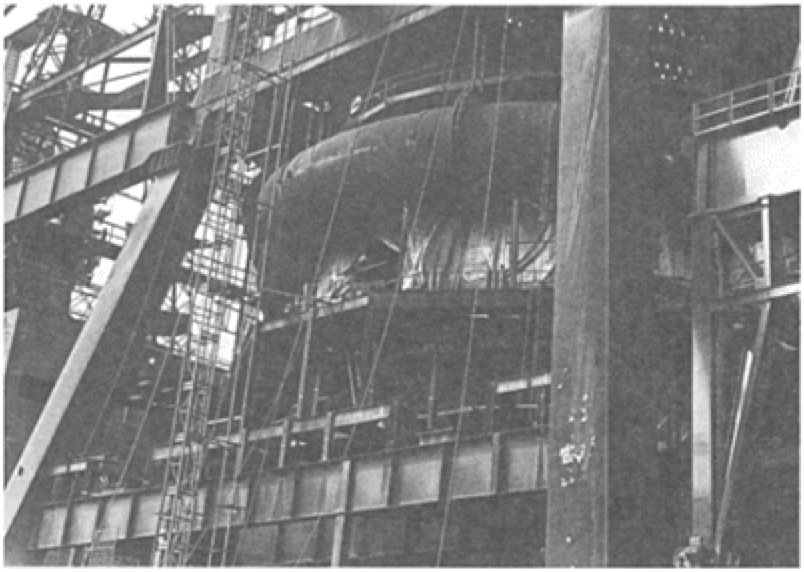


FIG. 8. View of a very large blast furnace under construction, showing the temporary protection for the welding operation.

(a) Arc strikes from poor earthing, which are shown in Fig. 10, from a rather precarious connection to a main structural member. The electrical discontinuity also leads to poor welding stability and increased defect risk.
(b) Poor illumination leads to risk of accidental arc strikes and inability to carry out efficient weld cleaning and inspection, all of which lead to reduced quality.
(c) If preheating equipment is not readily available, welders will be encouraged to ignore specified requirements.

Similarly, welding power supplies and other services should be efficiently maintained in order to avoid risks to quality.

Damaged cables, power sources and overloaded power supply can all lead to welding instability and general frustration. In some cases unusual and completely unexpected problems arise from deficient equipment. An extreme example is shown in Fig. 11, which shows a photomacrograph taken from a weld repair which had been excavated by air-arc gouging. In this instance the air flow had not been sufficiently powerful to eject the molten metal pool. The remaining highly carburised material had solidified as hard cementite which contaminated the subsequent repair welding, producing a martensitic structure and severe cracking problems.

Piecemeal correction of faults is inefficient, expensive and unpredictable. Planned maintenance systems are essential to ensure that all plant is working to its declared efficiency at all times.

REFERENCES

1. Report on Brittle Fracture of a High Pressure Boiler Drum at Cochenzie Power Station. South of Scotland Electricity Board Report, January 1967.
2. Anon. Brittle fracture of thick-walled pressure vessel, *BWRA Bulletin,* 7(6) (1966) 147–78.

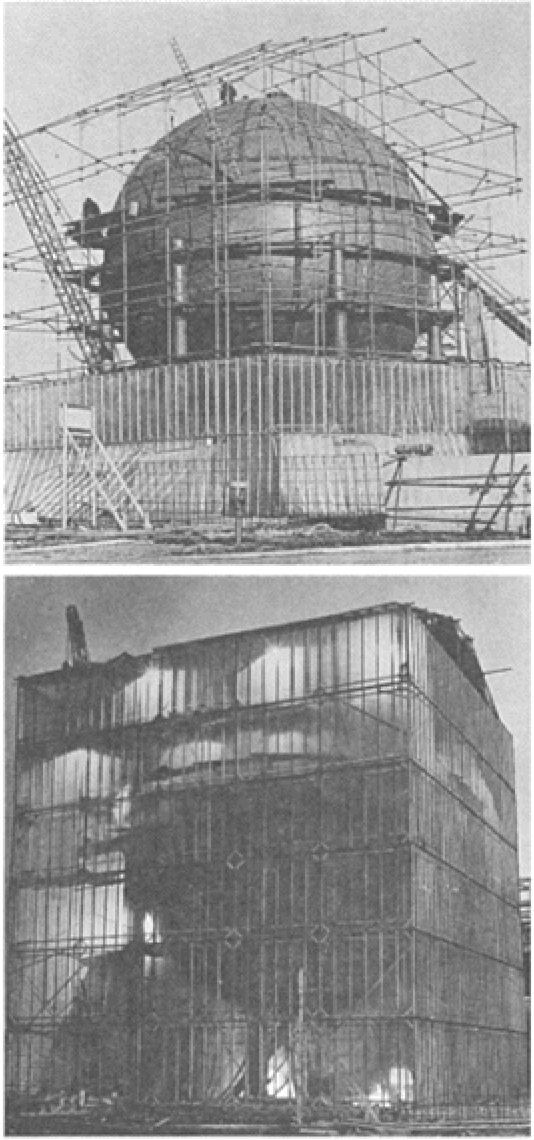


FIG. 9. Twelve metre diameter sphere completely encapsulated by temporary screening to ensure controlled conditions for site welding.

3. Clark, W.D. and Sutton, J.L. Avoidance of losses caused by confusion of materials in piping systems, *Weld. Met. Fab.,* **42**(1) (1974) 21–5.
4. Gifford, A.F. and Gorton, O.K. Paper 22, The Welding Institute Conference, November 1976, pp. 115–27.
5. British Steel Corporation, Welding of Steel Fabrications. Report CES 22.
6. Garland, J.G. and Butler, B.S., Paper 21, Welding Institute Conference, November 1976, pp. 103–13.

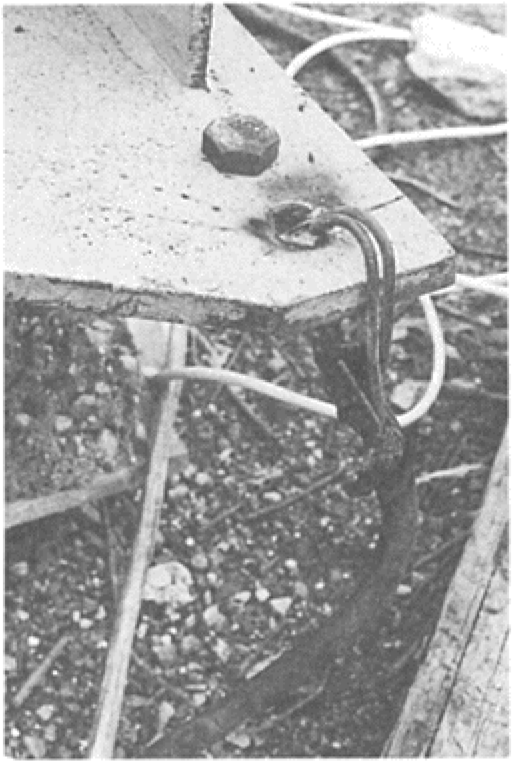


FIG. 10. A typical example of a poor and potentially hazardous site earth connection.

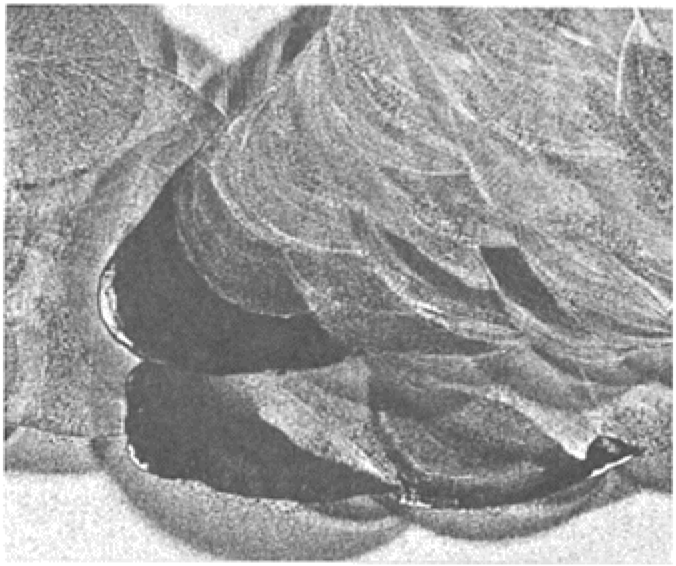


FIG. 11. Photomicrograph of a repair weld, showing severe carbon contamination from inefficient air-arc gouging.

6

Defects in Welds—Their Prevention and Their Significance

J.H.ROGERSON

Cranfield Institute of Technology, Bedford, UK

INTRODUCTION

Welding is a complex technology and in any welding process (including mechanised processes) the quality of the weld is a function of the interaction of a large number of variables, not all of which are controlled to the extent that is desirable. The difficulty of completely controlling the welding process means that most welds will contain some defects even if no ‘errors’ are made in selecting the materials, joint design or welding procedure. Also the continuous improvement in non-destructive testing methods means that such defects as are present are increasingly likely to be detected.

This situation leads, first, to a need to understand the cause of weld defects and how to prevent them occurring as far as is possible. Obviously any fabricator’s aim must be to prevent the production of defective welds. However, the difficulty and the cost of consistently producing welds without *any* defects is such that we must come to terms with the fact that welded structures produced at an economic cost may contain a proportion of weld defects. We need to know therefore the significance of the different weld defects in terms of weld performance so that we can define a safe and realistic tolerance limit for defects for each class of welded structure. It is, of course, a key factor in the quality assurance of any component or product that the specification of the quality standard be appropriate.

DEFECT TYPES AND THEIR EXPECTED FREQUENCY

The International Institute of Welding has proposed [1, 2] a comprehensive classification of defect types. In this classification six main groups of defect are identified:

(1) Cracks;
(2) Cavities (porosity and shrinkage cavities);
(3) Solid inclusions (slag, oxide);
(4) Lack of fusion and lack of penetration;
(5) Imperfect shape;
(6) Miscellaneous (e.g. spatter, arc strikes, grinding marks).

It is necessary to look at this classification in terms of the main causes of the defects, i.e. whether they are ‘technological’ defects or ‘workmanship’ defects. ‘Technological’ defects are defined as those resulting from a major inconsistency in the welding operation, such as a wrong electrode, incorrect heat treatment, inappropriate joint design, whereas ‘workmanship’ defects are those which arise from the inherent variability of the welding process or a chance error by an operator. The majority of the cracks and lack of fusion and lack of penetration defects can be considered as technological defects whereas the majority of cavities, solid inclusions, shape and miscellaneous defects can be considered as workmanship defects.

The amount of quantitative information on the number, size, type and distribution of weld defects in different classes of welded structure is not very extensive. The reliability of some of this information is also open to question because of the unknown reliability of some inspection methods (in particular ultrasonic inspection) and the unknown reliability of defect reporting methods.

Two pieces of work which are frequently quoted are that due to Salter and Gethin [3] who analysed defect lengths in radiographs of main seams of pressure vessels and that due to Kiharea *et al*. [4] who assessed the proportion of radiographs which indicated 'unacceptable' defects for a range of structures. Defect 'rates' for pressure vessel welding were of the order of 3% whilst for lower quality welding defect 'rates' of up to 20% or more were found. In all cases, though, the majority (usually an overwhelming majority) were minor workmanship defects. This general pattern has been confirmed by later work [5, 6] for a wide range of structures and Table 1 derived from the data in references 5 and 7 indicates this.

TABLE 1
COMPARATIVE AVERAGE DEFECT RATES (ALL INDICATIONS ≥ 2 mm RECORDED)

Structure type	*Average number of defects per metre of weld*
Aluminium pressure vessel (MIG welded)	1·6
Steel site welded tankage (MMA welded)	0·7–4·9
Steel site welded tankage (Sub arc welded)	3·4
Ships hulls (MMA welded)	4·9
Low alloy steel pressure vessel (MMA welded)	0·7–1·0
Low alloy steel pressure vessel (Sub arc welded)	0·3–0·5
Nodes in tubular offshore platform jacket (MMA welded)	5·9[a]

[a] Derived from ultrasonic test data, all other data derived from radiographs.

The distribution of the workmanship defects can be considered to be random [5, 7] and this is not surprising as such defects arise from chance (random) locally occurring variations in the welding conditions. The inherent variability of the arc, occasional errors in electrode manipulation, slag removal or fit-up, and the consistency of operation of the welding equipment are all events which occur randomly and which can result in minor workmanship defects. The major, technological, defects are defects resulting from significant errors (incorrect electrode, incorrect procedure, for example) and these will not be random events. Therefore there is no useful distribution function which we can use to describe the occurrence of such major defects.

The size distribution of defects is of importance because it is relevant to the detectability of defects by non-destructive testing. Clearly we would expect small defects to predominate and large defects to be much less frequent. This is, of course, the case but it is difficult to describe size distributions in a quantitative manner. Various sources of data exist, notably for PWR vessels [8] and for welds in offshore structures [9, 10]. Exponential [9, 11] or Weibull [9, 10] distributions have been variously assigned to this data. The parameters of the distribution, whichever distribution is used, will obviously vary with the quality levels of the fabrication although in the case of offshore structure welds a surprising degree of similarity has been found in the size distribution of defects in different structures.

CAUSES OF WELD DEFECTS AND THEIR PREVENTION

Technological Defects

A major type of technological defect is cracking which can be from various causes but all, essentially, a function of microstructure and stress:

(1) Hot (or supersolidus) cracking—possible in all alloy systems.
(2) Reheat cracking—almost exclusively restricted to creep resistant steels.
(3) Hydrogen induced cold cracking—ferritic steels only.
(4) Chevron cracking—high strength weld metals in ferritic steels only.
(5) Lamellar tearing—in principle possible in any material but in practice restricted to structural and pressure vessel ferritic steels.

Hot (or Solidification) Cracking

This is intergranular cracking (see Fig. 1) which occurs during or just after solidification and is normally found in the weld metal although a similar form of defect can occur in the heat affected zone immediately adjacent to the weld. During solidification weld metals pass through a temperature range in which the metal has a very low ductility and so cannot easily accommodate the localised strain resulting from the differential expansion and contraction of the weldment due to phase changes and the restraining imposed by the inherent properties of the partially solidified metal, i.e. interlocking of dendrites in the last stages of solidification [12, 13] or the presence of low melting point liquid films such as iron sulphides or iron-iron phosphide eutectics in ferritic steels [14].

Further subdivisions of the phenomenon have been proposed [15] but in all cases the cracking is a function of composition and stress so that the prevention of this defect type relies primarily on compositional control and, to a lesser extent, on the control of joint detail and procedure to reduce welding stresses. The main principle therefore is to select a weld metal composition which has a minimum freezing range so that the time the weld metal is in the low ductility region is at a minimum.

In the case of ferritic steels we find that sulphur, phosphorus, boron and niobium are the most harmful elements in terms of their effect on the solidification range. Therefore it is desirable to reduce the levels of such elements as much as possible. A complicating factor is that these elements are less soluble in austenite than in ferrite so that elements which promote austenite formation rather than ferrite formation on solidification via the peritectic reaction increase their severity. For example, elements such as carbon and nickel can be considered as undesirable from this point of view.

In practice the prevention of hot cracking by compositional control in ferritic steels relies on the control of sulphur and phosphorus to very low levels, minimising carbon contents and restricting nickel contents to 1·0% or less. Manganese which is normally present in ferritic steels helps to reduce the effect of sulphur by forming high melting point complex sulphides which effectively reduce the freezing range. Clearly the greater the manganese content the greater the tolerance for sulphur.

In cases where compositional control is not available (some very high strength ferritic steels) then procedure control must be used to limit the stress and alter the solidification rate. Because of the number of variables involved this has usually to be done in an empirical manner (almost by trial and error). For example, Machado [16] has shown, for the submerged arc welding of Q and T steels, that solidification microstructure and cracking tendency are related to solidification rate but that there is no simple relationship between the latter and the major, measurable welding parameters.

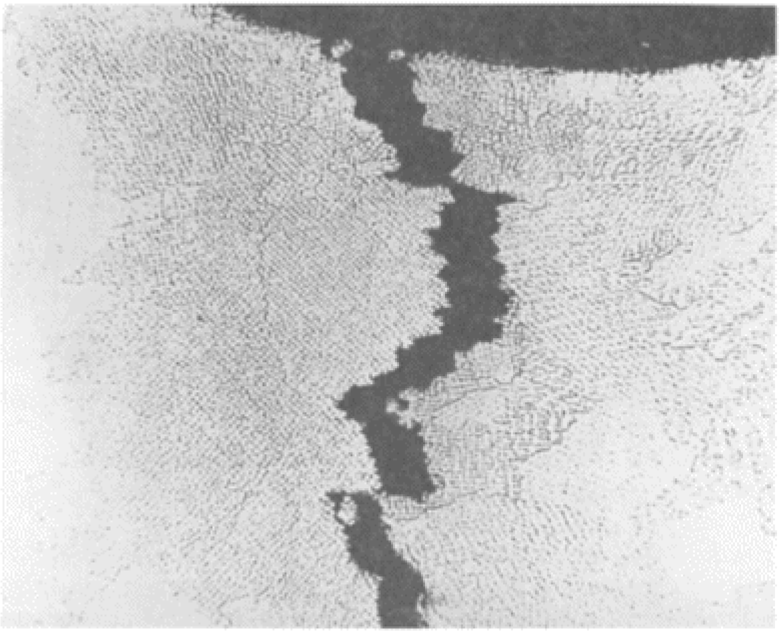


FIG. 1. Intergranular nature of a hot crack in a carbon-manganese steel (×50).

In austenitic steels prevention of hot cracking is frequently obtained by adjusting the composition to ensure that a minimum of 5–10% ferrite is obtained in the solidification structure. The initiation and propagation of cracks is much easier in an austenitic than in a ferritic material [17]. Where other considerations (e.g. corrosion control) forbid this approach then prevention must be by procedure and joint design control (i.e. limiting the stress). In practice, observable weld metal cracking in austenitic steels often occurs because of excessive welding speed [18]. In non-ferrous metals it is frequently the major alloying additions which determine the freezing range (e.g. magnesium in aluminium-magnesium alloys) and so hot shortness control is achieved by the selection of non-matching consumables to significantly alter the weld metal composition for alloys which have a hot shortness tendency. The approach is typified by the analysis of the situation for aluminium alloys given by Young [19].

Reheat Cracking

This is a very serious (and difficult to rectify) cracking problem which is restricted to low and high alloy steels and is mostly a problem confined to the pressure vessel industry particularly where creep resistant steels are used. A recent review by Dhooge and Vinckier [20] gives a very good and detailed survey of present knowledge together with views on the mechanisms involved.

One type of reheat cracking [21] is caused by the generation of excessive thermal stress during post-weld heat treatment leading to the initiation of cracking from pre-existing defects (small hot cracks or hydrogen cracks for example) and is a low temperature phenomenon (~ 300°C) of thick section vessels in low alloy steels. The prevention of this is by control of heating rates and temperature distributions and by the avoidance, as far as possible, of stress concentrations.

The second, and more intractable, form of reheat cracking [21] occurs at higher temperatures (temperatures within the creep range) where intercrystalline cracking in the coarse grained heat affected zone (and occasionally in the weld metal) results from insufficient creep ductility. This cracking occurs either during post-weld heat treatment or during high temperature service and arises because carbide precipitation and impurity segregation strengthens the matrix to such an extent that creep strain is accommodated by grain boundary cracking. This defect can be prevented by correct selection of material composition and heat treatment. In ferritic steels the carbide formers molybdenum, vanadium and chromium are the most detrimental elements together with the impurity elements tin, antimony, arsenic and phosphorus. Recent work has indicated that copper can have an effect [22], which has obvious implications in the use of copper-coated electrode wires. In austenitic steels niobium is the carbide forming element which causes the most problems and the use of molybdenum bearing steels instead is a prevention method.

Welding procedures which avoid the production of an excessively coarse grained heat affected zone (i.e. low heat input procedures) are also helpful in preventing this type of cracking as is a reduction in local stress levels (e.g. grinding of weld toes to reduce stress concentrations) and, in extreme cases, the selection of weld metals with a low hot strength.

There is a third type of reheat cracking similar to the creep cracking phenomenon which is the underclad cracking sometimes found in low alloy steels for nuclear vessels when clad with austenite steel. This very specific problem has been described in considerable detail elsewhere [23].

Hydrogen Induced Cold Cracking

This transgranular cracking phenomenon is associated with the heat affected zones and occasionally weld metals of ferritic steels. It occurs at low temperatures (<150°C) and sometimes only appears some hours after welding. This cracking is of very characteristic appearance (Fig. 2) and usually originates at a weld toe. It is caused by the diffusion of hydrogen from the weld pool into martensitic structures. This embrittles the martensite such that local strains resulting from excessive external restraint or differential expansion and contraction will cause cracking. Therefore, for this type of cracking to occur it is necessary for there to be a martensitic structure, a sufficient amount of hydrogen present to cause embrittlement and a sufficient stress to cause cracking of the embrittled structure.

This is a well understood welding phenomenon and the prevention and control of it is obtained by the control of microstructure, hydrogen level and/or stress level. For the majority of ferritic steels practical guidelines for their prevention and control are given in the form of tables and nomograms in BS 5135, Specification for Metal Arc Welding of Carbon and Carbon-Manganese Steel.

Control of hydrogen level: This is accomplished by the use of ‘low hydrogen’ consumables as the hydrogen in the weld pool mostly comes from moisture associated with fluxes. Manual metal arc electrodes and submerged arc fluxes are available (some of them without the need for very onerous baking and storing procedures) which can give weld metal hydrogen levels of less than 15ml/100g whereas TIG and MIG processes being fluxless can give even lower levels (5ml/100g or less). A more extreme measure is the use of austenitic electrodes (the diffusion rate of hydrogen is much less in austenite than in ferrite and it is also more soluble in austenite). The cleanness of the steel can also be a factor, albeit a minor one, in that the inclusions and microvoids which result from impurity elements such as sulphur can act as ‘traps’ for hydrogen and thus reduce the effective hydrogen content [24]. Such micro inclusions are also helpful in another way in that they promote the nucleation of more desirable austenite transformation products and thus lessen the chance of martensite formation. However, there seems to be little (if any) evidence of ultraclean steels causing HAZ cracking problems in practice [25].

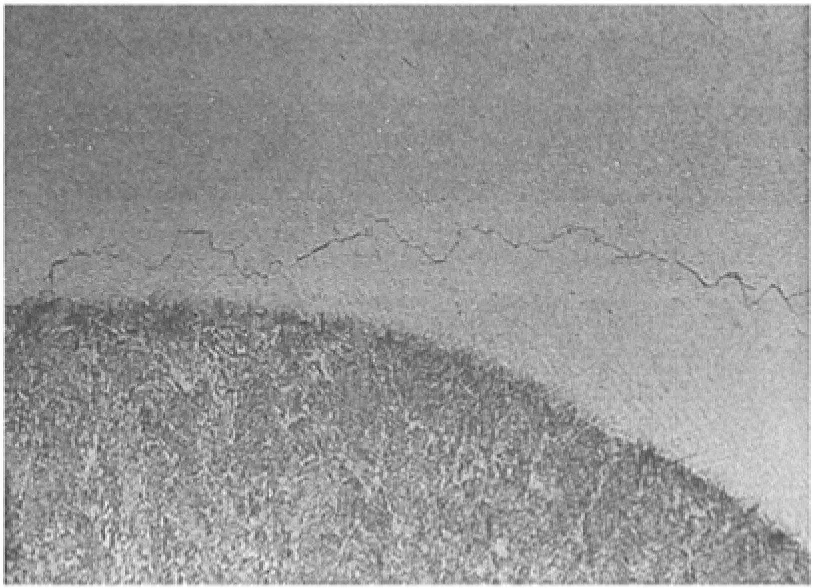


FIG. 2.Hydrogen induced cold crack in the martensitic HAZ of a steel of high carbon equivalent where insufficient preheat has been used.

Control of stress: Since hydrogen induced cracking normally initiates at regions of stress concentration, smooth weld contours and good fit-up will help to prevent the occurrence of this defect (fit-up is one of the variables which is catered for in Appendix E of BS 5135).

Control of microstructure: Either the composition or the cooling rate through the austenite transformation temperature range must be controlled to limit the formation of martensite in the heat affected zone (or weld metal). These two factors are interlinked in that as the hardenability of the steel increases the maximum cooling rate to avoid the formation of a susceptible microstructure decreases. Therefore hardenable steels such as low alloy and creep resistant pressure vessel steels, particularly when in relatively thick sections, will need a significant degree of preheat (and sometimes even some post heat) to reduce the heat affected zone cooling rate to an acceptable level. The hardenability of conventional ferritic steels is determined by the following formula:

$$\text{Carbon equivalent (CE)} = C + \frac{Mn}{6} + \frac{Ni + Cu}{15} + \frac{Cr + Mo + V}{5}$$

However, it should be noted that this formula is not appropriate for the very low (< 0·1%) carbon structural steels, as was shown as long ago as 1978 [26].

The very great significance of carbon content has led to the development of constructional carbon and carbon-manganese steels of ever lower carbon content (e.g. the BS 4360 steels) to lessen the requirement for preheat and permit a wider range of welding procedures to be safely used. In such steels the strengthening effect of carbon is replaced by microalloying additions to give a finer grain size (e.g. BS 4360 normalised steels or control rolled steels) or by thermo-mechanical treatments to modify the austenite transformation (e.g. pearlite reduced or acicular ferrite line pipe steels).

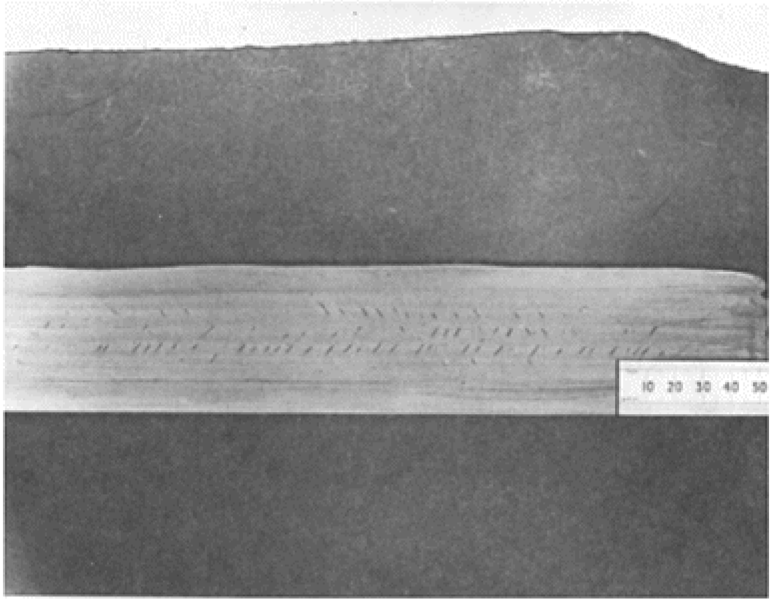


FIG. 3. Longitudinal section of a weld metal in a C-Mn steel showing chevron cracks.

In practice, the prevention of hydrogen induced cold cracking is normally obtained by a combination of methods—the use of low hydrogen consumables and preheat and heat input control together with, where possible, the use of low hardenability steels.

Chevron Cracking

A particular form of weld metal hydrogen induced cracking has recently become a significant problem. This type of cracking with its characteristic appearance (Fig. 3) is found in high strength ferritic steel weld metals and, although a hydrogen induced phenomenon, often originates at small hot tears [27]. The greater the weld metal strength and hardenability and the greater the tendency to hot cracking, the greater the potential problem. Although there is still disagreement over the precise mechanism of the cracking phenomenon (i.e. the relative importance of the low ductility found at high temperatures and the lower temperature hydrogen embrittlement), the best practical preventive measure is the reduction of the hydrogen level in the weld deposit (see Table 2).

Lamellar Tearing

This is not strictly a weld defect but a defect in plate which can be exposed by welding. The bonding between inclusions and the matrix in the base metal is weak and some of the inclusions will be brittle. Also these inclusions will tend to be elongated in the rolling direction of plate.

TABLE 2

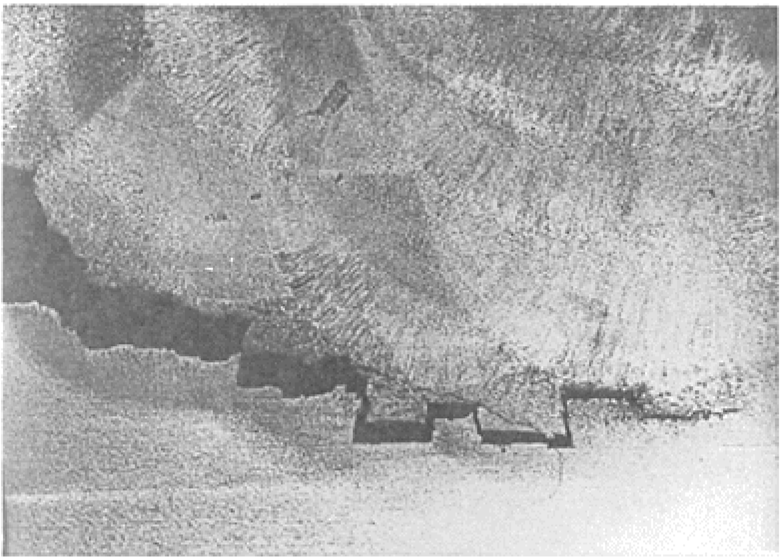


FIG. 4. Typical lamellar tear adjacent to a large fillet weld [39].

EFFECT OF PRE—TREATMENTS ON HYDROGEN LEVEL AND CHEVRON CRACKING TENDENCY IN SUBMERGED ARC AND WELD METAL [27]

Flux treatment	*Weld metal diffusible hydrogen (ml/100g)*	*Number of cracks per 100 mm of weld*
Baked at 450°C	2·5	0
As-received	3·7	2
Exposed to welding shop atmosphere for 10 days	6·2	10

Therefore excessive strain in the through thickness direction can cause decohesion and fracture of inclusions leading, sometimes, to extensive tearing (see Fig. 4). A weld is often the cause of such excessive strain and although modifications in welding procedure and joint design to reduce such strains are possible preventive measures, the most effective are those which improve the properties of the base metal. Therefore low inclusion levels (e.g. low sulphur steels) or modification of inclusions in terms of shape and ductility (e.g. rare earth treatments of steels) which improve the through thickness ductility (a minimum of 20% reduction of area is recommended for ferritic steels [28]) are the best methods of preventing this problem arising.

Workmanship Defects

Solid Inclusions

The most important (and most frequently occurring) type of solid inclusion is slag inclusion. Such inclusions arise because it is difficult to ensure that all pockets of slag are removed from the relatively uneven surface of a weld, particularly when access is difficult. Fluxes do vary somewhat in the ‘detachability’ of the slags they produce, for example the older highly basic submerged arc fluxes are being superseded partly because of their poor slag detachability.

Oxide inclusions are occasionally found, particularly in welds in aluminium where they result from inadequate precleaning of the joint surfaces.

Tungsten inclusions are a defect associated with TIG welding where the use of an excessive current for a given electrode size or the chance touching down of the electrode into the weld pool cause the melting off of some of the electrode.

Porosity

Porosity occurs when the solid weld metal is supersaturated with a particular gas (hydrogen, nitrogen or carbon monoxide) which then forms pores as a result of the nucleation of gas bubbles on discontinuities in the metal (grain boundaries, micro inclusions, etc.). Since there will always be a sufficient number of nucleating sites the incidence of porosity in a given weld metal is a function of the degree of supersaturation of the relevant gas.

Gases enter the weld pool through air entrainment in the arc atmosphere (hydrogen and nitrogen), grease and moisture on joint faces or welding consumables (hydrogen) or chemical reactions in the weld pool or arc (carbon monoxide in steel).

Compositional and welding process and procedure factors primarily determine the range of porosity which can be expected. Examples of this are the effectiveness of the deoxidation reaction in carbon dioxide welding on porosity due to carbon monoxide, the nitrogen porosity due to air entrainment in welds made with gasless cored wires and the tendency to hydrogen porosity in MIG welding of aluminium because of the large surface to volume ratio of the electrode wire and the relatively low solubility of hydrogen in solid aluminium. However, the actual occurrence of porosity is a function of such factors as instability of the arc column due to incorrect electrode manipulation, inefficient cleaning of edge preparations, inability to control the arc column at stops and starts; all of which locally increase the gas content of the weld metal.

Lack of Fusion and Lack of Penetration

These defects are generally a function of electrode manipulation, joint design and arc current or inadequate preparation of the joint surfaces. The result is that the welding arc is not sufficiently ‘penetrating’ to ‘wet’ the edge preparation or the previously laid weld run or does not completely fill the joint gap.

As for porosity defects, there are certain process and procedure factors which make the defect more or less likely even though an individual occurrence is a workmanship error. For example, high heat input processes such as submerged arc or electroslag welding are not very prone to this defect whereas solid wire MIG processes are. Cored wire processes are less prone than solid wire processes because the arc reactions are frequently exothermic and provide a more efficient heat source.

Shape Defects

This range of defects (poor profile, undercut, misalignment, excessive spatter, for example) is almost exclusively a consequence of poor electrode manipulation or bad fit-up and the cause is frequently self evident. Sometimes the cause is an incorrect procedure. For example, undercut can be caused by too high a welding current or too low a speed and excessive penetration can result from too high a heat input. Excessive spatter may not be a result of poor electrode manipulation but can be, in the case of gas shielded welding, due to too low a current in the case of spray transfer or insufficient inductance in the case of dip transfer. In certain circumstances however incorrect procedures (wrong current or arc voltage or incorrect ‘tuning’ of the short circuiting carbon dioxide process) can be the cause.

THE SIGNIFICANCE OF DEFECTS

The fabricator's aim is to produce a welded structure without defects but, as discussed above, this is in practice difficult if not impossible if a structure is to be fabricated at an economic cost. Therefore all the major codes and standards which govern the quality of welded structures permit some latitude in this respect. In other words, they all define a tolerance level for weld defects. These tolerance levels have been defined on the basis of experience and engineering judgement and are to some extent arbitrary. They implicitly define for each type of construction (e.g. pressure vessel, pipeline, storage tank, etc.) the minimum quality standard which a competent fabricator should be consistently able to meet. From a quality assurance and quality control point of view this is a very appropriate way of setting the acceptable defect level but from a purely technical point of view which considers a given defect in terms of its effect on the integrity of the structure this is an inexact and possibly over conservative approach. The accumulation over the past 20 years or so of a great amount of data on the effects of weld defects on weld performance has shown that in this strict technical sense the acceptance standards in many of the major codes and standards are inappropriate and over conservative. This has led to a continuing debate on the viability of such acceptance standards and the development of formal methods, based essentially on fracture mechanics analyses, for assessing the significance of particular defects on a 'fitness-for-purpose' basis.

The Effect of Defects on Weld Performance

From the point of view of their effect on the mechanical properties of welds we can classify defects into three main categories—volumetric (e.g. inclusions, porosity), planar (e.g. cracks, lack of fusion) and shape (e.g. undercut, misalignment) and we can consider their importance in quantitative terms on three types of loading or possible failure modes—static tensile, fatigue and fast fracture. Under this defect type classification we find that the majority of the planar defects will be technological defects whereas the majority of the volumetric and many of the shape defects will be workmanship defects. This has some bearing on the quality assurance and quality control implications.

Static Tensile Loading

Work on ferritic steels [4], aluminium alloys [29, 30] and copper alloys [31] indicates that we can assume, at least to a first approximation, a linear relationship between defect size and reduction in tensile strength. Volumetric defects by their nature cannot create a significant reduction in weld cross section (a weld with >5% by volume porosity, for example, is almost too bad to be achievable) so that, in practice, we can ignore such defects on a 'fitness-for-purpose' basis in terms of static loading. Planar defects are more important because they can, in principle, cause a significant reduction in cross section (>50% would not be impossible) and also because it is very difficult to accurately 'size' such defects in the through thickness direction with currently available NDT methods. Shape defects can also be significant (under-cut of 10–15% is not unknown) but the size of these defects can at least be accurately measured.

Fatigue Loading

Fatigue cracks originate from 'notches' which produce a stress concentration under an applied stress. A welded joint in itself generates a stress concentration, the magnitude of which varies considerably with the joint design. This being so the fatigue strength of a welded joint is highly dependent on the joint design (for example, a sound butt weld in carbon steel stressed transversely will have a fatigue strength for a given endurance some five times greater than a sound non-load bearing fillet welded attachment in the same material) and construction codes such as BS 5400 Steel, Concrete and Composite Bridges sensibly take this into account. Also, since the majority of the fatigue life of a welded joint consists of crack propagation rather than crack initiation and crack propagation rates are insensitive to microstructural variations and therefore to compositional changes the major variable which determines the fatigue performance of a welded joint is the stress concentration resulting from the joint design. This being so, the significance of any weld defect is determined by the degree to which it increases the already existing stress concentration. A given defect will therefore not necessarily have the same importance in welds of different types and, furthermore, the position of the defect within the weld cross section can be a critical factor.

Since weld shape is so important in determining the fatigue performance shape defects and surface breaking defects are generally the most serious. For example, in butt welds the fatigue strength can be related to the reinforcement angle. Volumetric defects can usually be ignored as they will have no significant effect on the stress concentration except in some very special cases [32] where the inherent stress concentration is very low and there are surface breaking volumetric defects.

The presence of planar defects can obviously result in an increase in stress concentration, the effect being greater if such a defect is at a weld toe and being relatively more serious the greater the inherent fatigue strength of the joint design. For these reasons the setting of weld quality standards where fatique is the operative failure mode must take into account the joint design, e.g. butt welds will need to be fabricated to a higher standard that fillet welds to avoid a degradation in fatigue strength. This is taken into account in the more enlightened structural codes (e.g. BS 5400).

Fracture

Fracture mechanics analyses demonstrate that fracture can initiate from a defect when under load if the stress intensification at the defect is sufficiently high for it to be energetically favourable for a crack to initiate. This implies a relationship between the defect size and position and the magnitude of the applied stress (the factors which determine the degree of stress intensification) and the toughness of the weldment in the vicinity of the defect (the factor which determines the critical level of stress intensification for a crack to initiate). This inter-relationship between a number of factors (not all of which can be accurately measured in many cases) means that the assessment of the significance of a defect in terms of fracture must be undertaken by a fracture mechanics analysis and standardised analytical methods are available for this (see next section). However, some general statements can be made. Volumetric defects are, again, of little significance in that because of their shape they cannot generate a sufficient stress intensification to be harmful in the materials normally used in welded construction. Shape defects, likewise, are unlikely to be serious defects. Planar defects are the most significant and the stress intensification resulting from such a defect will be a function of the applied stress and the defect size. Because of the difficulty in accurately measuring the size of the planar defects it is almost always necessary to consider planar defects as unacceptable if fracture is a possible failure mode unless the material toughness is extremely high in relation to the defect size.

Formal Methods for Assessing the Significance of Defects

The philosophy behind all the formal methods which have so far been introduced was propounded in two papers published by Harrison, Burdekin and Young in the late 1960s [33, 34]. Modifications to the details have been made subsequently (for example, Harrison [35, 36, 37]) and a critical review of the different methods has been produced by Burdekin [38].

In practice, the formal methods are concerned primarily with the possibility of a defect initiating fatigue failure or fast fracture and a defect is considered ‘acceptable’ if it can be shown by a fracture mechanics analysis that the possibility of failure occurring from the defect is remote. Since a fracture analysis of this type relies on making assumptions or best estimates of many of the parameters (stress distribution, flaw size, fracture toughness, fatigue crack growth rate, residual stress, for example) which are difficult to measure precisely there are bound to be differences between the different methods which relate primarily to the degree of conservativeness (or factor of safety) which is included in the calculations. Clearly, therefore, the more precise the design and material property data the more useful and reliable such fitness-for-purpose analyses can be. For example, the approach used in the ASME Boiler and Pressure Vessel code Section XI Appendix A for evaluating flaws found during in-service inspection of a nuclear component is very exact. The properties of the steels used are known with some precision as are the environmental effects (e.g. irradiation) on them. Very detailed design analyses will be available to cover all expected operating modes (including ‘fault’ and ‘emergency shutdown’ conditions) and, furthermore, the inspection techniques and hence the reliability of the flaw size estimate will be good. Even in this case a very large factor (10 on the flaw size necessary to cause failure under normal operating conditions) is used to estimate the tolerable flaw size and all flaws are considered in the same way there being no distinction between volumetric and planar defects.

The British Standard document PD 6493:1980 Guidance on Some Methods for the Derivation of Acceptance Levels for Defects in Fusion Welded Joints gives a method of analysis for all types of structure and is necessarily, therefore, less exact. It only requires an analysis of planar defects as volumetric defects are assumed to be insignificant unless the toughness is low (<1300 N mm$^{-3/2}$). A limit is set for volumetric and other minor defects which is a somewhat arbitrary limit based largely, one suspects, on what is thought to be an ‘acceptable’ quality level. Since the document can only give general rules because the amount of, and precision of, the relevant engineering data will vary considerably according to circumstances the document is perhaps not as widely usable as would be expected. Its major use, and that of other, similar, standards, in fact, may well be in material and welding process selection. If it can be assumed that for a given structure defects above a given size will either not occur or will be detected with a very high reliability then by making conservative assumptions about maximum stress levels and defect positions it is possible to calculate the minimum fracture toughness required of the materials and weldments so that fatigue or fracture are unlikely to occur. This fracture toughness level can then be imposed as a material specification and will be of major importance in the quality assurance of the structure.

CONCLUDING REMARKS

Weld defects are, obviously, undesirable by definition but the complexity of the technology of welding means that it is not usually a worthwhile aim to expect total freedom from all defects.

The major, technological defects (cracks and other planar defects) can and should be prevented to a large extent by proper quality control over materials, joint designs and welding procedures as the causes of such defects are well known.

The minor, workmanship defects are not totally preventable and a degree of tolerance for them is appropriate. Such tolerance levels are based largely on experience of what is achievable by competent fabricators and no significant change in this approach seems likely or, from a quality assurance point of view, desirable.

The analysis of the significance of defects supports what would intuitively be expected, the crack and crack-like defects are the most serious and volumetric (porosity and solid inclusions) defects are of little importance in terms of structural integrity. However formal methods of assessing crack-like defects in terms of their significance in relation to possible structural failure, whilst correct, are difficult to apply in many cases because of the lack of sufficiently detailed information on defect size, stress level and fracture toughness. These formal analytical methods, though, are of considerable importance from a quality assurance sense in helping to specify and characterise material property requirements.

REFERENCES

1. Classification of defects in metallic fusion welds with explanations. *Welding in the World,* **7** (1969) 200–10.
2. Parameter characterising defects in metallic fusion welds. *Welding in the World,* **9** (1971) 92–111.
3. Salter, E.R. and Gethin, J.W., 'Pressure Vessel Standards—The impact of change'. The Welding Institute, London 1972.
4. Kihara, H., Tada, Y., Watanate, M. and Ishii, Y., Non-destructive testing of welds and their strength, Society of Naval Architects of Japan, 60th Anniversary Series **7** (1960).
5. Rogerson, J.H., Quality assurance in welding construction, International Institute of Welding, Public Session, Estoril, 1980.
6. Rodrigues, P.E.L.B., Figueiredo, R., Moura, I. and Guerreiro, M., Quality assurance in welding construction, International Institute of Welding, Public Session, Estoril, 1980.
7. Rogerson, J.H., The development of efficient and rational sampling schemes for the NDT of welded fabrications, *Weld. Res. Int.,* **7** (1977) 412–33.
8. An Assessment of the Integrity of PWR Pressure Vessels. Report by a study group. UKAEA HMSO, 1976.
9. Rodrigues, P.E.L.B., Wong, K.H. and Rogerson, J.H., Paper 3693 Offshore Technology Conference, Houston, 1980.
10. Wong, W.K. and Rogerson, J.H. Weld defect distributions in offshore structures and their influence on structural reliability. Offshore Technology Conference, Houston, 1982.
11. Becher, P.E. and Hansen, B., Statistical Analysis of Defects in Welds, Danish Welding Institute, 1974.
12. Borland, J.C., Generalised theory of supersolidus cracking, *Br. Weld. J.*, **7** (1960) 508–12.
13. Borland, J.C., Suggested explanations of hot cracking in mild and low alloy steels, *Br. Weld. J.*, **8** (1961) 526–40.
14. Simpson, M., Solidification cracking during the submerged arc welding of carbon-manganese steels—a review, *Weld. Res. Int.,* **7** (1977) 177–92.
15. Hemsworth, B., Boniszewski, T. and Eaton, N.F., Classification and definition of high temperature welding cracks in alloys, *Metal Construction,* **1** (1969) 5–16.
16. Machado, I.,, *PhD Thesis,* Cranfield Institute of Technology, 1984.
17. Kajanpaa, V.P., David, S.A. and White, C.L., *Weld. J.* **65** (1986) 203–12.
18. Borland, J.C. and Rogerson, J.H., *Weld. J.,* **42** (1963) 160–3.
19. Young, J.G., Significance of filler metal composition in aluminium alloy welding, *Br. Weld. J.*, **8** (1961) 568–74.
20. Dhooge, A. and Vinckier, A.G., Reheat cracking, a review of recent studies. *Welding in the World,* **24** (5/6) (1986) 104–26.
21. Nichols, R.W., Reheat cracking in welded structures, *Welding in the World,* **7** (1969) 244–60.
22. O' Brien, T.J. and Wolstenholme, D.A., Effect of Copper on Transverse Cracking in 2Cr-Mo Submerged Arc Weld Metals. CEGB Report TPRD/ M/1356/R84, 1984.
23. Dhooge, A., Dolby, R.E., Sebill, J., Steinmetz, R. and Vinckier, A.G., A review of work related to reheat cracking in nuclear reactor pressure vessel steels, *Int. J. Press. Vess. Piping,* **6** (1973) 329–409.
24. Hart, P.H.M., Paper 20, Trends in Steels and Consumables for Welding, The Welding Institute, London, 1978.
25. Hart, P., Effects of steel inclusions and residual elements on weldability. *Metal Construction,* **18** (1986) 610–16.
26. Quinn, T.A. and Rogerson, J.H., A comparison of HAZ microstructures and properties of some low carbon linepipe steels. *Weld. Res. Int.* **8** (5) (1978) 349–67.
27. Mota, J.F. *PhD Thesis,* Cranfield Institute of Technology, 1979.
28. Wilson, W.E., Minimising lamellar tearing by improving 2-direction ductility, *Weld. J.*, **53** (1974) 691–5.

29. Dinsdale, W.O. and Young, J.G., Significance of Defects in Aluminium Fusion Welds, 2nd Commonwealth Welding Conference, London, 1965.
30. Lancaster, M.V. and Rogerson, J.H., Welding in Non Ferritic Materials, The Institute of Welding, London, 1967.
31. Hudson, M.E., Mota, J.F. and Rogerson, J.H. Cranfield Institute of Technology, unpublished work.
32. Dawes, M.G., Fatigue strength of ferritic steel shafts reclaimed by welding and metal spraying, *Br. Weld. J.*, **10** (1963) 418–38.
33. Burdekin, F.M., Harrison, J.D. and Young, J.G., 'The Significance of Defects in Welds', The Institute of Welding, London, 1967.
34. Harrison, J.D., Burdekin, F.M. and Young, J.G., A proposed acceptance standard for welded defects based on suitability for service, 2nd Conference on the Significance of Defects in Welds, The Welding Institute, London, 1968.
35. Harrison, J.D., Basis for a proposed acceptance standard for weld defects—Part 1: Porosity, *Metal Construction,* **4** (1972) 99–107.
36. Harrison, J.D., Basis for a proposed acceptance standard for weld defects—Part 2: Slag inclusions, *Metal Construction,* **4** (1972) 262–8.
37. Harrison, J.D., A re-analysis of fatigue data for butt welded specimens containing slag inclusions, *Weld. Res. Int.,* **8** (1978) 81–101.
38. Burdekin, F.M., Colloquium on the Practical Application of Fracture Mechanics, The International Institute of Welding, Bratislava, 1979.
39. Ferreira dos Santos, A.C., *PhD Thesis,* Cranfield Institute of Technology, 1978.

7
The Inspection of Welds and Welded Construction

N.T.BURGESS

Quality Management International Ltd, Egham, Surrey, UK

INTRODUCTION

Inspection is part of quality assurance and this chapter identifies some aspects of the work required. Inspection activity is the subject of many standards around the world to which reference should be made for detailed guidance in specific industries or instances [1–5].

GENERAL

As long as human beings are involved in welding operations, as welders or as machine operators there will be variability in performance and some inspection of their work will be required.

It was earlier hoped that the move to automatic and semi-automatic welding would improve on the quality of manually made welds and that the need for post inspection would decrease. This has not proved to be the case and, indeed, some feel that new developments in welding technology, material and in design have themselves contributed to welding problems by introducing complications that may not have been assessed for the effect on quality assurance. In Chapter 4, A.Gifford gives such examples.

Whilst it is true that quality control principles can be more readily applied to machine welding than to manual welding, we remain heavily reliant on the 'inspector' to determine whether welds meet the specified requirements or not. Inspection activity, however, must be seen as part of the total quality control effort and not as an end in itself. It must be programmed into the total scheme of checks since inspection alone as the main QA method would be too late to affect the quality of the product.

Inspection and NDT are often regarded as synonymous but this is not the case. Whilst NDT is a major tool in controlling welding quality, its contribution must be kept in perspective and reliance upon it treated cautiously (Chapter 8).

We must also be clear as to which party is best fitted to carry out the inspection of welds. Too often in welded construction inspection is left to the customer's inspector or to a third party or official inspectorates, although under the principles outlined in Chapter 1, it is primarily the manufacturer's responsibility to ensure that his welds are to specification. The initial inspection activity, therefore, must take place at his behest, in his time and on his premises. If his inspections are carried out effectively then there may be little or no need for further inspection by customers or third parties.

For such inspection activity to be effective, several factors must be considered: the skills of the inspector, the general inspection training he has received, the equipment he has (including his eyes) and the information and briefing he has received about specific weldments. Those involved with inspection and acceptance of welds require skills that span the total range of capabilities.

Although, as has been shown, the prime responsibilities rest with the shop (or site) inspector of the organisation making the weldment, there is a reluctance among manufacturers to recognise the need to adequately support this responsibility with the right people (or to have them approved). This is noted by customers, and the authorities and visiting inspection engineers (insurance companies, classification societies, etc.) who generally carry out 'witness inspection' may bring further knowledge into decisions concerning acceptance or rejection. It is felt that welding is so important that nothing but a specialised knowledge of the likely problem areas will suffice. However, manufacturers must be wary of the 'expert' overseer who, for example, may wish to interpret radiographs. This activity may look easy, but everyone including the 'expert' should be willing to demonstrate his expertise by being qualified in the skill.

Responsibility of Welding Inspectors

Inspection of welds should be carried out by qualified and specially trained personnel whether working for the manufacturer or the customer. In the oil, gas and structural industries, welding inspection is often recognised as a particular disicipline, whereas in other industries, inspection of welds is not specifically identified and the work is done as part of general inspection by mechanical inspectors and engineers. Welding is not picked out from machining, assembly etc. but as long as the individual recognises the importance of welding variables, and is trained and qualified, there should be no problem.

Many countries operate schemes for the certification of welding inspectors, examples being:

(a) UK—Certification Scheme for Weldment Inspection Personnel (CSWIP)
(b) USA—AWS Welding Inspector Qualification and Certification Scheme AWS QCl
(c) Canada—Qualification Code for Welding Inspection Organisation
(d) Australia—SAA Welding Certification Code, AS1796–1975 and SAA Structural Steel Welding Supervisors Certification Code, AS2214–1978.

The UK scheme, which is similar to the others, places specific responsibilities on the welding inspector as follows:

(1) *Codes and standards:* Interpretation of the requirements of codes and standards.
(2) *Welding procedures:* Establishing that a procedure is available, has been approved by the appropriate authority and is being employed in production.
(3) *Witnessing of welder and procedure approval tests:* Witnessing the preparation of test plates and destructive tests and verifying compliance with appropriate standards and specifications.
(4) *Welder approvals:* Verification that adequate and valid welder approvals are available, and that only approved welders are used in production.
(5) *Parent material identity:* Verification against documentation and markings of correctness of parent material.
(6) *Welding consumables identity:* Verification of correctness of welding consumables (electrodes, filler wires, consumable inserts, gases, fluxes etc.)
(7) *Pre-weld inspection:* Verification that dimensions, fit-up and weld preparations are in accordance with specifications.
(8) *Preheating:* Verification that preheat (where required) is in accordance with specified procedure.
(9) *In-process welding surveillance:* Surveillance during welding to verify compliance with specified procedure including any preheat, interpass temperature control and post heat requirements.

(10) *Post-weld heat treatment:* Verification that post weld heat treatment has been conducted in accordance with specification requirements.
(11) *Post-weld visual inspection:* Visual inspection and dimensional check of completed weldment against specification requirements and drawings.
(12) *NDT reports:* The study and cognisance of NDT results on any welding work for which the welding inspector is responsible. If the duties of the welding inspector include the interpretation of weld radiographs it is suggested that he seeks certification in accordance with the related approval schemes.
(13) *Reports:* Preparation of inspection reports.

A welding inspector with responsibilities and capability to meet the above will bring great benefit to the QA programme. To be accepted under the UK CSWIP scheme for welding inspectors, candidates must have had at least three years experience of the duties required, under qualified supervision. Successful completion of courses on welding inspection may qualify for a reduction in the period.

For certification of a welding inspector, approval consists of written, oral and practical examinations. For the guidance of candidates and their employers, a specimen written examination paper and syllabus is provided, which outlines the subjects covered in the examination. (The Welding Institute of the UK can provide further details.) The following summarises the main points.

Written Examination

The written examination is designed to test the candidate's knowledge of welding processes, procedures and their control, welder approval, defects and their origin, heat treatments, welding consumables, weldability of materials (as appropriate), destructive tests, terminology for welds, welded joints and weld defects, standards and codes of practice, capabilities of NDT methods, visual examination and dimensional checking, reporting. That part of the examination concerned with the interpiretation of codes and standards will be of the 'open book' type and candidates must take a copy of the standard with them.

Oral Examination

The oral examination is used to supplement the written examination and covers the same subject matter. It normally consists of a discussion with the examiner during the practical tests.

Practical Examination

Candidates are required to inspect and report on the following:

(i) at least two completed welds for compliance with stated requirements;
(ii) a set of destructive tests (including macros) for a welder or procedure approval examination intended to comply with a stated specification.

Similar requirements are being laid down in more and more countries and increasingly customers are specifying that people employed on their work should be so certified.

Stages of Inspection

In general, inspection can be:

(a) *Final Inspection* of the completed component. In the case of welded joints this may include the witnessing of performance tests, e.g. pressure test if a vessel is involved or a load test for structure or moving components.

(b) *Stage Inspection,* the normal activity for welded structures, in which the inspector's activity will commence as early as the design stage with checking of weld procedures against the specification (see the section headed 'Responsibility of Welding Inspectors') and continue to final inspection. (Stages are usually prescribed.)

(c) *Patrol Inspection,* most common in general engineering workshops, involving a combination of surveillance of production operations against instructions, physical inspections and examinations.

Which Party Should Do the Inspection?

Welded constructions have always been subject to a great deal of inspection by customers and third parties, in addition to the inspections that are carried out by the manufacturer or contractor himself. As noted earlier, however, the most effective inspection is generally that carried out by the manufacturer, since he is closest in all respects (physically and commercially). Unfortunately, even in well regulated systems, with certified staff, mistakes do occur, often due to human error, and customer activity is still common. This can be moderated to surveillance and monitoring of the manufacturer's QC action when this is more effective. A quality assurance policy introduces this possibility of quality surveillance, which can be considered as a comprehensive version of patrol inspection (c) (above) applicable to the case of welded structures by involving (a) and (b) also.

With properly set up quality control systems (see Chapter 1) surveillance or monitoring on the part of customers may be all that is necessary to assure quality. 'Witness' inspection may however be worthwhile where it forms part of a planned system for monitoring a manufacturer's QC system rather than for 'acceptance or rejection' (see quality plans).

Aids to Inspection

Acceptance of welded joints (other than by NDT) relies generally on visual inspection, for which one individual and the human eye are the main tools. 'Nothing can totally replace ever-open eyes, a sharp pair of ears and a quick pair of hands, all trained to act in response to the well programmed computer we all have between the ears'. Good eyesight, with the aid of properly focused glasses if necessary, is essential. Other useful equipment would be a magnifying glass; a torch for illuminating parts of the weldment not properly illuminated and a wire brush for removal of rust, slag, etc.

Illumination

Natural daylight is clearly beneficial to good inspection, but this may not always be possible. The effectiveness of illumination largely depends upon contrasts. The area to be examined should be adequately and evenly illuminated without shadow or glare. A general guide is that illumination should not be less than 500 lx. If good daylight is not available, then appropriate artificial lighting must be provided. Hand lamps can be useful for localised inspection. Fluorescent tubular lighting can largely eliminate shadow but may introduce some undesirable flicker.

Surface Cleanness

The surface of welds to be examined must be clearly exposed. This may require the removal of slag, rust, oil or other extraneous dirt, etc. (Inspectors should beware of being asked to inspect/accept weldments that have been painted.) Methods normally used for cleaning the material under examination may be used except any that could mask the feature for which examination is to be made. Some mechanical methods may tend to close discontinuities.

Dressing of Welds

This is a contentious subject, earlier the cause of trouble, nowadays regulated but nevertheless deserving of caution. Welds are dressed to improve shape and profile and therefore fatigue characteristics (see Chapter 3). Dressing to improve appearance or to clean up may be deleterious in masking defects, or, in the risk of over-flushing, may also be costly. Scratch brushing may be adequate in many cases. Where surface crack detection is specified preliminary dressing may be required. In all cases the QC specification should be clear on these points.

Other Aids

The sense of feel can be a useful adjunct to visual examination, e.g. the use of a pin to confirm or explore a crack or other surface defect. A straightened paper clip can be even more sensitive in that it is softer and so can bend, e.g. when inserted to assess the depth of a pore.

A common aid to vision is an ordinary low power pocket lens of magnifying power in the range of × 2 to × 10. The range of optical devices for the effective study of positions inaccessible to the eye is steadily increasing. Some using mirrors and lenses (e.g. intrascopes, borescopes) have been established for many years; others such as light guides and miniature television cameras are more recent developments. All can be very effective when appropriately used.

Dimensional and Shape Checks

The Welding Institute have produced an effective gauge for establishing the weld profile and other characteristics and this is particularly useful with fillet welds (Fig. 1). The gauge will determine fillet weld leg length, misalignment, throat size, depth of undercut or pitting and excess weld metal.

Human Factors in Inspection

We cannot eliminate human error or change human nature and even the decision makers need to make decisions about *which* decisions to make!

In mass production industries, automatic inspection is replacing much human inspections since a machine is generally more efficient in a 100% checking situation of a continuous flow line. But when production operatives and production conditions are variable, as with welding, it is difficult to find a machine capable of examining for the *several* different characteristics or for such indefinite attributes as ‘finish’.

It is necessary to make the best use of conditions for the inspector. The factors that affect his judgement are: working environment, temperature, noise and visual environment. Adverse conditions can reduce efficiency, produce physical discomfort or cause damage to eyesight (e.g. arc flash). As noted earlier, an important factor is the amount of lighting available for inspection.

Perhaps the most important factor however is the ‘social’ one. Fortunately, in welding constructions, the inspector is held in fairly high regard compared with his colleagues in the machine shop. This is probably

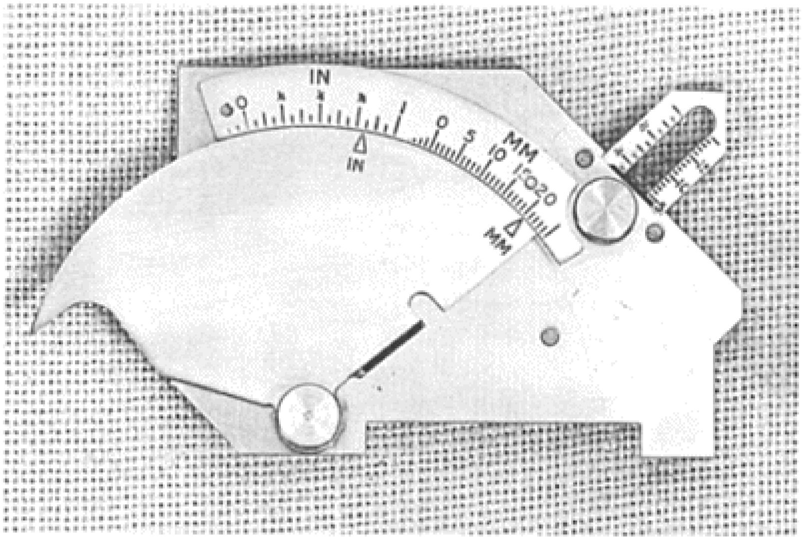


FIG. 1. Multi-purpose welding gauge.

the result of third party influence as noted earlier and also the number of technical aspects associated with welding. For shop or site inspections by the manufacturer/contractor, the relationship between inspector and production worker (welder) is critical. The welder may see the inspector as the person who aims to stop him producing the volume of work required. It may tempt the inspector to give concessions in order to remain friendly; equally an adverse relationship may cause friction to a degree that the inspector is unfairly rejecting items for trivial faults. Much welded work is judged subjectively rather than objectively since

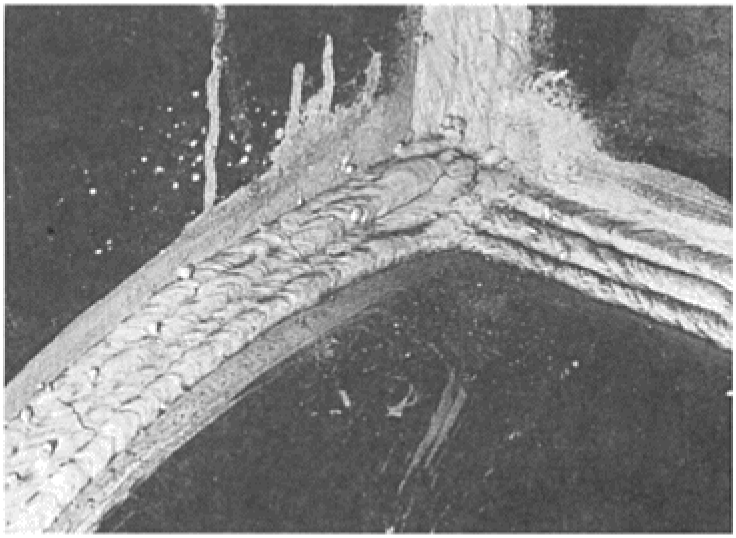


FIG. 2. Photograph of fillet weld finish (containing crack) showing how photographs can be used as reference standards.

some of the standards are unavoidably difficult to specify on paper. NDT has introduced a quantitative element but evaluation of, for example, surface profile and finish remains a problem and one that has cost many welding fabricators dearly in the past. This is due to reliance on the subjective views of the visiting inspector who may have a very personal view on what is acceptable. A clear company QC standard in this area would help. Plastic and rubber replicas of acceptable/unacceptable weld finishes have been used in the past. Photographs are also valuable (Fig. 2). Replicas available from the Welding Institute (UK) illustrate ten samples of welds with different severities of a particular defect: two replicas cover two variations in penetration and toe angle, others undercut [4].

A more general but very important point is that if the inspector (inside or visiting) spends too much time on one characteristic, particularly one that is *easy* to inspect, he may overlook other more important characteristics or defects. An example arises with the radiographic examination of welds in relation to porosity. Because porosity is readily apparent on most radiographs, it is easy to identify and comment upon, and the inspector may take a lot of convincing that large pores can be admitted as acceptable. Detailed discussion will ensue concerning size, depth, location, etc. before ultimate rejection, repair or acceptance. However, many crack types (see Chapter 6) may not so easily be seen on the same radiographs! There is no debate, and they may be overlooked in the argument concerning porosity. Figure 3 is a photograph of blowholes with associated (and potentially more serious) cracks that were missed in the radiographic report. It is now generally accepted [6] that quite large amounts of porosity may have little effect on the strength of welds, whereas quite small cracks and fissures most certainly do.

Guidance to Welding Inspectors—Fitness for Purpose and Acceptance Criteria

Figure 4 illustrates how the acceptance standard for products may be capable of adjustment to suit the needs of the design requirement rather than that of an arbitrarily written code. Where material characteristics of the construction are known (particularly the fracture toughness) and where NDT results can be accurate, ‘fitness-for-purpose’ levels of defects B can be determined and used for accept or reject decisions. This level

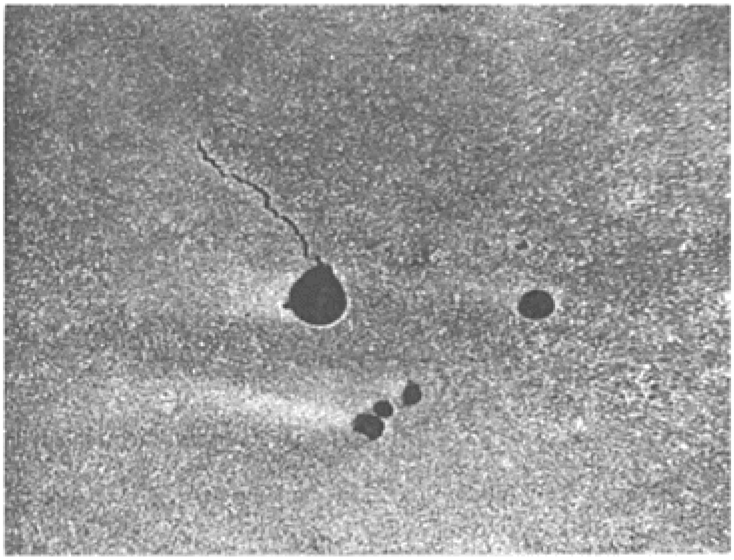


FIG. 3. Cracking associated with, and probably masked by, porosity.

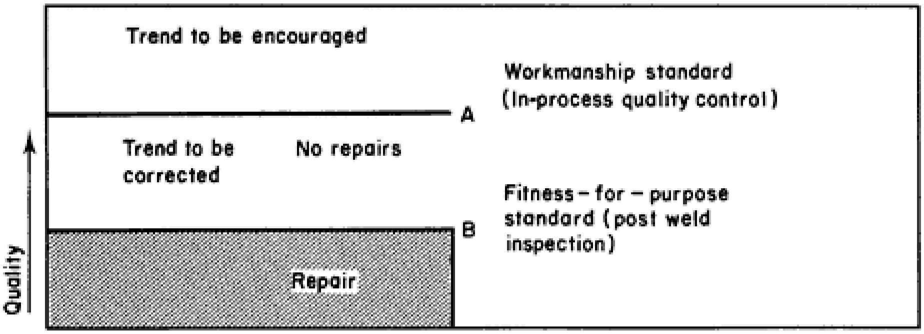


FIG. 4. Fitness for purpose/workmanship standards.

is the one below which welds cannot be accepted (at least without repairs, etc.). Above this level (i.e. less defects) welds may be acceptabe but if they contain defects greater in quantity or seriousness than level A welding operations must be subject to improved quality controls so as to bring quality standards up to the specified or quality control level.

A common sense approach is necessary because research work has shown that, for example, the tolerance of mild steel weld metal to spherical defects such as uniformly distributed porosity is so high that the acceptable level of porosity would probably prevent effective non-destructive testing of the seam from the point of view of the detection of more harmful defects, such as cracks, lack of fusion and lack of penetration! It follows that once the scientifically established (fitness-for-purpose) criteria are laid down, such criteria can only be used for those fabrications where 100% NDT is carried out. However, more and more organisations are using this approach.

For the monitoring of workmanship quality levels, i.e. using NDT during the fabrication process rather than for acceptance, it will still be necessary to use arbitrary levels of weld quality such as those appearing in many codes. As information on the significance of defects grows, these arbitrary levels of weld quality can be modified and set at suitable values. Of course, downward trends in quality must be corrected by attention to the fabrication process before the risk of poor quality becomes significant. Unfortunately, at the present time too many fabricators feel that it is cheaper to carry out repairs, however unnecessary, than to argue with the visiting inspector since argument itself can involve delays to production and delivery dates which may be even more expensive than the repair itself.

REPAIRS

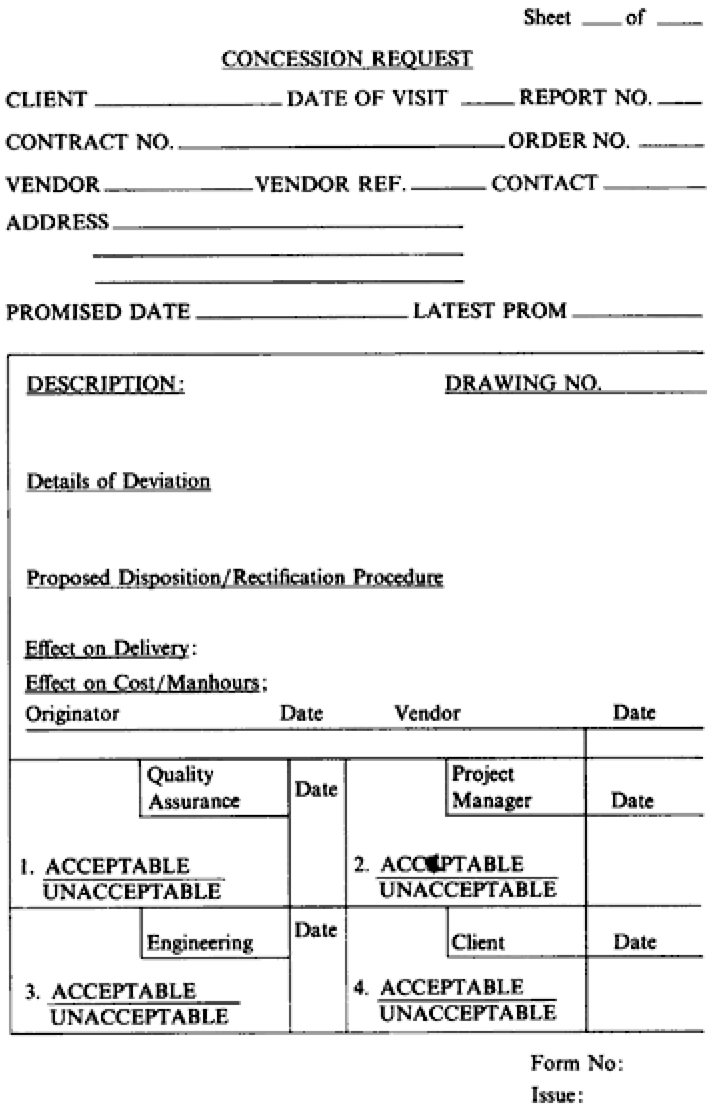
Apart from the 'black and white' accept or reject possibility there are various other options available to the manufacturer. These can be classified as follows:

1. Repair/rectify—remove the defects and reweld. Concession necessary.
2. Replace—the component. Concession may be necessary.
3. Rework—e.g. dress the weld to remove minor defects—then accept 'as is'. Concession probably necessary.

In most cases a quality assurance system will require that a concession procedure operates. This may involve the manufacturer or the inspector raising a report (concession request) to the designer, then customer, or some other party, which identifies the defect, states the problem requiring a concession and makes a recommendation. A concession format is shown in Fig. 5. Whatever action is taken, the details *must* be recorded accurately.

In most codes it is a requirement that repair procedures must employ the techniques and practices approved for the original work—preheat, preparation, filler metals, etc. However, weld repairs are generally to be avoided, since they may damage further the metallurgical characteristics of parent materials, and so any latent defects in the original weld may propagate under the heat effects of the repair. An investigation of boiler tubes failure by the UK power industry in the 1960s revealed that a large proportion of leaks occurred at welds that had been repaired. Several standards, e.g. BS 5289, give additional advice on inspection of repairs. For example:

(a) Removal process—ensure that the specified means of removing the defect, e.g. chipping, grinding, machining, thermal cutting or thermal gouging if used correctly. When a thermal process is employed check that if preheating is Specified it is correctly applied.
(b) Partially removed weld—check that the cut out portion is sufficiently deep and long to completely remove the defects. Ensure that at the ends and sides of the cut there is a gradual taper from the base of the cut to the surface of the weld metal, the width and profile of the cut being such that there is adequate access for re-welding.
(c) Completely removed weld—when a cut has been made through a faulty weld and there has been no serious loss of material, or when a section of material containing a faulty weld has been removed and a new section is to be inserted, check that each weld preparation is re-made in accordance with the welding procedures.



Sheet ____ of ____

CONCESSION REQUEST

CLIENT ____ DATE OF VISIT ____ REPORT NO. ____

CONTRACT NO. ____ ORDER NO. ____

VENDOR ____ VENDOR REF. ____ CONTACT ____

ADDRESS ____

PROMISED DATE ____ LATEST PROM ____

DESCRIPTION: DRAWING NO. ____

Details of Deviation

Proposed Disposition/Rectification Procedure

Effect on Delivery:

Effect on Cost/Manhours:

Originator Date Vendor Date

	Quality Assurance	Date		Project Manager	Date
1. ACCEPTABLE UNACCEPTABLE			2. ACCEPTABLE UNACCEPTABLE		
	Engineering	Date		Client	Date
3. ACCEPTABLE UNACCEPTABLE			4. ACCEPTABLE UNACCEPTABLE		

Form No:

Issue:

FIG. 5. Typical format for concessions.

INSPECTION SAMPLING SCHEMES

Where large numbers of welds are involved in a project, or when a construction involves a large number of welds, a sample only is often proposed for inspection and acceptance purposes. If 100% inspection (or NDT) is specified it must be made clear whether this means 100% of each and every weld, or one inspection (e.g. one radiographic shot) of each weld. '100% inspection' is a dangerous expression and largely meaningless without specifying which method of inspection should be used (i.e. visual or NDT) and to what standard it should be taken (i.e. what are the criteria for acceptance?). Beware also of simple sampling statements such as ‘10% radiography’. Which 10% should it be? 10% of each working shift, or 10% of all welds per day, or of each welder’s work, or on each component? Should butt welds, which are relatively easy to examine by NDT, be covered to the exclusion of fillet welds or does the percentage apply to both butts and fillets? What about the attachment welds? It is for such reasons that each construction needs inspection procedures as part of the quality/inspection plan.

THE INSPECTION PLAN

For smooth production and effective quality control it is necessary to plan for inspection, as for production. Figure 6 illustrates the build up of a typical plan which integrates inspection activity and customer’s involvement with the production phases. All actions should have a procedure or instruction which will be referenced or indicated on the plan. In general, work should not proceed to the next stage until it has been inspected. Route cards or shop travellers as they are sometimes known, are used to assist further the planning and records of work.

INSPECTION RECORDS AND CERTIFICATION

Inspection records are a key aspect of quality assurance and certification and must accompany each weld. Welds that have been inspected should be marked and identified by, for example, stencil or electrochemical marking. The record must show the area inspected and any defects or characteristics shall be identified. The record should show whether any repairs were made and if so, whether they were satisfactory or not, who accepted them, etc.

REFERENCES

1. Fitness for Purpose Validation of Welded Constructions (B037). Proceedings of International Conference. The Welding Institute, Cambridge.
2. Faults in Fusion Welds in Constructional Steels (Ref. B093) (booklet and slide set). The Welding Institute, Cambridge.
3. Halmshaw, R., Non-destructive Testing of Welded Joints (B104). The Welding Institute, Cambridge.
4. Weld Inspection Replicas (M809). The Welding Institute, Cambridge.

To obtain copies of the above, contact The Welding Institute, Abington Hall, Cambridge CBl 6AL, UK.

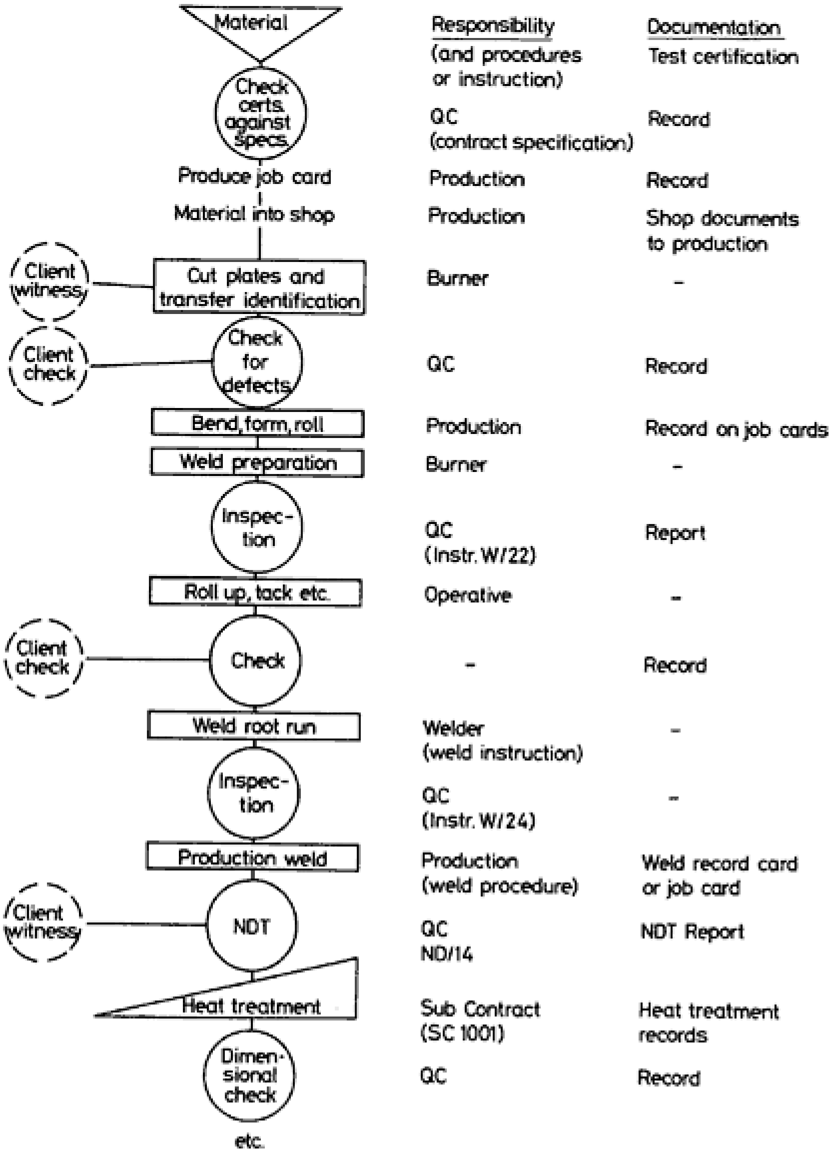


FIG. 6. A typical inspection plan. Symbols used: inverted triangle, input or supply; full line circle, QC check; rectangle, works operation; right angle triangle, sub-contract or special processes; dashed circle, client check or hold point. See also Chapter 4.

8

Non-destructive Testing of Welded Joints

P.J.MUDGE

The Welding Institute, Cambridge, UK

INTRODUCTION

Non-destructive testing (NDT) enables aspects of weld' quality to be revealed, which cannot be observed by the naked eye. Non-destructive testing techniques can be used for general assessment of material properties, for example for materials sorting, or for checking whether or not metals have been heat treated, but the most widespread use of NDT for welded fabrications is to detect and assess weld imperfections. Thus, NDT is properly part of the overall process of quality assurance for welded fabrications, as it provides:

(1) confirmation that weld quality levels predicted as a result of other quality control measures, such as control of materials and fabrication procedures and qualification tests for welders, have been maintained during fabrication of the product itself; and
(2) information which allows decisions to be made as to whether imperfections are acceptable flaws or unacceptable defects, according to the relevant fabrication standards.

The extent to which NDT is applied obviously depends upon the criticality and service conditions of the fabrication, which in turn govern the requirements of freedom from defects. However, in every case it is important to consider NDT as an integral part of the fabrication process if the maximum benefit in terms of product quality is to be realised, whilst minimising disruption to production, thus reducing cost penalties.

There is also a need to consider the practicality of carrying out the requisite NDT when designing welded details. It has always been necessary to urge designers to ensure that welds can be made to the required standard and at minimum cost; it is now realised that consideration should be given to the NDT requirements and how they are to be met at the design stage. It is essential that welding engineers and designers alike should be *au fait* with NDT methods to ensure the most effective use of NDT for quality control both during fabrication and for subsequent monitoring in service, if required.

The role of NDT has become increasingly important, particularly for high quality fabrications. This has been influenced by a number of factors:

(1) Operation of plant under more stringent conditions to improve productivity and optimisation of design to reduce capital costs have both tended to reduce the degree of over-design of welded plant, thereby requiring more detailed knowledge of fabrication quality.
(2) The ability to perform engineering critical assessments, based on fracture mechanics, to determine the fitness-for-purpose of welded fabrications, has led to a requirement for more precise information about

imperfections from NDT as input data for the calculations and for assessment of parameters of individual imperfections against predicted safe levels.

(3) The development of NDT techniques themselves to provide more detailed and more accurate results has led to greater demands for their use; for example, the increasing emphasis on the use of ultrasonic testing.
(4) The growing pressure of product liability has generated a demand for more documentary evidence to demonstrate the level of fabrication quality achieved.

The general requirement of the fabrication industry for maximum integrity at minimum cost, assisted by developments in welding technology and fitness-for-purpose considerations, has placed increasingly stringent demands on the capability of NDT methods. Recent developments, particularly in fracture mechanics, which have enabled critical defect sizes to be quantified, can require an accuracy of measurement of the sizes of imperfections in advance of the present NDT capability. However, it must be borne in mind that, for virtually all applications, NDT is used during fabrication as a quality control tool to assess quality of workmanship, and it is acknowledged that high degrees of accuracy, for defect height measurement, say, are not always achieved; nor are they generally necessary. It is recognised that where high levels of accuracy are necessary, for example to monitor a crack growing in service, special techniques and procedures need to be used.

Improvement of both efficiency and performance of NDT has advantages for the fabrication industry because it allows better quality products to be produced for lower marginal costs. Non-destructive testing is now a major research topic in its own right, with principal research areas consisting of:

(1) Improving flaw detection capability, covering both the sensitivity of the various methods to flaws and ensuring that the requisite area has been examined to a sufficiently thorough extent. An often stated aim of such work is to demonstrate that a flaw above a certain minimum size will be found with a known degree of certainty, usually around 95%.
(2) Improving the accuracy of flaw evaluation. This refers both to more reliable diagnosis of flaw type and accuracy of flaw size measurement.
(3) Development of mechanised application of NDT and of improved recording of results. The former allows an increase in testing speed and controls the degree of coverage, whilst the latter improves the degree of quality control which can be exercised over the test itself and allows third party scrutiny of the results.
(4) Development of revised codes and standards in the light of both greater knowledge of existing NDT methods and development of novel techniques.

This chapter describes the NDT methods commonly used for weld inspection, their capabilities and limitations, together with a summary of recent developments and applications. For convenience, the methods have been divided into two categories: those capable of detecting surface flaws only, and those capable of detecting internal flaws. Consideration is also given to how NDT is incorporated into the overall QA framework for fabrication. A list of standards relevant to NDT appears in the Appendix.

PRINCIPAL NDT METHODS

Detection of Surface Flaws

Surface-breaking flaws are more detrimental to weld integrity than embedded flaws of the same size, so that their detection and removal is required by most codes. Welding imperfections such as undercut [1] can still be most conveniently detected by simple visual examination; this important NDT method should never be ignored because external weld appearance can also provide much useful information about the conditions under which the weld was made (see Chapter 6). Smaller flaws such as surface cracks, however, require an increase in visual contrast between the flaw and its background to be detected. This may be achieved by either the magnetic particle or the dye penetrant method [2, 3]. Both these methods are relatively inexpensive. Eddy current testing is also capable of detecting surface flaws but may be difficult to apply to welds. All these methods have the limitation that flaw depth sizing is not possible.

Magnetic Particle Method [2, 3]

This method is based on the principle that a discontinuity in a magnetic field causes flux leakage which strongly attracts magnetic particles because of the magnetic poles set up at the site of the flaw. Surface flaws and those lying just beneath the surface may be detected by this method. The magnetic field is set up in the test specimen either by passing current through it (for example, by means of hand-held prods), placing it in a current-carrying coil, or using a powerful permanent magnet or electromagnet. A looped conductor technique may have advantages for more complex joint geometries such as those found in offshore structures [3]. The magnetic particles are normally held in suspension in a suitable liquid and sprayed on to the test specimen while the magnetic field is applied. The direction of the magnetic field depends on the magnetising method, and for greatest sensitivity the field must be applied in a direction normal to the flaw. Since the magnetic particles are black, it is often necessary to paint the object under test white for direct viewing. Alternatively, fluorescent inks can be used for viewing under ultraviolet light.

Determination of the effectiveness of magnetic particle tests for detecting flaws is difficult because this depends heavily on the local magnetic field strength in the testpiece. Research is in progress to quantify the relationship between the field generated in the material and the limit of detection of flaws, and to optimise test procedures for maximum detection capability [4].

An obvious limitation of this method is that it can be used only on ferromagnetic materials.

Dye Penetrant Method [2, 5]

A liquid penetrant coloured with a distinctive dye (normally red) is sprayed on to the test specimen. Time is allowed for the liquid to penetrate fully into any surface breaking and then all traces of excess penetrant are removed from the surface. A developer consisting of an absorbent powder (normally white in colour) is then sprayed on. This causes any remaining penetrant, which has seeped into flaws, to be drawn to the surface. Again, a fluorescent penetrant can be used for final viewing under ultraviolet light.

Penetrant testing is generally regarded as being less sensitive than the magnetic particle method, although it is easier to apply with simple aerosol packaging. It is commonly used for quick checks in between weld runs or to ensure that the correct amount of back chipping or gouging has been achieved.

Penetrant testing is an important NDT method for non-ferromagnetic materials, e.g. stainless steels and non-ferrous alloys. The necessity of a seepage path for the dye to enter a flaw makes the method suitable only for detection of surface-breaking discontinuities. Problems of detection can be experienced where plastic deformation of the surface, resulting for example from heavy grinding, has effectively closed the mouth of the flaw, thereby preventing the dye from entering it. The effectiveness of the test is also related to the length of time for which the dye is allowed to soak into a flaw before the excess is removed for viewing. For critical tests soak times of several hours can be required.

Eddy Current Testing [2]

Eddy current testing is another method capable of detecting surface or near-surface flaws, but is not often used for testing welded joints because of the many variables than can affect the result, particularly metallurgical structure and surface profile. However, the method is used for the inspection of welded tube and claims have been made with regard to the in-service inspection of offshore structures [6].

The principle of the method is that eddy currents are induced into metals whenever they are brought into an a.c. field, thus creating a secondary field which opposes the inducing field. The presence of discontinuities or variations in the material alters the eddy current, thus changing the apparent impedance of the inducing coil or of a separate detecting coil. Thus eddy current tests are generally used in a comparative manner, using some known sample as a reference. The differences in the eddy current response can be displayed on a simple meter, but this masks the true nature of the signal. Eddy current responses are better represented by the deflection of a spot on a cathode ray tube (CRT), so that both amplitude and phase angle can be measured. More advanced instruments use a CRT display and some allow simultaneous generation of eddy current signals at more than one frequency so that unwanted variables can be suppressed.

Eddy current probes consist of a coil, which can be of a wide range of sizes and number of turns. It may or may not be wound on a ferrite core. Probe design is therefore very flexible and probes can be tailor-made for specific applications. The use of eddy current testing is restricted for welds because the responses are highly sensitive to both the electromagnetic properties of the material under test (and therefore to the highly variable microstructure around welds) and to small variations in the distance between the test coil and the surface (again highly difficult to control around welds). Eddy current testing is only suitable for detection of surface defects in ferromagnetic materials, although eddy currents will penetrate several millimetres into non-ferromagnetic materials.

It is possible to correlate the magnitude of eddy current response with the depth of surface-breaking notches on machined samples, but depth measurement is not a practical proposition for weld flaws.

Depth Measurement

As already mentioned, the inability to measure flaw depth is a limitation of all the above methods. This is perhaps not a serious limitation when ‘workmanship’ acceptance criteria (see Chapter 7) are being used, because the ability to detect and identify a planar flaw would be sufficient. However, if fitness-for-purpose criteria are applied to either pre- or inservice inspection, a depth measurement of a surface-breaking flaw is essential.

Attention has been paid to the development of methods capable of providing such a measurement. Two techniques appear to be particularly promising: one is the ultrasonic time-of-flight technique which is discussed later; the other is the a.c. potential drop (ACPD) technique. A.c. potential drop is based on the principle that a high frequency electrical current tends to flow close to the surface (the ‘skin effect’) and therefore any potential drop measurement along the current path will be a function of the path length. Extension to the path length due to the presence of surface-breaking flaws will therefore increase the potential drop. The method has been shown to provide high accuracy for the measurement of fatigue cracks [7].

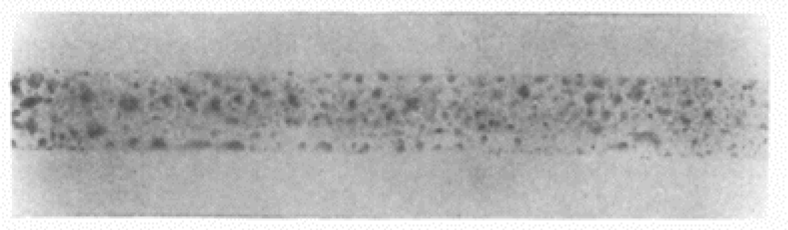


FIG. 1. Radiograph, showing gross porosity in weld metal.

Detection of Internal Flaws

Most critical welded fabrications undergo examinations for internal flaws at some stage of construction. Increasing demand for joint integrity and closer tolerances of design has meant constant usage and development of NDT. Of the two methods commonly used, radiography is the olderestablished technique, used since 1917; ultrasonic testing was introduced much later, in 1942. The principal differences between radiography and ultrasonic testing are that the former produces an image of the lateral extent of flaws on photographic film which can then-be scrutinised, whereas the latter, as conventionally applied, produces echo signals on a CRT display which have to be converted into a geometric plot of flaws by the technician. Ultrasonic testing can be used to measure the height of flaws, but despite this advantage radiography continues to be favoured for some applications owing to the benefit of the pictorial record of weld quality provided by the radiograph.

Radiography [8]

Electromagnetic waves of the same nature as visible light, but of much shorter wavelength, have the ability to pass through solid objects. Absorption of the waves takes place according to the material density and thickness. The presence of flaws, voids, inclusions, etc., changes the degree of absorption so that they can be revealed as a shadow image pattern, which can be recorded on a photographic emulsion. An example of a radiograph showing gross porosity is shown in Fig. 1.

As well as equipment for the production and control of the electromagnetic radiation, darkroom facilities for the development of photographic films are required. Additionally, because of the health hazard imposed by radiation of this type, safety aspects are a prime consideration. If radiography cannot be carried out in a shielded bunker designed to prevent the escape of radiation, considerable precautions are required to ensure that personnel are excluded from the danger zone around the radiation source. Two distinct types of electromagnetic radiation are used for weld inspection, X-rays and gamma-rays.

(1) X-rays (wavelength range 10^{-5}–10^{-8} mm). X-rays are generated in a Coolidge tube by bombarding a dense metal target with fast-moving electrons accelerated from a heated filament by an electric field. The higher the voltage across the tube, the shorter the wavelength and hence the greater the energy and penetrative power of the X-rays. For welds in steel, tube potentials of 50–400 kV are used to inspect thicknesses of 5–100 mm. For thicker sections, the more penetrative gamma-rays are required. Although the smaller X-ray sets are transportable, some of the larger sets of 300 kV and above are bulky and have to be housed in purpose-built X-ray facilities to which samples have to be transported. Higher energy X-rays for testing materials in excess of 120 mm thick can be generated by particle accelerators such as a betatron or linear accelerator. Maximum energies up to around 10 MeV can be

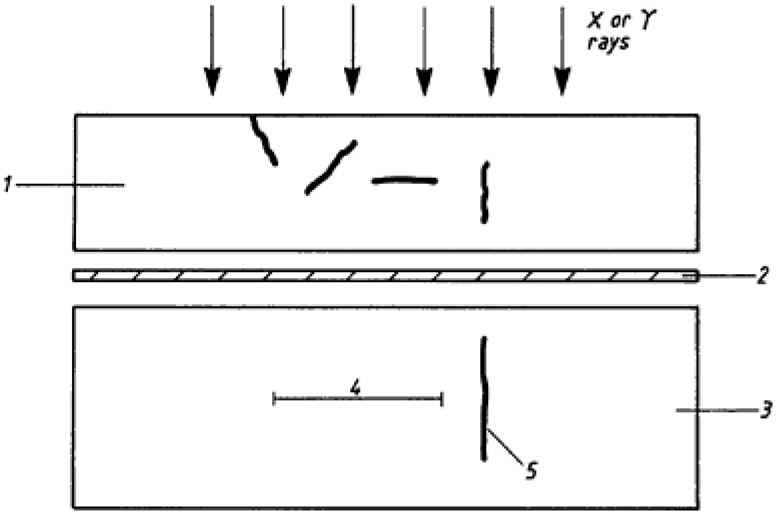


FIG. 2. Detection of planar defects by radiography (schematic). 1, Test specimen; 2, film during exposure; 3, developed film; 4, no images; 5, image of vertical planar defect.

produced, capable of penetrating up to 300 mm or more of steel. Facilities for carrying out such tests are, however, uncommon owing to the limited necessity for such high radiation energies, the high capital cost of the equipment and the extensive protection required to shield personnel from the radiation.

(2) Gamma-rays (wavelength range 10^{-7}–10^{-10} mm). Gamma-rays differ from X-rays in two fundamental ways. First, they are continuously emitted from radioactive isotopes and cannot be switched off and on. Secondly, they have a single wavelength, characteristic of the particular isotope used (a line spectrum), whereas X-rays are composed of various wavelengths (a continuous spectrum). Isotopes commonly used for weld testing are iridium-192, cobalt-60 and caesium-137. These are used to test steel thicknesses of 60–120 mm. The equipment is easily transportable and is of low initial cost compared to the X-ray sets needed to test comparable thicknesses. Strict safety precautions must be adhered to when storing or transporting radioactive isotopes, involving the use of thick-walled, lead-lined containers.

Radiographic testing is excellent for the detection of three-dimensional flaws such as slag inclusions and porosity, as they readily produce shadow images on the film. Planar flaws, however, are sometimes difficult to detect since they tend to be narrow and, unless they are well aligned with the radiation beam, the difference in absorption compared with the surrounding material will be minimal and no shadow image will appear on the film. This effect is shown schematically in Fig. 2. It should nevertheless be noted that, when detected, a planar flaw can usually be readily identified as such. The ability of radiography to detect non-planar flaws makes it ideal for use as a quality control method to enable the quality of workmanship to be assessed. Where it is required to be used for more critical applications in which detection of planar flaws is of importance, a number of additional exposures may be necessary to ensure that such flaws lying in a variety of orientations would be found.

The sensitivity of radiography is governed by the definition and contrast of the resultant radiograph. These parameters in turn are governed by the exposure conditions, photographic film, and development procedures; all of which should be carefully controlled to achieve the required sensitivity. A measure of sensitivity (defined as the percentage thickness change detectable) is presented on the radiograph by means of an image quality indicator (IQI) [9]. This can be either a series of small wires or steps (of similar material to that under test) and is placed on the specimen at the maximum thickness of radiographic interest. Sensitivity is then measured from the smallest wire or step visible on the radiograph.

Interpretation of radiographs requires personnel with skill, experience and a knowledge of what to look for in any particular circumstance. A darkroom and viewing equipment with high intensity illuminators is necessary for critical interpretation. Small magnifying glasses are sometimes used if the film grain size is adequately small. A major advantage of the radiographic method is that the results can be easily stored for subsequent viewing and discussion by as many personnel as desired. However, problems can be caused by disagreements amongst radiographic interpreters, particularly where images are faint or indistinct.

One way of increasing radiographic sensitivity is to reduce the size of the radiation emitter (focal spot) [10]. This reduces the penumbral unsharpness resulting from the use of a focal spot of finite size. Microfocus X-ray tubes are now available commercially with a spot size as small as 10 μm (cf. 2–4 mm for conventional sets) and are applied in instances where high sensitivity and resolution are of paramount importance, for example, in the inspection of microcircuit interconnections.

Apart from insensitivity to planar defects, another limitation of radiography is the difficulty in measuring defect size in the through-thickness direction. Some work has been carried out on the use of densitometric methods [11]; that is, measuring the radiographic density (darkness) of the defect image and comparing it with the density of sound areas. However, these methods are prone to error and can only be regarded as qualitative at present.

Developments in radiography have been chiefly in equipment design, such as constant potential power sources for X-ray generation, and in imaging systems. Devices for capturing the image as a video signal have developed from fluoroscopic techniques and, currently, high performance detectors are available which are capable of capturing a high resolution, low noise image that can be displayed directly on a video monitor or fed into a digital image processing system. Such processing can be used to enhance features of the image which would otherwise be unclear and to detect the presence of flaws automatically. This latter feature is beginning to be used in some mass-production applications, where nominally identical items can be compared with a standard by a computerised system.

As far as gamma-ray testing is concerned, a new low energy radioisotope source, ytterbium-169, has been shown to have major advantages over other sources for the inspection of thin-wall small-bore tubes [12].

Ultrasonic Testing [13]

Ultrasonic inspection of welded joints is based on the fact that a discontinuity within a material will reflect high frequency elastic vibrations propagated through the material. The pulse echo technique is predominantly used. Electrical pulses are generated in a test instrument and converted by a piezoelectric transducer into mechanical vibrations of ultrasonic frequency. The transducer normally takes the form of a handheld probe scanned on the material under test using a suitable liquid couplant. Reflected pulses are received (generally by the same transducer) and converted back into electrical energy for display on the CRT of the flaw detector instrument after being rectified and smoothed. Figure 3 shows a typical ultrasonic test being carried out.

All flaw types are generally easily detected by the ultrasonic method. The best reflections are obtained at normal incidence to the surface of the reflector. For adequate detection of planar flaws, the ultrasonic beam must be generally normal to the plane of the flaw, although if its surface is rough it may be detected from oblique incidence.

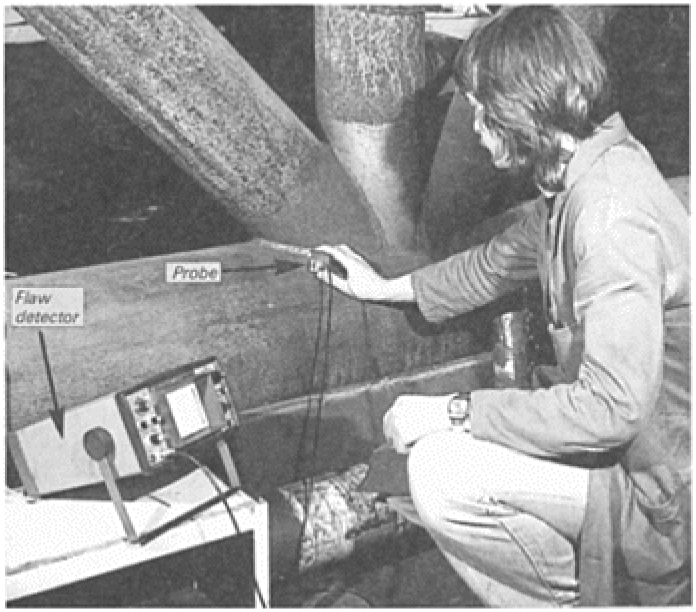


FIG. 3. Manual ultrasonic test.

Two types of wave motion are generally used for weld testing: compression and shear. Compression (or longitudinal) waves are caused by successive tension and compression of particles along the direction of propagation. Shear (or transverse) waves are caused by a shearing action of particles across the direction of propagation. Compression waves are generally introduced at right angles to the surface of the testpiece and are normally used for thickness gauging and to check for plate laminations or inclusions prior to weld testing, the weld cap preventing access for testing by this type of transducer. For weld testing, shear wave transducers emitting angled beams of ultrasound are normally used. Where the weld has been ground smooth, a compression wave probe may be used in conjunction with shear wave probes to detect weld flaws. Various angles of shear wave probes are used, so that there is the best chance of detection irrespective of flaw orientation.

The test frequency is chosen on the basis of a trade-off between penetrative power (low frequency) and detection capability (high frequency). A frequency in the range 2–6 MHz is commonly used for weld testing. Sensitivity is controlled on the flaw detection equipment by a calibrated attenuator and a normally uncalibrated amplifier gain. Setting sensitivity is achieved by either setting the echo from a small machined defect (e.g. a 1·5 mm diameter side-drilled hole) to a known level; or by setting 'grass' (the name given to noise on the CRT timebase caused by scatter from the material's microstructure) to a stipulated level. It is becoming common to use test procedures which compensate for the fact that echoes from defects of a particular size will be smaller the further they are away from the transducer. This is done by comparing reflections from flaws with the amplitude of a distance amplitude correction (DAC) curve, set on known reflectors such as drilled holes. This allows all responses to be normalised, irrespective of range. This approach is incorporated in the ultrasonic inspection requirements of the ASME Boiler and Pressure Vessel Code [14], and is also specified in some proprietary procedures. An alternative means of setting sensitivity

FIG. 4. Ultrasonic testing using the portable computerised P-scan system, being operated in ultrasonic pitch-catch mode.

and of compensating for the effects of increasing test range is to use the distance, gain size (DGS) method, which compares signal amplitude with that from disc reflectors of known diameter [15].

Having detected a flaw, the next stage is to locate, size and characterise it, as required by the code of construction in force. Location is facilitated by calibrating the timebase of the CRT, reading off the position of the echo on the timebase, and then applying simple trigonometry. Location accuracy is generally good and typically within 5% of the wall thickness.

Sizing flaws by ultrasonics has been a major source of controversy for many years. In the USA and on the continent of Europe, it is common to use echo amplitude as a measure of defect severity [15, 16], but this is too simplistic, as amplitude is also governed by other factors, particularly flaw orientation and roughness. In the UK, the most widely used sizing techniques for welds rely on defining the flaw's extremities by measuring the probe movement which gives a stipulated amplitude drop (20 dB for small flaws). This requires more thorough calibration of probe characteristics than the amplitude techniques. However, probe movement techniques are also subject to errors. The magnitude of these errors has been assessed in a number of trials and has been found to be significant (typically ±5 mm at the 95% probability level) [17, 18].

Characterisation of flaws (i.e. predicting flaw type) by conventional ultrasonics is also difficult. Identifying the complex source of a response from a single 'blip' on a CRT is obviously subjective and open to question. In some cases, however, directionality of the source (i.e. detectable from one angle but not from another) can be used to indicate a planar flaw. Attempts have been made to standardise the analysis of echo patterns to provide uniform reporting of flaw type [19]. However, a general drawback is that only 'live' responses are displayed on the flaw detector CRT. These are lost as soon as the transducer is moved or removed from the workpiece.

FIG. 5. Analysis and reporting of data stored on floppy disk by the P-scan system, using a personal computer.

The above limitations often create problems when attempting to interpret the results of an ultrasonic test to a given code, particularly since the latter have tended to evolve from radiographic inspection standards. A great deal of research and development work has been carried out to solve some of the problems, on the basis that ultrasonic testing is the only method which has the potential to provide all the necessary details about the flaw type, shape and size and significant progress has been made, as discussed below.

Other limitations of ultrasonic testing are: difficulties in testing materials with coarse grains, e.g. austenitic steel weld metal [20], due to severe disruption of the ultrasonic beam; and difficulties with welds in thin materials (e.g. less than 6 mm), where the volume being inspected is appreciably less than the ultrasonic beam diameter.

Attempts to assist the interpretation of ultrasonic tests have involved the development of better display techniques. The ability to view the defect in its correct position in relation to the weld has clear advantages over the conventional amplitude/timebase (A-scan) display. The advent of readily available electronic components which allow digital capture, storage and display of ultrasonic signals has prompted the development of a number of computer controlled systems for ultrasonic testing. Such systems allow the ultrasonic test data to be plotted, so that flaw size and location can be shown in relation to the weld geometry on hard-copy printouts. At the most basic level, such systems can be used as an extension to manual testing, with a passive positioner to locate the transducer in relation to specified datum points. They can also be used in conjunction with mechanical scanning devices, incorporating multiple transducer heads to provide thorough, rapid coverage of large components. An example of one such digital system is the P-scan produced by the Danish Welding Institute (Fig. 4). This can be operated with mechanised or manually manipulated scanners and produces a computer-generated plot of the ultrasonic reflectors in their correct position relative to weld datum points (Fig. 5).

The inherent inaccuracies in probe movement sizing have prompted workers to examine new techniques. The time-of-flight technique was originally developed for surface-breaking flaws [21], but is now an

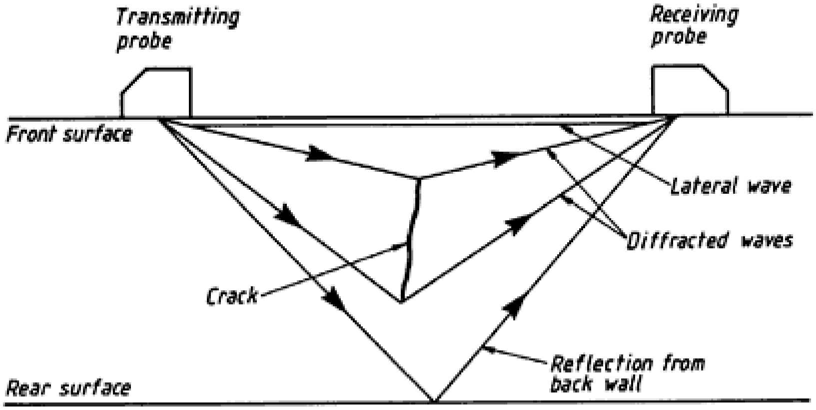


FIG. 6. Principle of operation of the ultrasonic time-of-flight diffraction flaw measurement technique.

established means of sizing internal flaws [22]. The principle is shown in Fig. 6. By measuring the arrival times of the separate diffracted waves from the defect extremities and knowing the velocity in the material and the separation of the transmitting and receiving probes, the vertical through-thickness dimension of the flaw can be estimated. The technique has been shown to be substantially more accurate than probe movement techniques for measuring both planar and non-planar weld flaws [23].

QUALITY ASSURANCE APPLIED TO NDT

One often-neglected aspect of NDT is the need to apply quality assurance to the testing process itself. To obtain satisfactory results in order to enable the condition of a fabrication to be assessed accurately, much reliance needs to be placed on:

(a) following of prescribed procedures by the test technician;
(b) adequacy of calibration of test equipment;
(c) accurate recording of test data at the time of testing and transcription of results on to drawings of details tested;
(d) ensuring that correct details have been tested or that details examined are correctly identified.

Thus a QA framework needs to be established for NDT in the same way as for welding, or indeed any other fabrication activity, if the desired performance is to be achieved. As far as NDT is concerned QA can be thought of as having five principal functions:

(1) To record that a specific task has been requested—including identification of the test object or region to be tested, specification of techniques to be applied, codes of acceptance for flaws, and so on.
(2) To specify how it will be done—the procedure to be used.
(3) To provide evidence that results can be relied upon—including personnel certification, equipment calibration, specific calibrations associated with the test, e.g. sensitivity.
(4) To ensure that results are reported correctly.

(5) To record that the job is completed, and that the findings and actions arising from them are communicated to the appropriate authority.

Items (1) and (5) are essentially interfaces with the wider QA system for any fabrication, whereas (2), (3) and (4) relate specifically to NDT. Specification of an adequate procedure is fundamental to ensuring good NDT performance, and assuring that it is followed as an important quality control function. Personnel certification has long been recognised as playing an important part in ensuring proper application of NDT procedures via the CSWIP (Certification Scheme for Weld Inspection Personnel) scheme, latterly coming under the banner of PCN (Personnel Certification for Non-destructive Testing) scheme. Other proprietary and national schemes also exist, such as the widely used American Society for Non-destructive Testing (ASNT) TC-IA scheme.

More recently, there has been an increased interest in the adequacy of equipment calibration. Both the NATLAS (National Testing Laboratory Accreditation Scheme) and NAMAS (National Measurement Accreditation Service) in the UK have identified NDT as an area where standards of equipment calibration and traceability of standards to national or otherwise accredited sources have been poor. Examples of parameters which are becoming more closely scrutinised are: electrical performance of ultrasonic flaw detectors; current measurement for magnetic particle inspection; temperature control for radiographic developing tanks; dimensional control of ultrasonic calibration blocks; measurement of ultraviolet and ambient light levels for fluorescent magnetic particle and dye penetrant tests; and densitometer accuracy for checking radiographic density.

The accreditation bodies are seeking to define minimum standards for QA for NDT by requiring both traceability of calibration via the use of (for the UK) British Calibration Service approval bodies for provision of reference standards or measurements, and a demonstration that a quality framework for carrying out NDT exists in order that the functions described above are maintained.

CONCLUDING REMARKS

It is hoped that this chapter has provided the reader with some guidance on principles of operation, application and current developments of NDT methods for welded joints. Further details on the techniques discussed here, and many others too numerous to mention, can be found in the references.

Research and development work on NDT is expected to continue as welded structures are subjected to increasingly hazardous environments and as public concern with regard to the safety of large structures grows. Perhaps the most obvious example is nuclear power generation plant. A significant proportion of expenditure on NDT research in the USA can be attributed to problems with, or concern about, the safety of nuclear plants. Similarly, in the UK, the safety case for the pressurised water reactor system has provided the impetus for rigorous evaluations of NDT capabilities [23]. These efforts, on both sides of the Atlantic, are rewarding not only in solving the problems to which they are addressed, but also in the many spin-offs which find applications in a large number of other industries.

It cannot be claimed that NDT is now capable of providing all the answers, but developments in recent years have been significant in determining what can and cannot be achieved with both conventional and more specialised equipment. Further, the increasing awareness of the need to exercise quality control over the NDT process itself will allow the potential of the techniques being developed to be fully realised.

REFERENCES

1. Jubb, J.E.M., Undercut or toe groove—the cinderella defect. *Metal Construction,* **13** (2) (1981) 94.
2. Blitz, J.G., King, W.G. and Rogers, D.G., Electrical, Magnetic and Visual Methods of Testing Materials. Butterworth, London, 1969.
3. Lumb, R.F. and Winship, P., Magnetic particle crack detection, Part 1: Basic principles, limitations and parameter definitions, Part 2: Flux generation and potential applications to offshore structures. *Metal Construction,* **9** (8, 9) (1977) 293, 331.
4. Forshaw, M.E. and Mudge, P.J., Optimisation of magnetic particle testing techniques for welded joints. Proc. 4th European Conference on NDT, London, 13–17 September 1987, Pergamon Press.
5. BS 6443: 1984, Method for Penetrant Flaw Detection.
6. Chrisholm, J., Introducing the EMD MK III—a new dimension in NDT. *Offshore Oil International,* October 1981.
7. Dover, W.D. *et al.,* The use of AC field measurements for non-destructive testing, in The Measurement of Crack Length and Shape during Fatigue and Fracture, Ed. C.J. Beevers. EMAS Warley, 1980, pp. 222–60.
8. Halmshaw, R., Industrial Radiography; Theory and Practice. Applied Science Publishers, London, 1982.
9. BS 3971:1980, Specification for Image Quality Indicators for Industrial Radiography (including guidance on their use).
10. Parrish, R.W. and Rockett, P., A wide energy range, high resolution microfocal X-ray source. *Brit. J. NDT,* **28** (1986) 84.
11. Placious, R.C., Garrett, D.A., Kasen, M.B. and Berger, H., Dimensioning flaws in pipeline girth welds by radiographic methods. *Materials Evaluation,* 39(8) (1981) 755.
12. Pullen, D. and Hayward, P., Gamma radiography of welds in small diameter steel pipes using enriched ytterbium-169 sources. *Br. J. NDT,* **21** (4) (1979) 179.
13. Handbook on the Ultrasonic Examination of Welds. The Welding Institute, Cambridge, 1979.
14. Boiler and Pressure Vessel Code, Section V: Non-destructive Testing. American Society of Mechanical Engineers (ASME), New York, 1986.
15. Krautkrämer, J., Determination of defect size by the ultrasonic pulse-echo method. *Br. J. Appl. Phys.,* **10** (1959) 240–50.
16. American Welding Society, AWS D1.1 Structural Welding Code—Steel.
17. Jessop, T.J. *et al.,* Size Measurement and Characterisation of Weld Defects in Ferritic Steel by Ultrasonic Testing Part 1. (March 1979): Non-planar Defects. Part 2 (October 1982): Planar defects Part 3. (October 1982): Metallurgical Features Part 4. (January 1983): Complex Geometries and Practical Applications. The Welding Institute Report Series Publications.
18. Silk, M.G., Stoneham, A.M. and Temple, J.A.G., The Reliability of Nondestructive Inspection: Assessing the Assessment of Structures under Stress. Adam Hilger, Bristol, 1987.
19. BS3923: Part 1:1986, Methods for Ultrasonic Examination of Welds—Manual Examination of Fusion Welds in Ferritic Steels.
20. Ogilvy, J.A., The influence of austenitic weld geometry and manufacture on ultrasonic inspection of welded joints. *Br. J. NDT,* **29** (3) (1987), 147–56.
21. Silk, M.G. and Lidington, B.H., Defect sizing using an ultrasonic time delay approach. *Br. J. NDT,* **17** (2) (1975) 33–6.
22. Silk, M.G. The use of diffraction based time of flight measurements to locate ad size defects. *Br. J. NDT,* **26,** (1984) 208.
23. Watkins, B. *et al.*, Results obtained from the inspection of test plates 1 and 2 of the Defect Dectection Trials. *Br. J. NDT,* **25** (1983) 186–92.

APPENDIX: RELEVANT STANDARDS

British Standards

BS3683: Part 2:1985, Glossary of Terms Used in NDT—Magnetic Particle Flaw Detection.

BS 4069:1982, Magnetic Flaw Detection Inks and Powders.

BS 4080:1966, Methods for Non-destructive Testing of Steel Castings.

BS 6072:1981, Methods for Magnetic Particle Flaw Detection.

BS3683: Part 1:1985, Glossary of Terms Used in NDT—Penetrant Flaw Detection.

BS 6443:1984, Method for Penetrant Flaw Detection.

BS4489:1984, Method for Assessing Black Light Used in Nondestructive Testing.

BS3683: Part 5:1965, Glossary of Terms—Eddy Current Flaw Detection.

BS3889: Part 2A:1986, Eddy Current Testing of Ferrous Pipes on Tubes.

BS 3889: Part 2B:1966, Eddy Current Testing of Non-ferrous Tubes.

BS 2600:1983, General Recommendations for the Radiographic Examination of Fusion Welded Butt Joints in Steel.

BS 2633:1987, Class 1 Arc Welding of Ferritic Steel Pipework for Carrying Fluids.

BS 2910:1986, General Recommendations of the Radiographic Examination of Fusion Welded Circumferential Butt Joints in Steel Pipe.

BS 3385:1973, Direct-reading Personal Dosemeters for X and Gamma-Radiation.

BS3451:1973, Testing Fusion Welds in Aluminium and Aluminium Alloys.

BS 3455:1973, Glossary of Terms Used in Nuclear Science.

BS 3510:1968, A Basic Symbol to Denote the Actual Potential Presence of lonising Radiation.

BS 5288:1976, Gamma-radiography Sealed Sources.

BS3683: Part 3:1984, Glossary of Terms Used in Non-destructive Testing—Radiological Flaw Detection.

BS 4727: Part 5:1985, Radiography and Radiological Physics Terminology.

BS 3971:1980, Image Quality Indicators for Radiography and Recommendations for Their Use.

BS 5650:1978, Apparatus for Gamma Radiography.

BS 4206:1967, Methods of Testing Fusion Welds in Copper and Copper Alloys.

BS 2704:1978, Calibration Blocks and Recommendations for Their Use in Ultrasonic Flaw Detection.

BS 3683: Part 4:1965, Glossary of Terms—Ultrasonic Flaw Detection.

BS3923: Part 1:1986, Methods for Ultrasonic Examination of Welds—Manual Examination of Welds in Ferritic Steels.

BS 4331: Part 1:1978, Methods for Assessing the Performance Characteristics of Ultrasonic Flaw Detection Equipment—Overall Performance: On-site Methods.

BS 5996:1980, Methods for Ultrasonic Testing and Specifying Quality Grades of Ferritic Steel Plate.

BS 6208:1982, Methods for Ultrasonic Testing and Specifying Quality Levels of Ferritic Castings.

American Standards

AWS D1.1—1986, Structural Welding Code—Steel. American Welding Society.

ASTM Annual Book of Standards Volume 03.03, Non-destructive Testing, 1987.

ASME Boiler and Pressure Vessel Code, Section V Non-destructive Examination, 1986.

West German Standards

DIN 54112, Non-destructive Testing, Films, Exposure Screens. Cassettes for X and Gamma-ray Radiographs, Dimensions, 1977.

DIN 54116 T1, Non-destructive Testing, Film Viewing, Viewing Conditions, 1973.

DIN 54116 T2, Non-destructive Testing, Viewing Films, Film Viewing Boxes, 1976.

DIN V 54119, Non-destructive Testing, Ultrasonic Testing, Definitions, 1981.

DIN E 54119, Non-destructive Testing, Ultrasonic Testing, Concepts, 1981.

DIN E 54124 T1, Non-destructive Testing, Control of Test Equipment with Ultrasonic Echo Instruments, Control at the Test Plate, 1983.

DIN E 54126 T1, Non-destructive Testing, General Rules for Ultrasonic Testing, Requirements for Test Systems and Test Objects, 1982.

DIN E 54126 T2, Non-destructive testing, General Rules for Ultrasonic Testing, Performance of Test, 1982.

DIN54131T1, Non-destructive Testing, Magnetising Equipment for Magnetic Particle Inspection—Stationary and Transportable Equipment Except Transportable Magnetic Yoke, 1984.

DIN 54132, Non-destructive Testing, Determining the Properties of Test Media for the Magnetic Particle Test, 1980.

DIN 54140 T1, Non-destructive Testing, Electromagnetic (Eddy Current Methods), Generalities, 1976.

DIN 54152 T1, Non-destructive Testing, Penetrant Testing, Execution, 1979.

DIN 54109 T1, Non-destructive Testing, Image Quality of Radiographs of Metallic Materials, Terms, Image Quality Indicators, Determinations of Image Quality Values, 1985.

DIN 54109 T2, Non-destructive Testing, Image Quality of X-ray and Gamma-ray Radiographs on Metallic Materials, Directives for the Classification of the Image Quality, 1964.

DIN 54111 T1, Non-destructive Testing, Testing of Welds of Metallic Materials by X- or Gamma-rays, Radiographic Techniques, 1985.

DIN 54123, Non-destructive Testing, Ultrasonic Methods of Testing Claddings Produced by Welding, Rolling and Explosion, 1980.

9

Codes and Standards Relevant to the Quality Assurance of Welded Constructions

J.H.ROGERSON

Cranfield Institute of Technology, Bedford, UK

INTRODUCTION

In the quality assurance and quality control of any manufactured product it is necessary to have defined standards against which quality can be assessed. Such standards will include not only standards of performance of the completed article but also design standards, construction standards (e.g. for dimensional tolerances or methods of manufacture), inspection standards (standardised inspection and test methods) and standards for the materials of construction. Since welding is defined in quality assurance terms as a ‘special process’ it follows that the ability of the welders and the procedures they use must come under the scrutiny of the quality control and quality assurance systems. Therefore a further set of standards must be defined which relate to the welder’s ability (welder approval standards) and the quality of a welding procedure (welding procedure approval standards).

The standards, codes and specifications which are particularly relevant to the quality control and quality assurance of welded fabrications can therefore be categorised as follows:

(1) Standards for consumables (e.g. BS 639, DIN 1913 ANSI/AWS A5.1–81).
(2) Standards for welding procedure approval (e.g. BS 4870, ASME Section IX).
(3) Standards for welder approval (e.g. BS4871, BS4872, ASME Section IX, DIN 8560).
(4) Standards for the quality of a completed fabrication (e.g. application standards such as BS 5500, ASME Section VIII, AWS Structural Welding Code).

One further category of standards exists which is relevant and that is the category of standard which defines quality system requirements, e.g. BS 5750, NS 5801 and ISO 9000–4. As Chapter 1 explains, these standards are not specifically written for the fabrication industry but, obviously, the assurance and control in welded fabrications must be governed by them.

In a sense, therefore, the first four categories of standard listed are specific to welded construction and are used, in a quality sense, to help ensure that the broader criteria of the quality system standards are complied with in respect of ‘special process control’.

In this context the subtle difference between ‘standards’ and ‘specifications’ must be emphasised as the terms are frequently used indiscriminately. A standard is defined as ‘a thing serving as basis of comparison’, or ‘weight or measure by which the accuracy of others is judged’ whereas a specification is defined as ‘detailed description of construction, workmanship, materials, etc., of work undertaken by an engineer’ [1].

As well as there being generally agreed national and international standards relating to the construction of welded articles there are frequently more specific requirements relating to a particular product which are imposed (usually) by the client. Such requirements are the specifications which are often more rigorous and definitive than the relevant standards. A typical example is the specification of welding consumables for the welding of primary structures for offshore oil and gas installations in low temperature environments (Northern North Sea or Arctic). Because of the concern about the possibility of fracture it is considered necessary that consumables should be capable of depositing weld metals of a very high fracture toughness at low temperatures. Such a specific quality requirement is not included in the available standards for welding consumables (e.g. BS 639 or AWS A51.78) so clients will specify fracture toughness levels for consumables to be used on their projects. The use of specifications as well as established standards is inevitable given the varied nature of welded products but badly devised specifications can cause trouble for fabricator and client alike. Standards, because of the wide range of experience that is likely to be consulted in their formulation, may be excessively conservative but are very rarely badly devised. It is therefore good practice to work as far as possible within the confines of established standards.

STANDARDS FOR WELDING CONSUMABLES

It must be recognised that a standard for a welding consumable, be it for an electrode, a MIG wire or a submerged arc flux cannot entirely define the performance characteristics of the consumable. More detailed and precise specifications may be able to do this for particular circumstances. A standard (or a specification) can only usefully define those attributes of a material which can be quantified and readily measured. In the case of a welding consumable many of the quantifiable attributes of interest are attributes of the deposited weld metal rather than the consumable itself so there is usually a requirement for ‘standard’ test welds as part of the standard for a consumable.

We can group the properties of a consumable which can be defined for the purposes of a standard into three categories:

(1) Dimensions (for example electrode size, wire diameter, spool size)
(2) Packaging (for example type of packaging for electrodes and fluxes, identification markings of type and batch number)
(3) Properties of the weld deposit (chemical composition, mechanical properties and soundness of the deposit)

Standards for dimensions are easily definable and must obviously be compatible with related standards (for example standards for wire and rod and standards for welding equipment dimensions and capacities). There is no real problem in this area and it is rare for welding consumables not to conform to dimensional standards and tolerances.

It is less easy to precisely define a packaging standard, particularly for a hydrogen controlled consumable, but, again, this is not normally a problem area in a quality assurance sense. The marking and identification of consumables has been the subject of much dispute [2] but this is more a problem of control of materials in a fabricator’s stores and workshops than a problem of the standards themselves. For instance, however well the marking system for bags or tins of submerged arc flux is defined it has little relevance to the control of flux on the shop floor when excess flux is being recycled into the flux hoppers.

The contentious and difficult aspect of standards for consumables is the definition of performance characteristics. It is possible to write standards which define the mechanical properties of a weld deposit (usually the yield strength and sometimes the fracture toughness—the latter in terms of an impact test requirement) and the chemical composition, but more difficult to write standards which quantitatively define the soundness of the deposit. This very restricted set of requirements for performance standards clearly leaves much undefined about the properties of a consumable particularly as the performance characteristics are measured on a test weld which may not be representative of any of the welds in a particular structure.

This being the case it is necessary to view standards for welding consumables more as a way of classifying types of consumable and aiding the manufacturer's quality control system rather than as a way of defining performance standards. The corollary to this is that the welding procedure approval exercise takes over the role of defining the quality of the consumables because if the consumable used in the procedure test produces a weld which meets the performance requirements then this implies that the quality of the consumable is satisfactory in terms of its performance characteristics.

Nevertheless, there is often a desire by fabricators (often as a result of pressure from their clients) to obtain 'certification' of consumables on a batch basis. This is a contentious issue as it usually involves extra test work and documentation on the part of the consumable supplier who will, naturally, want to be recompensed in some way. The real point at issue is as follows. When is this batch certification really needed (bearing in mind the limitations of the testing of consumables anyway), and when is it being asked for merely to provide an extra (and often spurious) piece of documentation? Often it is the latter situation which exists.

British Standards

If we consider three typical British Standards for consumables—BS 639 Covered Electrodes for the Manual Metal Arc Welding of Carbon and Carbon-Manganese Steels, BS 4165 Electrode Wires and Fluxes for the Submerged Arc Welding of Carbon Steel and Medium Tensile Steel and BS 2901 Filler Rods and Wires for Gas Shielded Arc Welding—we can see the limitations of such standards from a quality assurance point of view.

BS 639 defines an electrode in terms of mechanical property level, coating type (e.g. rutile, cellulosic, basic), deposit efficiency, electrical polarity and positional capability. The mechanical property levels are assessed by all weld metal tensile and impact tests and bend tests on standardised test welds. Hydrogen levels in hydrogen controlled electrodes are also assessed by a standardised method. These requirements have to be met initially and regularly checked. It is required that the manufacturer has a QC programme which ensures 'testing' (not defined) of each batch (again, not defined) of product.

BS 4165 has a similar approach except that a distinction is made between multirun and two run welds for mechanical property classification. In particular deposit compositions are not defined (except for maximum levels of sulphur and phosphorus).

BS 2901 defines the electrode properties in terms of the chemical composition of the wire and makes no attempt to define deposit properties either in terms of composition or mechanical properties. This is because the deposit properties are significantly affected by the choice of shielding gas and the welding process characteristics.

German Standards

These follow, in a technical sense and in their philosophy, very closely to the BSI standards—a typical example being DIN 1913 Covered Electrodes for Joint Welding of Unalloyed and Low Alloy Steels.

American Standards

The appropriate standards are those produced by the American Welding Society and, in a technical sense, are very similar to the above mentioned British Standards but with some important differences. There is an attempt to define the 'usability' of the consumable and some guidance is given on quality assurance in the procurement of consumables.

If we take as examples ANSI/AWS A51–81 Specification for Covered Carbon Steel Arc Welding Electrodes and AWS A5.17.80 Specification for Carbon Steel Electrodes and Fluxes for Submerged Arc Welding it can be seen that consumables are classified according to mechanical properties, type of coating, position and type of current, i.e. very similar to the BSI classification. Weld deposit properties are also defined in a very similar way—a standardized test weld is made which is evaluated in terms of transverse tensile strength, all weld metal tensile strength, deposit chemical composition, impact strength and ability to pass a guided bend test (though not all of these tests are required for every consumable class). Extra tests though are required to assess the useability of the consumable in terms of its ability to deposit sound weld metal. This is done by the radiography of butt welds (assessed according to a defined quality standard) and the visual inspection and fracture testing of fillet welds. This type of test is a very valuable part of a standard for welding consumables in that it defines an acceptable level of 'usability'.

The previously mentioned standards (British, American and German) define the properties of consumables but they do not define precisely how often these properties should be checked, and this is necessary to control and assure the quality. Without a defined intensity and frequency of testing the fact that a consumable has once been shown to meet a particular consumable standard requirement is of little value to the user. American Welding Society A5.01.78 Filler Metal Procurement Guidelines goes a long way towards defining such matters. Its scope includes the following section: 'It is intended to provide a method for preparing those portions of a procurement document which consists of the following: (1) the filler metal classification, (2) the lot classification, (3) the intensity of testing…'. It follows good QA practice by asserting the consumable manufacturer should have a QA programme and states that a consumable manufacturer certifies that his product meets the appropriate AWS classification if he puts a label on his product identifying it as such. The terminology used in consumable production (dry batch, dry blend, heat, lot, etc.) is defined and the intensity of testing is defined at different levels ranging from 'the manufacturer's standards' to 'all tests specified by the purchaser for each lot shipped'. This standard therefore provides a well defined base upon which the quality assurance of consumables can be established by agreement between purchaser and supplier.

STANDARDS FOR WELDING PROCEDURE APPROVAL

There are a large number of standards and specifications for procedure approval. As well as national and international standards classification societies, some large client organisations (The Ministry of Defence for example in the UK) establish their own standards for different products. This proliferation is undesirable and costly to the fabricator and ultimately to the client. Farrar [2] has estimated that a medium size fabricator could spend more than £100000 (1978 prices) per annum on welding procedure qualification tests if he must satisfy the requirements of a number of standards and specifications.

The reason for welding procedure approval is to demonstrate that a given welding procedure, if followed, will produce welds of adequate quality. A welding procedure approval standard, therefore, provides a measure against which a particular procedure can be judged. All the standards are similar in that a test weld (or welds) is made which is representative of the procedure to be approved and is then subjected to a range of destructive and non-destructive tests to assess its quality. The requisite quality standard for a test weld is allied to the quality of welding required for the fabrication. The significant difference between different standards which cover the same type of fabrication and the one that has the most bearing on the cost of welding procedure approval lies in the range of welding procedures which are 'approved' or 'qualified' by the making of a given test weld to the requisite standard.

There is an important difference in philosophy between the American approach (typified by the ASME Boiler and Pressure Vessel Code Section IX, and the AWS Structural Welding Code) and the European approach (typified by BS 4870) to welding procedure approval standards. The welding procedure approval sections of these American codes are integral parts of codes which deal with all aspects of the relevant type of fabrication. For example, the ASME Boiler and Pressure Vessel Code covers design, materials, fabrication methods, inspection and quality assurance of welded pressure vessels as well as the qualification of welding procedures and welders. The AWS Structural Welding Code and API 1104 Standard for Welding Pipelines and Related Facilities similarly cover the whole range of quality related activities for the types of welded fabrication within their scope. The welding procedure approval requirements of these codes are therefore meant to apply only when *all* other code requirements apply. Consequently it is possible to limit the testing of a test weld to a relatively small number of tests and to permit some considerable latitude in the variations in a welding procedure which are covered by a given test procedure. The European approach is in general different in that welding procedure standards (for example BS 4870 Approval Testing of Procedures) are designed for a wide range of products and circumstances. Consequently it is not possible to rely on other sections of a design and fabrication standard to limit the scope of the welding procedure standard. The amount of testing required on the test weld is therefore greater and the latitude in the variations of welding procedure covered by a given test procedure is less than in comparable American codes. Paradoxically, also, more flexibility and lack of precision is inherent in such a philosophy.

BS 4870: Specification for Approval Testing of Welding Procedures

This standard, being a British Standard, is accepted by all major interests in the UK and is the welding procedure approval standard called up in other British Standards (e.g. BS 5500 Unfired Fusion Welded Pressure Vessels). The standard lists the items to be recorded in the procedure test (e.g. base metal specification, edge preparation, run sequence, etc.) and stipulates the changes in procedure which invalidate an approval (i.e. the 'essential variables'). These are, briefly, changes in welding process, welding position, base metal thickness, range, electrode type, electrode size (subject to some exceptions), change in polarity, significant changes in preheat and post-weld heat treatment. Base metals are divided into groups and separate approvals are required for plate and pipe. Three test piece types are covered by the standard—a butt joint, a fillet joint, and a branch connection for pipes although 'special' test pieces which are more representative of the joint to be approved are also allowed.

All test welds must be subjected to visual, magnetic particle (or dye penetrant) testing, radiography and/or ultrasonic examination and the quality standard required to be achieved is high and equivalent to that demanded for production welds in BS 5500.

Butt joints require, in addition, macro-examination, a hardness survey, transverse tensile and all weld metal tensile tests, and bend tests whilst fillet joints require macro-examination, a hardness survey and (for single sided welds) a fracture test. Pipe branch connections require macro-examination and a hardness survey. A slightly ambiguous note suggests that more extensive testing (e.g. fracture testing) may be useful and advantageous.

This standard therefore requires a comprehensive testing scheme and is somewhat open ended in that special test pieces and/or extra tests may be included with the agreement of the contracting parties. This is the drawback of a standard which sets out to cover all circumstances. The fact that a fabricator has a procedure qualified to BS 4870 may therefore *not* mean that this qualification is acceptable to another client who also asks for procedure qualification to BS 4870. His interpretation of the requirements may be different even though it is expected that a procedure test witnessed and approved by one inspection authority to this standard should be acceptable, without further testing, to another inspection authority.

ASME Boiler and Pressure Vessel Code Section IX

Welding procedure approval to this standard can be equated with an approval to BS 4870 in that in each case procedures are being approved to the highest realistic standard—that demanded for the fabrication of pressure vessels. However, the requirements of ASME Section IX are very different from those of BS 4870.

The responsibility for qualifying procedures is held by the manufacturer (fabricator) and all procedures must be documented in a welding procedure specification (WPS) which lists the details of the procedure which are defined as either 'essential' or 'nonessential' variables. Each procedure must be qualified by the welding and testing of a test coupon which is recorded in a 'procedure qualification record' (PQR). This latter documents the essential variables of the welding procedure and any change in the essential variables requires a requalification of the procedure. Essential and nonessential variables are precisely defined but are, in many ways, less restrictive than in BS 4870. For example, a groove weld (butt weld) qualification test will also qualify procedures for fillet welds in all material thicknesses within the range of the other applicable essential variables for most base metal groups and combinations. Also, a qualification of a procedure in one welding position usually qualifies the procedure for use in all positions.

The test requirements of this code are less extensive than in BS 4870 and comprise, for groove welds, transverse tensile tests and bend tests and for fillet welds (where these are separately qualified) macro-examination of sections.

The apparently very inadequate checking of welding procedures which is specified by this code is acceptable because ASME Section IX assumes that *all* other relevant code requirements are being followed and that the manufacturer is authorised by ASME as a competent fabricator, i.e. the ASME code requirements presuppose that the fabricator who works to them has already been shown to be a competent and responsible fabricator of pressure vessels. This illustrates the danger of using ASME Section IX out of context and specifying its requirements as a convenient standard for approving welding procedures. Unfortunately ASME Section IX is frequently used in this way.

API 1104 Standard for Welding Pipelines and Related Facilities

This American code is widely used internationally as a guide for standards of weld quality in oil and gas pipelines. The standard requires that welding procedures be fully documented in terms of essential and nonessential variables, changes in the former of course require a requalification. Essential variables include, as expected, pipe materials, welding process, filler metal, welding position, flux, shielding gas and travel speed. Essential variables specific to pipe welding should be noted—changes in time lapse between root bead and second bead and changes in welding direction (vertical uphill to vertical downhill and vice versa).

The test requirements of this standard are transverse tensile (except for small diameter pipe), bend tests and nick break tests for butt welds and nick break tests for fillet welds.

Again, this limited degree of testing is generally acceptable because of the control exercised on the design and selection of materials and because a pipeline is a well defined and well understood 'structure'. In some special circumstances (e.g. very high yield strength steels, pipelines for arctic conditions or subsea pipelines) more extensive procedure testing is desirable particularly in terms of guaranteeing fracture properties or maximum HAZ hardnesses. In these cases API 1104 is not a sufficient standard for procedure approval.

AWS Structural Welding Code

This code covers a wide range of structures (excluding pressure vessels and pipelines) and is an appropriate code for buildings, bridges and tubular structures. It covers structures welded in carbon and low alloy steels and, like the ASME Boiler and Pressure Vessel Code, is a code complete in itself.

Groove (butt) weld procedures are qualified on the basis of bend tests and transverse tensile tests and fillet weld procedures are qualified on the basis of nick fracture and macro tests. Groove weld procedure qualification is also permitted on the basis of radiography instead of destructive tests. As in other standards there are essential and nonessential variables in a procedure, alteration in the former requiring requalification.

The distinctive feature about procedure approval according to this code is that procedures may be considered ‘prequalified’ (i.e. actual procedure tests are not required) provided that they meet certain criteria. The convenience and economic value of this to the fabricator and, ultimately to the client, is obvious.

These criteria are that the welding process is MMA, submerged arc, MIG/MAG or flux core, the joint design is limited to those recommended in the code, the quality of workmanship (e.g. fit-up, distortion) meets the defined standards and the ‘technique’ also meets the defined standards (e.g. filler metal type, minimum preheat and interpass temperatures).

The fact that this method of procedure qualification is satisfactory further emphasises the philosophy that formal procedure approval testing is only one of many factors which make up a quality control and quality assurance system for welded fabrications.

STANDARDS FOR WELDER APPROVAL

Standards and specifications for welder approval (for which there are probably a greater number than there are for procedure approval) are superficially very similar to those for welding procedure approval but the aim is quite different. In this case the aim is to demonstrate that the welder is capable of producing a weld of acceptable quality provided he is given a suitable procedure to work to. Therefore in assessing the quality of a test weld any defects which do not relate to the welder (e.g. defects arising from faulty material or an inadequate procedure) should be discounted. Also the essential and nonessential variables are likely to be different even under the same code for welder approval and for procedure approval. A further point is that in most situations far more welder approvals will be needed than procedure approvals so economic necessity requires that welder approval testing should rely as far as possible on simple, quick (and therefore cheap) test methods. Finally, since a person’s skill is being assessed, any standard must include a provision for ensuring that a welder, once qualified, does not automatically remain a qualified welder unless he is maintaining his skill. Most standards therefore either require a welder to be requalified at regular time intervals or else require a welder to be continuously employed on an appropriate type of welding and producing welds to a satisfactory standard to maintain his qualification. This latter approach is the more logical of the two and is the one most frequently adopted. It has the disadvantage, however, from the quality assurance auditor’s point of view of being more difficult to ‘police’. The main American and British codes have many similarities in that they tend to be tied to relevant procedure qualification standards. Some others (particularly DIN 8560 and 8561) seem to come from a different philosophy in that they try to define a welder’s skill in a more general and wider sense.

BS 4871 Approval Testing of Welders Working to Approved Welding Procedures

This is the counterpart document to BS 4870 (see previous section). The test weld requirements are the same as for BS 4870 but the inspection and testing of the test weld is much more limited. Assessment can be either by non-destructive testing (supplemented by macro–examination or bend testing in certain specified situations) or by destructive testing (bend tests for butt welds and fracture tests for fillet welds). The quality standards demanded are equivalent to those in the counterpart standard for procedure approval (BS 4870). The essential variables are primarily position and base metal thickness range. Changes in procedure such as preheat or post-weld heat treatment for example do not require a welder requalification and there are also clauses which permit repeat tests to be taken if a test piece fails to meet the required quality standard as a result of metallurgical or extraneous causes not attributed to the welder’s workmanship. Also, if the welder realises the test weld is likely to fail he is permitted to withold its submission and prepare a second test weld. These differences between 4871 and 4870 are a recognition that it is the welder’s skill and his ability to make judgements on his own work which are being assessed.

A welder, once qualified, remains qualified provided he can be shown to have been reasonably continuously employed on work of the appropriate quality and that his workmanship has been satisfactory.

BS 4872 Approval Testing of Welders When Welding Procedure Approval is Not Required

This standard is designed to cater for the very large category of welding where there is no mandatory or contractual requirement for the welding procedure to be formally approved but where a ‘good’ standard of welding is required. The quality of welding in such cases is very dependent upon the skill of the welder and BS 4872 defines an approval scheme for ensuring that welders in a wide range of industries can be qualified to a comparable standard.

A wide range of test pieces is specified (butt and fillet welds in sheet, single sided butt welds in plate with and without backing, double sided butt welds in plate, fillet welds in plate and butt and fillet welds in pipe) and assessment is on the basis of simple destructive tests (macro, bend and nick fracture tests) with a required quality standard somewhat lower than in BS 4871. Other than thickness range, position and joint type (which are essential variables) the essential and non-essential variables are not precisely defined because the very wide applicability of this standard makes it impossible. Such decisions must be made by the engineer (or inspecting authority) according to the particular circumstances. This lack of precision is a disadvantage because it may lead to incorrect and inappropriate interpretation of the standard but this is a minor point compared with the considerable advantage of having a sensible welder approval standard for the very large amount of welding which is not covered by the construction standards for pressure vessels, pipework, storage tanks and other high integrity components.

ASME Boiler and Pressure Vessel Code Section IX

A distinction is made between ‘welders’ and ‘welding operators’ and the qualification requirements are slightly different. Qualification in either case requires the welding of a test piece in accordance with a qualified welding procedure, with the option that for a welding operator the 3 ft length of his first production weld may be taken as the test piece.

The tests required of the test weld for welders are bend tests (groove welds) and macro and fracture tests (fillet welds) although for most processes and material groups the test weld for a groove weld qualification can be examined by radiography instead. In such a case his first production weld can be taken as the test piece. In all cases a welding operator may be assessed on the basis of radiography. The standard of quality required in the test piece is equivalent to that required for procedure and, in fact, a welder or operator who makes the weld which qualifies a particular procedure is automatically qualified to use that procedure. The essential and non-essential variables as always in this code are precisely defined but are different from those for procedure qualification, the most important difference being that welding position is an essential variable for performance testing. In most cases a groove weld qualification will cover the welding of fillet welds but not vice versa.

The continuity of the approval is governed by similar rules to those in BS 4871 and 4872; the approval remains valid provided the welder or operator is essentially continuously employed on the appropriate quality of work.

API 1104 Standard for Welding Pipelines and Related Facilities

The welder qualification requirements fall into two parts—'single qualification' where the test weld is a butt weld (each position being an essential variable) or 'multiple qualification' where a butt weld in pipe of diameter and wall thickness equal to at least 6 5/8 in (168·3 mm) and 1/4 in (6·35 mm) respectively is followed by the fitting and welding of a full size branch connection. If this multiple qualification is obtained then there are naturally fewer 'essential variables' which limit the welder's scope. As in the case of ASME Section IX, weld quality is evaluated by tensile, bend and nick fracture tests or, as an alternative, by radiography. There are no rigidly defined limits to the continued validity of a qualification except that it is stated that welder 'may be required' to requalify if there is a question about his ability.

AWS Structural Welding Code

The rules for welder qualification follow the same style as those in ASME Section IX except that the quality requirements for the test welds are lower and the latitude on variables is much greater. For example, a welder qualification on one steel type covered by the code covers the welding of all steels covered by the code. Welding process is an essential variable but a qualification with one electrode and shielding medium covers another electrode and shielding medium provided the process is the same.

Although the standard of attainment required to qualify according to this code is lower than that needed to qualify according to ASME Section IX it is probably higher than that required to qualify on an equivalent joint type according to BS 4872.

DIN 8560 Testing of Welders for Welding Steel and DIN 8561 Testing of Welders for Welding Non-ferrous Metals

These two German standards are, of course, similar in their approach and can be discussed together. They illustrate a very different philosophy of welder qualification to that followed in British and American codes. The British and American approach is to strictly limit qualification to a restricted range of joints and welding process variables usually in conjunction with a corresponding procedure (e.g. BS 4870 and 4871).

This leads inevitably to a large number of qualification tests being carried out and a given welder often possessing a number of different qualifications. The DIN approach views a welder qualification more as a certificate the possession of which defines a person as a skilled craftsman. To qualify under DIN 8560 or 8561 a welder must first undergo a recognised training scheme (such as a DVS course) and as well as demonstrating his practical skills in a way (and to a level) very similar to that required in BS 4871 and ASME Section IX successfully pass a test of his theoretical knowledge of welding technology. This theoretical knowledge comprises safety precautions, operation of the equipment, preparation for welding, welding terms and symbols, knowledge of materials and of factors which govern the quality of a weld. All testing and examination must be carried out by an approved test centre (the normally expected method) or by a welding engineer recognised by the company. This approach, although presumably involving significant administration costs, is excellent from a quality assurance point of view in that nationally defined and administered standards for welder qualification lead to a more consistent standard of approval.

STANDARDS FOR THE QUALITY OF A COMPLETED FABRICATION

When we define the quality standard for a welded component we define it in terms of a defect level (type, size and number of defects) and sometimes, also, in terms of the mechanical properties of the weldment. In either case the definition of a method, or methods, of inspection together with the extent of inspection is necessary to establish the quality standard required. As stated in Chapter 5 there is very little available data on expected defect levels in welded fabrications in terms of type, size and, particularly, distribution. There is also very little data on the expected distribution of mechanical properties (tensile strength, toughness) along a weld made to a given procedure. This lack of data makes the setting of quality standards and the associated inspection requirements difficult with the consequence that arbitrary standards, which are sometimes difficult to justify logically, are often found. A further important generalisation which must be appreciated is that the higher the integrity required of the welded structure the greater will be the precision with which the quality standard (and associated inspection methods) will be defined.

Pressure vessel codes define the required weld quality standard very precisely and quantitatively whereas construction codes for ‘general structures’ (bridges, ships, buildings, for example) define quality standards in terms such as ‘welds are to be sound, uniform and substantially free from slag inclusions and porosity’. This imprecision in the latter type of standard can lead to disputes about what is an acceptable quality level but, perhaps more importantly, results in the assurance of quality becoming more reliant on the design, material selection and welder and welding procedure approval. This means that the final inspection of the structure becomes relatively less important as a means of guaranteeing structural integrity.

Pressure Vessel Standards

It is not intended to discuss in detail the differing requirements of the major internationally used pressure vessel codes. In all cases the defined acceptance standards for weld quality are based on experience and judgement of what minimum quality standard a competent fabricator could be expected to consistently achieve. In only one of them (BS 5500) is there the possibility of defining a standard which is more logically related to the design and service environment of a particular vessel. Clauses 5.7.3.2. and 5.7.3.3. state that ‘when acceptance levels different from those given in Table 5.7. have been established for a particular application and are suitably documented, they may be adopted by specific agreement’ and ‘particular defects in excess of those permitted in Table 5.7 may be accepted by specific agreement between the purchaser, the manufacturer and the inspecting authority after due consideration of material, stress and environmental factors'.

Normally, however, weld quality for pressure vessels is defined in terms of acceptable defect levels which are disclosed by non-destructive testing. Although ultrasonic testing is widely used in the fabricating industry the quality standards are still derived on the basis of radiographic examination. Cracks and other planar defects such as lack of fusion, lack of penetration, aligned porosity are always unacceptable. (except for the BS 5500 possibilities mentioned above), but there is a tolerance limit on volumetric defects such as porosity and slag inclusions and shape defects such as undercut. There are differences between the pressure vessel codes in terms of the acceptable level of such defects and obviously these differences are very important in a contractual sense. In practice the differences are insignificant from an engineering point of view and only arise because different committees have defined an arbitrary standard in slightly different ways.

The extent of non-destructive testing varies in that 100% testing of welds is normally called for but for vessels of lower construction categories (lower stresses, simpler materials, less hazardous situations) only sampling inspection is called for. Although the results of such sampling inspection are judged against the same defect acceptance standards the minimum acceptable quality level will be lower in this case. The arbitrary and illogical nature of such sampling inspection schemes has been discussed elsewhere [4] but if they are considered as cost effective ways of ensuring that a certain but perhaps not closely defined quality level is maintained then they have some value. The fact which must be appreciated is that a sampling inspection scheme deals in probabilities not certainties and therefore with such an inspection scheme there is a significant probability that serious defects such as cracks will not be found. This situation must be catered for by either greatly reducing the risks of such defects occurring (procedure qualification and process control) or designing the structure such that its integrity is not impaired by their presence (e.g. ensuring that materials have a high fracture toughness or design stresses are low). This latter approach is the one which is being followed, of course, when sampling NDT is applied to pressure vessels.

Pipelines and Piping Systems

Quality standards for welds in pipelines and pipe systems can be compared to those for pressure vessels because in each case a fluid is being contained under high pressure and a similar degree of integrity is required. Furthermore, in many cases piping systems will be associated with pressure vessels in process plant and similar quality levels are obviously appropriate and are in fact defined in the various standards (e.g. API 1104 and BS 2633 Class I Arc Welding of Ferritic Steel Pipework for Carrying Fluids).

The various pipe welding standards have been written on the basis of manual metal arc welding, inspection by radiography and, particularly in the case of API 1104, the use of conventional pipe line steels. That is not to say that the standards do not cover other processes and materials as of course they do. The important consequence is that sometimes these standards are inappropriate (particularly if high yield steels or gas shielded arc welding processes are used) as they do not take into sufficient account fracture properties or the type of defects which may occur. This is an area where specification for quality standards and testing methods which are different from the available standards frequently need to be defined.

General Structures

The various standards which cover structures such as bridges, ships, buildings (examples are BS 5400, AWS Structural Welding Code, Classification Society Rules) do not define weld quality standards in a quantitative and therefore unambiguous way, that is if they attempt to define weld quality standards at all.

The difficulties in producing such definitions are, of course, great because 'general structures' covers a wide range of constructions which will require to be built to an equally wide range of quality levels. The best that standards can do in this area is to categorise structures into 'quality bands' and to define who should establish the quality standard and associated inspection level and at what stage in negotiations. The AWS structural welding code is perhaps a good model in this respect.

One further point about the AWS structural code which is very relevant in a quality assurance sense is that it very carefully discriminates between fabrication/erection inspection and testing, which is the responsibility of the manufacturer and verification inspection and testing, which is the responsibility of the owner. Inspection must also be carried out by AWS certified welding inspectors (i.e. to AWS QCI). The definition of responsibilities for quality related activities and the guarantee that these responsibilities are discharged by suitably competent people are fundamental principles of any quality assurance programme.

QUALITY ASSURANCE GUIDELINES FOR WELDING OPERATIONS

In 'quality' jargon, welding (and the associated activities of NDT and heat treatment) is a 'special process'. This is because welding operations (and to an extent NDT and heat treatment) are characterised by the following features:

(1) Operator control is critical to success.
(2) The technology is complex so that the interaction and influence of variables on performance is difficult to predict.
(3) In-process monitoring and continuous feedback is difficult except for the newer processes.

This means that an *essential* part of the control and assurance of quality is ensuring that procedures are adequate and operators are competent; hence the existence of standards for the approval of procedures and operators. Unfortunately, the recognised quality system standards (e.g. BS 5750 and the ISO 9000 series), because of their very general nature, do not address this issue very precisely.

If we look at, for example, clause 4.12.2 of BS 5750 Part 1, it states: 'The supplier shall establish and maintain control of all special processes that form part of production or inspection. Equipment, essential processing environment and any necessary personnel qualifications shall be prescribed to the satisfaction of the Purchaser's Representative.'

This clause is not, of course, incorrect but it needs 'interpreting' in the context of welding (and NDT and heat treatment).

There is no *specific* requirement in the standard for the documentation or approval of procedures or the special measures needed for the control of consumables. Consequently, there is almost always a need in a fabrication of any criticality to devise specifications to cover those points which make specific reference to the technical standards for procedure, operator and consumable control.

THE ROLE OF CERTIFICATION BODIES

Whatever means a fabricator employs to control and assure the quality of his products, there is a need for his client to be satisfied about these methods and their effectiveness. The most direct way is for the client to audit the fabricator's quality systems, but this is expensive for the client unless he is a large company wih sufficient engineering resources to do this.

An alternative method which is now used in the UK (although non-UK companies can be included in the scheme) is to carry out third party assessment. Properly constituted cerification bodies, representing different industry sectors and conforming to certain principles laid down by the National Accreditation Council for Certification Bodies (the NACCB) which are in accordance with the ISO/IEC guide 40 'General Requirements for the Acceptance of Certification Bodies', can assess the quality system of a company against the criteria of BS 5750. If the company meets the criteria then it can be given a certificate recognising that fact and is placed on the UK list of 'Registered Firms of Assessed Capability'.

The important thing to remember about third party certification is that companies are assessed strictly against a standard which may or may not be totally relevant to a client's particular requirements. It is frequently the case that specifications for a fabrication detail particular quality requirements which may not strictly coincide with the necessarily 'general' approach taken by a third party certification body. Approval by a third party certification body means that a company has a good quality system but it does *not* necessarily mean that it conforms with all the requirements of a particular client.

The alternative route to minimising the assessment load is the route taken by QUASCO, which is a body set up by oil and gas companies operating in the North Sea. This organisation audits companies' quality systems but does *not* attempt to state that they are 'acceptable' or 'unacceptable'. The detailed audit report is available to QUASCO members who can then decide their action on the use of the company for a specific contract. This is perhaps the more satisfactory method for the fabrication industry, given the prevalence of individual client quality specifications and the lack of precision of standards such as BS 5750 in respect of special process control.

CONCLUDING REMARKS

Standards are a vital part of any quality assurance activity because they provide the technical guidelines against which designs, material properties, construction standards and inspection methods are specified.

Traditionally, the welding fabrication industry has worked on a 'build then inspect' philosophy and only recently has moved towards a quality assurance philosophy. The technical standards related to welding fabrication inevitably reflect this traditional view and also reflect the great reliance placed upon the craft skill of the welder and the difficulty of defining important aspects of 'weldability'. This means for example that standards concerned with welder qualification and welding procedure qualification are well developed and very specific whereas standards concerned with welding consumables are less definitive. From a quality assurance point of view the greatest omission in many standards (notable exceptions being some of the American and German ones) is the clear definition of responsibilities and qualification requirements for those who discharge these responsibilities. It can be argued that such matters are not the concern of technical standards but it is in practice impossible to consider the technical requirements of a standard without considering also the manner in which these requirements are imposed and controlled. This is the core of quality assurance and quality control practices.

REFERENCES

1. *The Oxford English Dictionary*. Oxford University Press, Oxford.
2. Quality Control and Non-Destructive Testing in Welding, discussion in *Proc. Conf.,* The Welding Institute, 1974.
3. Farrar, J.C.M., Weld Procedure Qualification—The Costs and Benefits Seminar Welding Approvals—A Testing Time for all, The Welding Institute Sheffield and East Midlands Branches, April, 1979.
4. Rogerson, J.H., The Implications of Sampling Inspection for the Quality Control of Welded Fabrications. IIW Public Session Quality Assurance in Welded Construction, Estoril, 1980.

Index