Materials for Rigid and Flexible Printed Wiring Boards

Martin W. Jawitz
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Martin W. Jawitz
Jaw-Mac Enterprise
Las Vegas, Nevada

Michael J. Jawitz
The Boeing Company
Satellite Development Center
El Segundo, California

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Acknowledgments

Over the years many people and organizations have prepared articles and books on materials relating to the fabrication of rigid and flexible printed wiring boards. However, no one article or book encompasses all the details as to the properties of these materials nor in some cases how they are made. This book is intended to be an overall aid to the designer, engineer, and the fabricator in the proper selection of materials in order to successfully produce a circuit board that will meet the end item application. In most cases, data for the various materials was obtained directly from the manufacturer's data sheet. We hope that the data holds typical values.

A special thanks to Chester (Chet) Guiles for his critique and comments in the preparation of various chapters.

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Authors

Martin W. Jawitz has been associated with the printed circuit and electroplated industry for more than 40 years. He began his career as a chemist in the commercial electroplating field and then migrated into the aerospace industry where he concentrated his efforts on printed wiring.

Marty has been in the printed wiring industry from its inception and has gone through the early learning processes. Since the early 60s, he has been responsible in some form for printed wiring boards from design through fabrication and failure analysis.

He has been chairman of several IPC committees relating to printed wiring (including chairman of committees for metal core substrates, rigid-flex specifications, and rigid-flex round-robin test programs). For ten years, he has taught IPC rigid-flex workshops on design, materials, and fabrication.

At Litton Industries, he was chairman of the corporate Materials and Processing Committee. One of the functions of this committee was to develop and maintain a corporate printed wiring design standard. This standard included design requirements for rigid single-sided through multi-layer boards, plus metal core, surface mount flex and rigid-flex printed wiring boards. Included in this standard were sections on material, coatings, and plating. During the latest updating of this manual, he completely redefined and incorporated the latest technology and processes.

He has written and published many articles pertaining to the printed wiring industry for *Electrical Insulation*, *Electroplating and Surface Finishing Magazine*, and the *IPC Review*. He has also presented many papers at the California Circuit Association, IPC (including the world meeting in Germany), and the American Electroplating Society.

In 1953, he earned his Bachelor of Science degree in chemistry from Long Island University. He has since completed post-graduate work at Polytechnic University in Brooklyn and William Paterson University.

Michael Jawitz has been involved in the printed circuit board industry for more than 30 years. He began his career as a draftsman in electronic packaging in the aerospace industry and has since focused his efforts in rigid and rigid flex packaging.

Since the mid-70s he has been involved in new product designs, research, and development of materials for both rigid and rigid-flex printed wiring boards. He was one of the early designers at Hughes

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Aircraft utilizing computer-aided design systems to design high-speed, very complex, multi-layer rigid and rigid-flex designs used for military products and was responsible for establishing many company design and fabrication standards.

He has worked on several IPC committees relating to the design of rigid and rigid-flex boards. He was also on the IPC Computer-Aided Design Committee.

At Boeing Satellite Development Center (formally Hughes Space and Communication), he is currently a scientist in the materials and processing group responsible for printed wiring board designs, anomalies, and failures. He holds several patents relating to the fabrication of multi-layer rigid-flex products. He is a member of the Corporate Advisory Board of Electronic Designs, Corporate Printed Wiring Board Technology Committee, and is a representative to the IPC.

He is currently working toward his Masters in Business Management at the University of Phoenix.

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1

Reinforcement Materials

1.0 Reinforcement Materials — Rigid

Materials that fall into this category include woven glass, chopped glass fibers, and nonwoven aramids. Woven quartz fabric, woven aramid fabric, and high-silica woven glasses such as S-glass and D-glass have also had limited use in specialized applications.

1.1 Glass

The most popular of the rigid reinforcements for printed wiring boards is woven E-glass (electrical-grade glass) fabric. These fabrics are constructed to meet weight, thickness, strength, and cost objectives. The woven fabric is used in many industries as reinforcements for thermoplastic and thermosetting plastic parts. Thermosetting laminates are particularly enhanced by the properties of the glass fabric. Organic resins such as epoxy, phenolic, polyester, cyanate ester, and polyimide are low-strength and often brittle synthetics, but when reinforced with glass they are used to produce parts with superior durability, high-strength, and excellent insulating properties.

The electrical and electronics industries achieved great benefits from glass-reinforced laminates, especially when used in printed wiring applications. The combination of glass fabric and organic resins is the basic material combination that enjoys the greatest usage in printed wiring due to the resins' heat resistance, electrical properties, and processability. Glass fibers do not shrink even under extremely severe temperatures or under processing stresses. Woven glass fabrics impart stability to thermoset laminates by acting as a restraining force on the resin. Organic solvents, bacterial attack, and most acidic or basic solvents/liquids do not affect these fabrics. The fibers exhibit no appreciable water absorption or water-induced deterioration.

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Glass fabrics have a very high strength-to-weight ratio. The tensile strength and rigidity of glass fibers impart superior stress resistance to reinforced laminates in the *xy*-direction. Glass is an excellent electrical insulator with a high dielectric strength and a relatively high dielectric constant (Dk approximately 6.4), and its low moisture absorption also contributes to a very stable electrical fabric.

1.2 Glass Composition

In the production of glass fibers, a mixture of at least seven different raw materials will be required and may include oxides of silica, sand, limestone, aluminum, calcium, clay, or boron (with either sand or silica being the predominant material). These materials are mixed together to form a glass batch mixture. The fibers that are formed from this mixture are tiny filaments of glass as small as 0.00015 inch (0.0038 mm) in diameter that have sufficient flexibility to be woven into a fabric. Currently there are four main glass formulations that are used as glass reinforcements (D, E, S, and quartz) for printed wiring laminates. The chemical compositions of these four glass fibers are shown in Table 1.1, and their physical properties are described in Table 1.2 and below.

1.2.1 D-Glass

D-glass fibers have a lower Dk and density than E-glass and were developed to improve the electrical performances of the finished material but

TABLE 1.1

Properties of Various Glasses

Property		Glass Grades			
Chemical Composition	Chemical Formula	D-Glass	E-Glass	S-Glass	Quartz
Silicon oxide	SiO_2	72–75	52–56	64–66	99.97
Aluminum oxide	Al_2O_3	0–1	12.0–16.0	24–26	0.015
Iron oxide	Fe_2O_3	0.3	0.05–0.4	0.3	0.0001
Calcium oxide	CaO	0–1	15–25	10	0.0032
Magnesium oxide	MgO	0.5–0.6	0–5	9.0–11.0	—
Barium oxide	Ba_2O_3	21–24	5.0–10.0	0–1.2	—
Sodium oxide	Na_2O	0–4	0–2	0–0.3	0.0022
Potassium oxide	K_2O	0–4	0–2	0–0.3	—
Zirconium oxide	ZrO_2	—	—	—	—
Sulfur dioxide	SO_2	—	—	—	—
Lithium oxide	Li_2O	0.5	—	—	—

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TABLE 1.2

Physical Properties of Glass Fibers

Property	Units	D-Glass	E-Glass	S-Glass	Quartz
Physical					
Specific gravity		2	2.54	2.49+	—
Tensile strength	psi	350,000	500,000	665,000	—
Tensile modulus of elasticity	psi	7,500,000	10,500,000	12,500,000	—
Tensile strength (23°C)	Mpa	2,415	3,445	4,890	—
Young's modulus (23°C)	Gpa	51.7	72.3	86.9	—
Elongation	%	4.6	4.8	5.7	—
Density	gm/cc	2.11	2.58	2.46	0.61
Percent elongation	%	4.5	4.8	5.5	2.2
Hardness	mohs	5	6.5	6.5	5.0–6.0
Thermal					
Softening point	°C	771	846	1,056	—
Annealing point	°C	521	657	816	—
Strain point	°C	477	613	766	—
Coefficient of thermal expansion	in./in.°F	17×10^7	28×10^7	17×10^7	5×10^6
Specific heat (23°C)	J/G-C	0.733	0.81	0.737	0.23
Thermal conductivity	kcal/mh°C	0.9	0.89	0.9	1.1
Electrical					
Electrical constant	1 MHz	3.8	6.6	5.3	—
	10 GHz	4	6.1	5.2	—
Dissipation factor	1 MHz	0.0005	0.0025	0.0028	0.002
	10 GHz	0.0026	0.0038	0.0068	—
Volume resistivity	Megaohm-cm	—	4.20E+14	9.05E+12	—
Surface resistivity	Megaohm	—	4.20E+15	8.86E+12	—
Dielectric strength	v/mil	—	262	330	—
Optical					
Index of Refraction		1.465	1.5558	1.521	1.45

at a cost of approximately 20 times that of standard E-glass. Because cost is a significant factor in material selection for PWBs, there is a very limited supply of this material available.

1.2.2 E-Glass

Even though the lower-cost E-glass exhibits a fairly high Dk, it is still the primary glass fiber used to make glass-reinforced laminates for rigid

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printed wiring applications. This is primarily due to its low cost, good electrical characteristics, and mechanical properties in combination with resistance to heat, water, and acid. Commercial E-glass has a tensile strength of ~200,000 to 300,000 psi (~582,289 to 877,920 kg/cm^2), a modulus of elasticity of ~10,500,000 psi (~29,264,000 kg/cm^2), and a specific gravity of ~2.6. E-glass can elongate to break at about 3.5%. Fibers are available in diameters from about 0.00015 to 0.001 inch (~3.8 to 25 microns).

1.2.3 S-Glass

S-glass and its S-2 derivative offer strength-to-weight ratios that exceed those of most metals. S-2 glass has a higher percentage of both silicon dioxide and aluminum oxide. It has a lower Dk and dissipation factor (Df) due to the higher silicon dioxide content than E-glass but is also five times the cost. Due to its high strength (~650,000 psi [~1,902,160 kg/cm^2]) and high modulus of elasticity (~12,400,000 psi [~36,287,360 kg/cm^2]), this glass is basically used for advanced composite-type printed wiring boards for critical military and aerospace applications.

1.2.4 Quartz

Quartz has a very low Dk and coefficient of thermal expansion (CTE) but is ~40 times the cost compared to E-glass. Quartz materials have a high strength-to-weight ratio and a tensile strength almost equal to that of glass. These fibers have good dimensional stability, low expansion rate, good electrical properties, and excellent chemical resistance (except to hydrofluoric [HF] and hot phosphoric acids [H_3PO_4]).

The term *quartz* refers solely to fused quartz as opposed to crystalline quartz. Fused quartz is an inorganic glass, composed principally of fused silica (SiO_2). Historically, the main reason for using quartz as a laminate material is a CTE in the *xy*-plane that is lower than that of E-glass and matches more closely to that of the ceramic chip carrier, allowing for higher solder joint reliability during thermal cycling. The selection of quartz is otherwise only justified when the finished laminate Dk (~3.7, especially at X-band) and a very low Df (~0.005) are of primary concern; that makes this material very attractive for some microwave applications such as radomes and microwave polarizers. Any incremental improvement in the CTE due to the quartz fabric has to be viewed in light of higher cost and processing difficulties, in particular drilling, as the quartz is very abrasive. The chemical composition of the quartz fibers is given in Table 1.1 and the physical properties are shown in Table 1.2.

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1.3 Glass Fiber Manufacturing

The manufacturing of a glass fiber product involves three steps: glass melting, drawing of the glass filaments, and the conversion of the filaments into a usable form. Schematic diagrams for the direct melt process for making glass fibers is shown in Figure 1.1.

The first step begins with the mixing of various ingredients to meet a specific formula. These ingredients are then melted in a high-temperature furnace heated between 2370 and 2730°F (1300 to 1500°C). While in the molten state, the glass is drawn through tiny holes in the platinum/rhodium bushings by high-speed precision winders. The diameter of the glass fiber is controlled by the viscosity of the glass melt and the rate of extrusion, which can be between 1,500 and 20,000 ft/min (4,921 to 65,616 m/min). Currently there are several glass filaments with different diameters commercially available to weave the glass fabric, as shown in Table 1.3. The smallest-diameter filament used for laminates is 5 μm (~0.00021 in.), and the largest is 9 μm (~0.00036 in.).

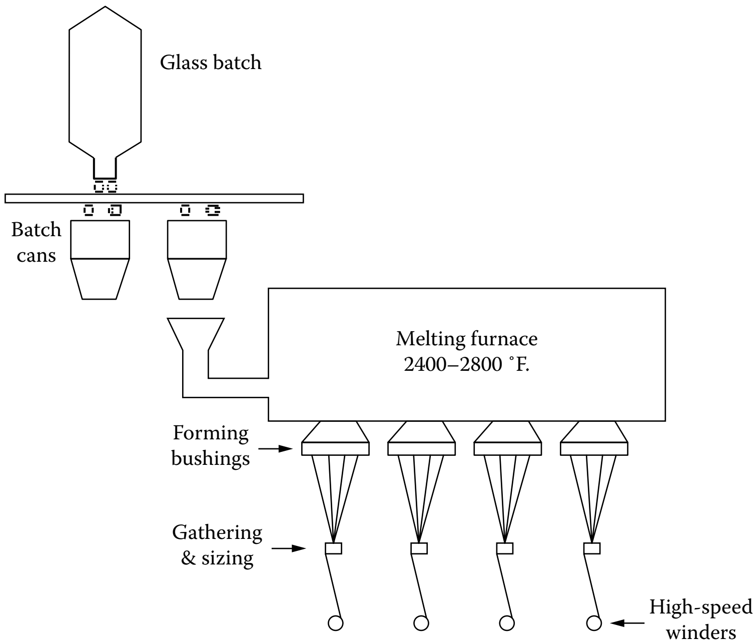

FIGURE 1.1
Schematic diagram of glass fiber manufacturing.

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TABLE 1.3

Glass Filament Diameter

Filament Designation	Filament Diameter		
	Inch	Microns	SI Units
A	0.00012–0.000129	3.04–3.17	3
B	0.00013–0.000159	3.30–4.05	4
C	0.00016–0.000189	4.06–4.82	5
D	0.00019–0.000229	4.83–5.83	5
DE	0.00023–0.000269	5.84–6.85	6
E	0.00025–0.000299	6.35–7.61	7
F	0.000300–0.000349	7.62–8.88	8
G	0.000350–0.000399	8.89–10.15	9
H	0.000400–0.000449	10.16–11.42	11
J	0.000450–0.000499	11.43–12.69	12
K	0.000500–0.000549	12.70–13.96	13
L	0.000550–0.000599	13.97–15.23	14
M	0.000600–0.000649	15.24–16.50	16
N	0.000650–0.000699	16.51–17.77	17
P	0.000700–0.000749	17.78–19.04	18
Q	0.000750–0.000799	19.05 –20.31	20
R	0.000800–0.000849	20.32–21.58	21
S	0.000850–0.000899	21.59–22.85	22
T	0.000900–0.000999	22.86–24.12	23
U	0.000950–0.001045	24.13–25.40	24

The filaments are cooled almost instantly as they leave the bushing by a water spray. A chemical protective treatment called "sizing" or "binder" is applied immediately to each filament during the winding process. Because the bare glass fibers have a low resistance to abrasion, these treatments help coat and lubricate the filaments against abrasive contact, thus reducing fiber breakage during processing. The coatings may later be removed from the woven glass by a controlled heat cleaning process where the glass is placed on a steel mandrel and subjected to a heat cycle for 60 to 70 hours at a temperature of 600 to 670°F (315 to 370°C). During the heat cleaning cycle, all the organic matter is removed and the fabric is ready to be coated with the various finishes used for circuit board laminates.

The basic form of glass fibers used for textile yarns is continuous filament. These are filaments whose length extends throughout the strand. For textile applications, strands are twisted to obtain a uniform product that processes more easily than untwisted strands. In the "S" twist, the strands assume an ascending right-to-left configuration, as in the central portion of the letter *S*, whereas in the "Z" twist, the strands assume an ascending left-to-right configuration, as in the central portion of the letter *Z* (Figure 1.2).

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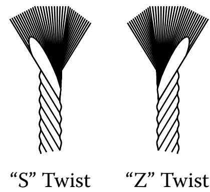

FIGURE 1.2
In an "S" Twist, the strands assume a right to left configuration. In a "Z" Twist, the strands assume a left to right configuration.

1.4 From Yarn to Fabric

Using the data shown in Table 1.1 and Table 1.2, an engineer or designer can now construct fabrics to meet weight, thickness, and strength as required by the printed circuit industry. Available fabric construction that could be used for printed circuit laminates is shown in Table 1.4. Most are plain weave fabrics that produce the smoothest surfaces. These fabrics are very uniform in weight and lend themselves readily to coating and impregnation to a uniform weight. The selection of twisted and plied glass styles will aid in the dimensional stability of the laminate. Shown below (Figure 1.3) is a typical microsection of woven fiberglass fabrics.

1.5 Glass Types and Construction

There is a broad range of woven fiberglass fabrics available to produce laminates for the printed wiring industry. The filament diameter, count, twist, and ply of the yarns used will determine, to a great extent, the characteristics of thickness, mass, pliability, surface texture, and tensile strength that will be present in the woven fiberglass. The weave pattern will control such characteristics as stability, dielectric strength, pliability, and appearance of the fabric. The count of the fabric (number of warp ends and fill per inch) also affects the strength, durability, and appearance of the fabric, as well as the cost.

Interlacing two systems of yarns at right angles to each other produces a woven glass fabric. The warp is a system of yarn or thread that runs vertically or lengthwise in the fabric. Warp can also be referred to as "warp ends," "woof," or simply "ends." Fill is the system of yarns running

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TABLE 1.4

Typical Glass Laminates Construction

Style	Construction (Warp × Fill)	Inches Thickness	oz/sq/yd (osy)	Construction (mm)	Metric Thickness	oz/sq yd gm/m	Plied/ Unplied	Weave
104	60 × 52	0.0011	0.55	118 × 102	0.0028	18.6	Unplied	Plain
106	56 × 56	0.0013	0.72	110 × 110	0.033	24.4	Unplied	—
1070	60 × 35	0.0018	0.99	118 × 69	0.046	34.2	—	Plain
108	60 × 47	0.0024	1.4	118 × 93	0.061	47.5	Plied	Plain
1080	60 × 47	0.0021	1.39	118 × 93	0.053	46.8	Unplied	Plain
112	40 × 39	0.0036	2.09	79 × 77	0.092	70.5	Plied	Plain
2112	40 × 39	0.0032	2.06	79 × 77	0.081	69.2	Unplied	Plain
113	60 × 64	0.0034	2.42	118 × 126	0.087	81	Plied	—
2113	60 × 56	0.0032	2.3	118 × 110	0.079	77.3	Unplied	—
2313	60 × 64	0.0033	2.4	118 × 126	0.084	80.5	Unplied	—
116	60 × 58	0.004	3.09	118 × 114	0.102	102	Plied	Plain
2116	60 × 58	0.0038	3.07	118 × 114	0.094	104	Unplied	Plain
119	54 × 50	0.0036	2.75	106 × 98	0.091	91.8	—	—
2119	60 × 46	0.0034	2.77	106 × 98	0.086	121	—	—
1165	60 × 52	0.004	3.53	118 × 102	0.101	104	Plied	—
2165	60 × 52	0.004	3.55	118 × 102	0.101	120.4	Unplied	—
2125	40 × 39	0.0036	2.58	79 × 77	0.091	86.1	Unplied	—
1652	52 × 52	0.0045	4.18	102 × 102	0.114	136	—	—
1500	49 × 42	0.0059	4.95	96 × 83	0.149	164		—
1674	40 × 32	0.004	2.87	79 × 63	0.097	95.6	—	—
1675	40 × 32	0.004	2.84	79 × 63	0.101	86.3	Unplied	Plain
1678	40 × 40	0.0036	3.12	79 × 79	0.091	105.8	—	—
3070	70 × 70	0.0031	2.74	138 × 138	0.078	93.6	—	—
3313	60 × 62	0.00333	2.38	118 × 122	0.084	80.5	—	—
6060	60 × 60	0.0019	1.15	118 × 118	0.084	39	—	—
7628	44 × 32	0.0068	6	87 × 61	0.173	203.4	Unplied	Plain
7629	44 × 34	0.007	6.25	87 × 67	0.18	210	—	—
7635	44 × 29	0.0071	6.9	86 × 57	0.196	230.9	—	—
7642	44 × 20	0.0099	6.7	87 × 39	0.254	227.8	Unplied	Plain
7652	32 × 32	0.0087	7.43	63 × 63	0.22	252	—	—

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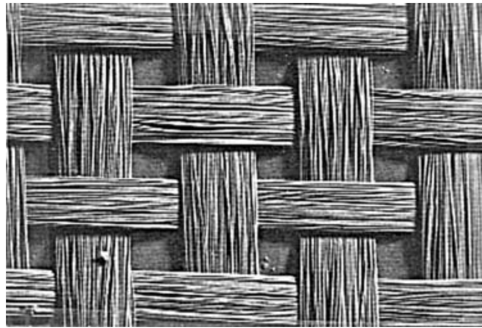

FIGURE 1.3
Typical microsection (50×) of woven fiberglass fabric.

horizontally or crosswise in the fabric. Filling is sometimes referred to as "filling pics," "weft," or "pics." Woven fiberglass fabrics can be woven into various types of weave. A fabric with balanced construction in the warp and fill direction will give the best stability to the laminate. By "balanced construction," we mean that the number of yarns in the warp (machine direction) equals those in the fill direction (cross direction).

1.6 Glass Fabric Weave

Fiberglass fabrics are available in at least five weaving styles for industrial applications. These glass styles are described below.

1.6.1 Plain Weave

This weave design consists of a simple interlacing pattern: one yarn over and one yarn under every other cross yarn (Figure 1.4a). The plain weave is characterized as being the most stable with respect to yarn slippage and fabric distortion and is very uniform in weight and thickness. Most fabrics used for printed wiring board laminates are fabricated with the plain weave. When impregnated with a resin, the plain weave is easily and thoroughly wetted into a uniform B-stage fabric that can be used to bond prepreg or core laminates.

1.6.2 Twill Weave

The twill weave is a basic weave characterized by a diagonal rib or twill line. Each warp end floats over at least two consecutive pics (Figure 1.4b).

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1.6.3 Long-Shaft Satin

The long-shaft satin construction has one warp end weaving over three or more and under one filling pic. Satin weave fabrics are the most pliable and conformable to compound curves of any of the weaves. The satin weave can be woven with the highest count and produce high strength in all directions (Figure 1.4c).

1.6.4 Basket Weave

The basket weave is similar to the plain weave but has two or more parallel warp ends weaving alternately with two or more filling pics. The basket weave is more pliable and will conform to simple contours better than a plain weave (Figure 1.4d).

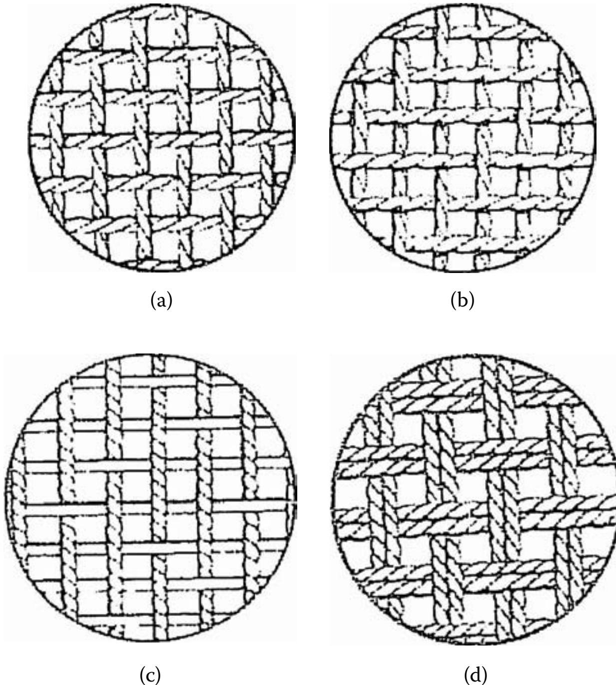

FIGURE 1.4
(a) The plain weave is the most simple, commonly used weave. In this type of weave, the warp and filling yarns cross alternately. (b) The basic weave characterized by a diagonal rib or twill line. Each warp end floats over at least two consecutive pics. (c) This construction has one warp alternately with ends weaving over three or more and under one filling pic. (d) This type of weave has two warp yarns cross alternately with two or more filling pic.

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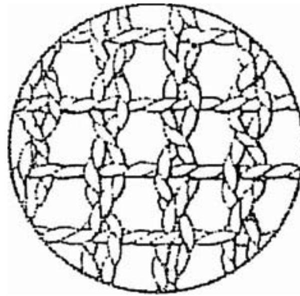

(e)

FIGURE 1.4 (continued)
(e) The Leno weave is a locking-type weave in which two or more warp yearns cross over each other and interlace with one or more filling yarns. It is primarily to prevent shifting of the yarn in open fabrics.

1.6.5 Leno Weave

A leno weave is a locking-type weave in which two or more warp yarns cross over each other and interlace with one or more filling yarns. It is used primarily to prevent the shifting of yarns in open fabric (Figure 1.4e).

The plain weave is basically used to produce standard fiberglass laminates. The basket, satin, and leno weaves are used in producing quartz fabrics.

1.7 Surfacing Mat, Paper, or Veil

These reinforcements are composed of chopped or continuous strands in nonwoven random matting, usually held together by a resin binder. They are cost-competitive reinforcements that provide fast wet-out, even tension, and abrasion resistance during processing. This type of reinforcements had been popular with the production of polyester-based laminate. Originally, these reinforcements were utilized to cover reinforcing mat and fabrics to block out underlying fiber patterns and to impart a smooth outer surface. More recently, this type of mat has been used as a replacement for cellulose paper in various laminates as a core substrate. The composite materials are classified as CEM-3 and CRM-5 laminates where various layers of the surfacing mats are sandwiched between woven fabric layers.

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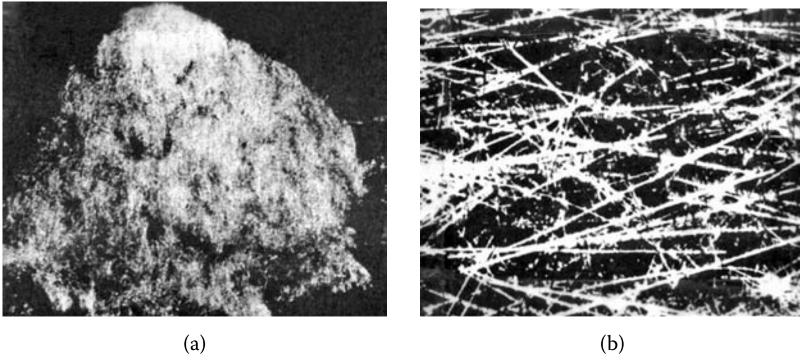

(a) (b)

FIGURE 1.5
(a) Chopped fibers; (b) chopped mat.

1.8 Glass Fiber Paper

A technique for manufacturing glass fiber mat or "paper" has been developed and is called "wet process." Glass fiber wet-formed products borrow from the technology of the paper-making industry. Chopped fibers of glass are suspended in a water slurry and then collected on a forming screen.

The wet-formed mat is saturated with binders, dried, and cured into a mat or "paper" product (Figure 1.5a and Figure 1.5b). "Wet process" glass fibers are treated with a chemical size to enhance various processing and physical characteristics.

A particular advantage of the wet process is the ease with which glass fibers can be blended with other fiberglass or nonglass to combine the advantages of the different materials. As a core material in printed circuit board laminates, the glass fiber wet-formed mat improves punchability of the laminate and has excellent dimensional stability and strength.

1.9 Quartz

The manufacturing process for quartz fibers is more expensive than that for E-glass because the softening point of silica is ~3038°F (~1669°C), which is very close to the melting point of platinum (~3216°F [~1769°C]); silica fibers must be drawn singly and directly from the silica glass canes. The finished diameter is limited to relatively large sizes. Because the quartz

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TABLE 1.5

Quartz Fabric Construction

Style	Construction (Warp × Fill)	Inches		Weave
		Inches	Metric (mm)	
503	50 × 40	0.005	0.127	Plain
507	27 × 25	0.004	0.1016	Plain
525	50 × 50	0.003	0.0762	Plain
527	42 × 32	0.009	0.2286	Plain
533	18 × 18	0.007	0.1778	Basket
570	38 × 24	0.027	0.6858	5H satin
572	17 × 16	0.017	0.4318	Plain
581	57 × 54	0.011	0.2794	5H satin
593	46 × 46	0.01	0.254	5H satin
594	29 × 10	0.008	0.2032	Leno

fibers are thicker, so are the fabrics and the resultant laminate. In most respects, quartz fibers behave like glass, which allows their being processed with any type of resin. The reduced Dk (3.5 to 3.8 at X-band) and low Df (~0.005) make this material attractive for some microwave applications such as radomes or microwave polarizers. The chemical properties of quartz are shown in Table 1.1, and the physical properties are given in Table 1.2.

Various fabric constructions for quartz fabrics are given in Table 1.5. The two primary fabric styles used for printed wiring board laminates are styles 503 (which has limited availability) and 525 (which is the most commonly used). The process for manufacturing quartz fibers is shown in Figure 1.6.

1.10 Properties of Glass Fabrics

1.10.1 Moisture and Chemical Resistance

Organic solvents, bacterial attack, or many acidic or basic corrosives do not affect the inorganic fibers. These fibers exhibit no appreciable water absorption or water-induced deterioration.

1.10.2 Electrical Properties

Glass is an electrical insulator with high Dk and relatively low Df. Its low moisture absorption also contributes to very stable electrical characteristics.

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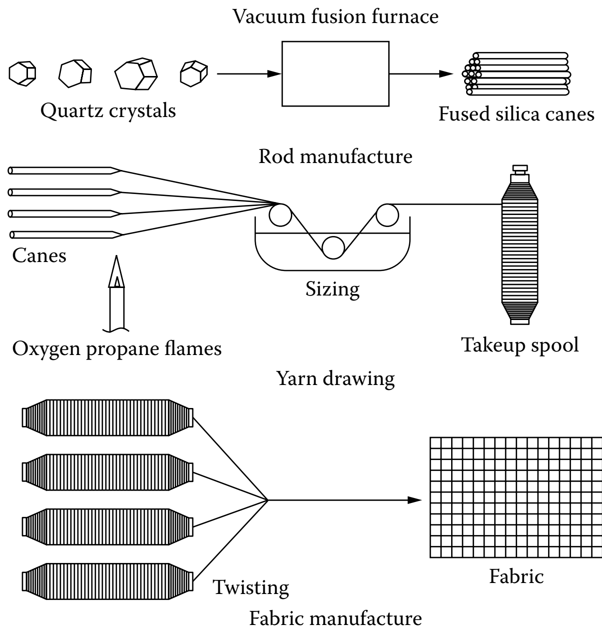

FIGURE 1.6
Manufacturing quartz fibers.

1.10.3 Heat and Fire Resistance

Being an inorganic, glass fabric is incombustible. Glass retains about 50% of its initial strength at 698°F (370°C) and 25% at 993°F (534°C). Normal laminating and printed circuit board processing temperatures leave the fabric reinforcement of laminate materials unaffected.

1.10.4 Thermal Conductivity

Glass fibers rapidly dissipate heat, particularly in printed circuit board applications requiring dimensional stability and heat resistance.

1.11 Aramids

1.11.1 Nonwoven Aramid (Thermount®)

Nonwoven aramid fibers meet the demands for increased dimensional stability and improved control of the CTE. These reinforcements help

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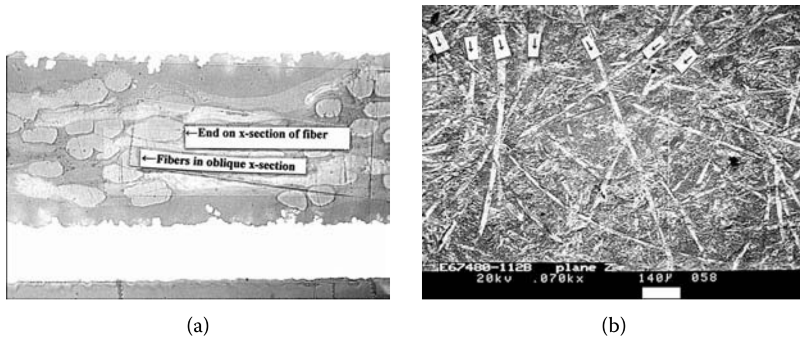

(a) (b)

FIGURE 1.7
(a) Fibers (arrows) in oblique section; (b) arrows point along fibers.

eliminate microcracking and weave print-through that can occur with woven fabrics. Nonwoven aramid reinforcements have the same basic structure as phenolic paper. The result is a very smooth surface and flat sheet that processes like glass-based laminates but with improved dielectric properties, dimensional consistencies, better drilling, and laser and plasma compatibility.

Thermount is the name that DuPont has applied to the nonwoven aramid fabric. Three thicknesses of nonwoven 100% aramid reinforcement are available: types E-210, E-220, and E-230. Nonwoven aramid is made entirely from two forms of synthetic aramid: a short fiber (floc) and a binder. The ingredients are combined into a sheet structure using a nonwoven forming technology. These sheets are subsequently processed to densify the structure and "lock" the constituents together (Figure 1.7a and Figure 1.7b). This step helps the material develop superior strength, improved dimensional stability, and lower CTE, which then carry over into the laminate and printed wiring board. The physical properties of the aramid laminate are shown in Table 1.6.

Para-aramid polymeric fibers (nylon, polyester) were made from flexible "melt" polymers. While these fibers were suitable for textile and some industrial end users, they offered limited strength and low melt point. In 1965, DuPont discovered a method for producing an almost perfect polymer chain using the polymer poly-*p*-benzamide. The key structural feature of this molecule is the para orientation of the benzene ring, which allows it to form rodlike structures with a simple repeating molecular structure. The term *aramid* now refers generically to organic fibers in the aromatic polyamide family. Kevlar® was the first para-aramid polymer fiber.

Aramids have a Dk near 4.0 as opposed to E-glass, which has a Dk of 6.3. Para-aramid fibers have a high modulus and low CTE when compared to other fibers used as reinforcements in printed wiring boards. The CTE

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TABLE 1.6

Aramid Fibers (Nonwoven)

Property (As a Reinforcement)	Units	Style E-210	Style E-220	Style E-230
Thickness	Mils (micron)	1.70 (43)	2.87 (73)	3.55 (90)
Base weight	oz/yd² (g/m²)	0.90 (31)	1.6 (54)	2.00 (68)
Thickness	Microns	0.036–0.046	0.060–0.072	0.076–0.092
Density	g/cc	61–91	0.72–0.92	0.71–0.91
Breaking strength	kg/cm			
MD		0.9–1.3	1.1–1.7	1.6–2.4
XD		0.7–1.1	1.1–1.7	1.6–2.4
Elongation	%			
MD		0.9–1.3	1.0–1.6	1.0–1.6
XD		0.5–0.9	0.4–m0.8	0.5–0.9
Elmen tear				
MD	g	30–60	56-96	100–160
XD		20–60	53–93	85–145
Gurley–Hill porosity	sec	20<	20<	20<
Tensile strength	lbs/in. (kg/cm)	5.3 (1.0)	9.1 (1.6)	11.1 (2.0)
Equilibrium moisture @ 55%	%	3.4	3.4	3.4

is in fact negative in the axial direction. When combined with thermoset resins, which typically have a high CTE in the range of 40 to 60 ppm/°C, para-aramid fibers restrain the expansion of the resin when heat is applied to the composite laminate. The para-aramid fibers have both a low specific gravity and a low Dk.

1.12 Constraining Dielectric Materials (Kevlar)

Kevlar (aramid) fiber reinforcement yarns are polyaramid fibers made by the DuPont Company. This fiber is available as either a woven or a nonwoven laminate (i.e., paper). Kevlar is a lightweight organic fiber with a much lower density (~1.44), Dk (~3.6), and CTE (~–4 ppm/°C, in the *xy*-axis) when compared to E-glass.

There are several Kevlar fabric styles available. However, for printed wiring applications, style 108 (now largely obsolete due to high cost) and 120 are used. Style 108 fabrics at 8 to 10 ppm/°C offer two-ply construction in a 0.005- to 0.006-in.-thick (0.125- to 0.15-mm-thick) laminate. Only style 120 (Figure 1.8) carries a low enough resin content to achieve a 3 to 5 ppm/°C CTE value, and then its thickness in single-ply laminates comes down against the 0.0035-in. (0.082-mm) minimum peak-to-peak requirement. A resin content of about 64% results in a 0.005-in. (0.127-mm) laminate, and

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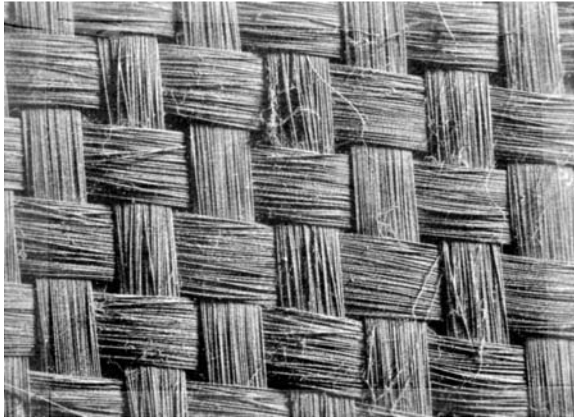

FIGURE 1.8
Microsection (20×) of Kevlar 120 glass fabric.

that translates into about 8 ppm/°C. The principal Kevlar woven fabric made for electronic laminate application was style 120, which is about 4 to 5 mils (0.0102 to 0.0127 cm) thick. However, the requirements for two sheets of dielectric cloth between each layer of circuitry made the multilayer board too thick and the plated-through-hole reliability suffered. The surface of the 120 cloth (Figure 1.8) was relatively coarse due to the coarse weave patterns used, making the copper-clad surface not smooth enough to etch fine lines at high yields. For this reason, a 108 style cloth (Figure 1.9) was made with Kevlar 49 fiber, which is about 2.5 mils (0.0064 mm) thick. However, the modulus was found to be about 26% lower and the CTE to be 67% higher using the same resin content as used with the 120 fabrics

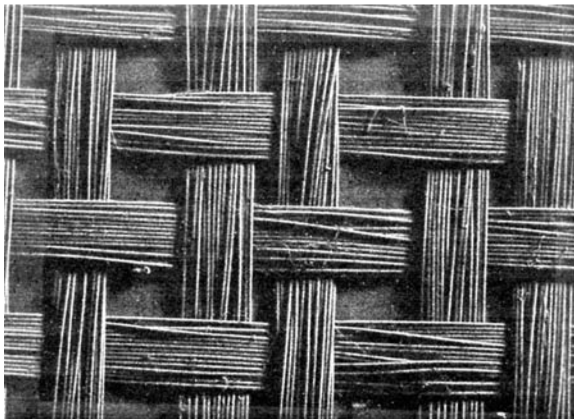

FIGURE 1.9
Typical microsection of style 108 Kevlar fabric.

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and it has largely fallen into disuse, with programs using woven Kevlar granting waivers to allow exception to the two-ply requirement to use 120 style Kevlar.

There are several questions pertaining to Kevlar.

The first question concerns microcracking. Kevlar has a negative CTE in the *xy*-plane because the fibers themselves shrink in plane at –4 ppm/°C when heated and expand radially at the same time. At the fiber crossover, a substantial stress concentration occurs where the cracks are initiated and from where they can propagate. This tends to limit Kevlar-reinforced laminate to epoxy systems, which are relatively flexible. The properties of Kevlar are shown in Table 1.7.

TABLE 1.7

Aramid Fibers (Kevlar)

Property	Units	K-49 Kevlar
Physical		
Density	lb/in.^{3}	0.052
Specific gravity	g/cm^3	1.44
Moh hardness		
Moisture absorption	%	3.5
Mechanical		
Tensile strength	psi	425,000
Tensile modulus of elasticity	psi (72°F)	12.5–13 × 10^6
Elongation at break	%	2.5–2.9
Thermal		
Coefficient of thermal expansion	in./in./°F	23 × 10^6
Thermal conductivity	BTU-in./hr ft^2 °F	0.3–10
Specific heat	BTU/lb °F	32
Electrical		
Relative permittivity	1 MHz	4.0–4.1
	10 GHz	3.85
Dissipation factor	1 MHz	0.014
	10 GHz	0.01
Volume resistivity	500 vdc	0.5 × 10^{12}
Surface resistivity	500 vdc	10^{12}–10^{14}
Optical		
Refractive index		1.6–2.0

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Another issue is thermal management. Kevlar-reinforced laminates transfer heat at about half the rate of conventional glass-reinforced laminates. The heat transfer coefficient for a typical epoxy or polyimide glass laminate is around 0.3 Btu/hr-°F-ft, while Kevlar, in the same system of units, is about 0.15 Btu/hr-°F-ft. Because conventional laminates are not especially good heat conductors, and numerous strategies are employed to remove heat, those techniques will have to be applied with even more vigor with Kevlar laminates.

Because of the constraint of the *xy*-expansion and the contribution to *z*-direction expansion of the Kevlar itself (expanding radially when heated), the net *z*-direction expansion of Kevlar-reinforced laminates is greater than for an equivalent epoxy or polyimide glass-reinforced material.

References

Arlon Materials for Electronics Division, *Everything You Ever Wanted to Know about Laminates … But Were Afraid to Ask*, 6th ed., 1995.

Blalock and Fraizer, *Basic Properties of Glass Filaments, Yarns and Fabric Used in Circuit Boards,* IPC TA-720, Sect. 1.

Bolin, Spinning a glass yarn, *PC Fab,* Dec. 1983.

Maher, *Polyimide Quartz, A Chip Carrier Compatible Laminate Material,* IPC Meeting, Sept. 1982.

Norplex, Technical Bulletins #1005.

Owens-Corning Fiberglass, *Yarns*.

PPG Industries, *Fiberglass Yarns Product Handbook.*

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2

Resins

2.0 Introduction

The resin systems that are used today to produce printed circuit laminates vary with the design requirements, intended application, end item requirements, and cost. For many commercial and consumer applications (e.g., automotive, appliances, toys) that do not require high-performance resins, the board manufacturer will usually use the lowest-cost resin system. However, for the medical, military, aerospace, and high-reliability fields, high-performance resin systems (i.e., the high-Tg epoxies, polyimides, and cyanate esters) are required. Before deciding which resin system to use, consider the possible reasons for choosing one type over another:

- Processability — The resin should perform well within the existing established processes and parameters.
- Flammability — Because of the Underwriter Laboratory's (UL) flammability requirements, almost all laminates and prepregs made today are required to pass the UL 94 V-O specification. This means that some type of flame retardant chemical (bromine, antimony oxide, phosphorous, etc.) must be included in the selected resin. This usually results in a compromise in some of the properties of the resin such as dielectric loss or long-term thermal stability.
- Chemical resistance — Laminates are subjected to many chemicals, solvents, moisture, and high temperatures during fabrications and assembly. The resin system that is selected must be capable of surviving all these conditions with minimal deterioration of the resin properties.
- Electrical properties — Electrical properties are one of the most important factors in selecting a particular resin. Resins with a low Dk and Df are critical for high-speed digital or microwave applications. The changes in electrical property values as a result of frequency, moisture content, and temperature can limit the use of some resins. High breakdown voltages may be required for some types of buried capacitors.

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- Thermal stability — The thermal stability of the resins is an important consideration especially for high-temperature applications and high-layer-count multilayer boards. Sometimes assembly-related factors (e.g., wire bonding to a circuit, rework) can cause copper cracking in the plated through hole. Using a resin with a high glass transition (Tg) can minimize these problems. The Tg can be thought of as a temperature at which the resin begins to act as a rubbery solid rather than a rigid solid. Above the Tg, the rate of thermal expansion increases more rapidly than it does below the Tg. High-Tg materials will exhibit less *z*-axis expansion and will be less likely to cause cracking of the copper in the plated through hole. Also important is the thermal decomposition temperature (Td), which is an indicator of the long-term serviceability of the resin at elevated temperatures.

A wide variety of materials have been developed for use in the fabrication of printed wiring boards. Each resin has its targeted application, and when used within design guidelines, the printed wiring board will be fabricated at the lowest raw material cost possible while still satisfying cost-performance goals for the intended applications. Selection of the "right" resin system for any given application requires that the "must-have" characteristics of the finished product be defined and that the material to be used not be overspecified, thus adding unnecessary material and labor cost to the project.

Exotic resin systems serve many purposes in terms of providing high-performance characteristics such as low (or high) Dk and low Df, high Tg and Td, improved thermal conductivity, and other factors that cannot be fully met by conventional FR-4 systems. The designer should determine what properties are critical and select materials accordingly. Over the years, many resins have been developed as possible resin systems for printed wiring laminates (silicone-based resins such as Sycar®, etc.) that have been tried and discarded after a period of time. This section will describe the commonly used resins, including polyester, epoxy (difunctional, multifunctional, tetrafunctional, and high Tg), polyimide, cyanate ester, polyethylene oxide, polyetherimide, and Teflon®. After reviewing all the data, choose your material wisely.

2.1 Polyester Resin

Polyester is the generic name for a whole family of polymeric materials. They may be either thermoplastic or thermosetting in behavior. Thermosetting polyester resins are generally based on the condensation polymerization

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of polyhydric alcohol (such as propylene glycol) and a polybasic acid (maleic or phthalic anhydride) to form a resin that is cross-linked with a reactive monomer. Reactive monomers such as styrene along with a peroxide catalyst are added to complete the basic system. The basic building blocks can be further modified with special diols and monomers to alter chemical, environmental, and flame-retardant properties. This combination is reacted with heat in the laminating press to complete the reaction. The polyester resin has certain inherent advantages over the other resin systems. The monomer acts as a solvent for the base resin, giving a 100% solid system. The chemistry of the polyester resin is simpler than epoxies and much easier to make fire-resistant. Epoxies are loaded with as much bromine as they can hold and that may not be enough, whereas polyesters have plenty of extra leeway before they are saturated. The polyesters are less catalyst-sensitive, whereas epoxy catalyst levels must be tightly controlled.

2.2 Epoxy

One of the more successful resins used in the circuit board industry has been the epoxy or modified epoxy. These are thermosetting resins (resins that cure into a hard final product) rather than a thermoplastic (which can be remelted many times over). These resins are dissolved in relatively inexpensive solvents and bond well to both copper foil and glass fibers. Epoxy resins are characterized by the presence of two or more carbon-oxygen-carbon (epoxide) groups, which are the reaction sites during the polymerization process. Molecules having two epoxide groups are called difunctional, while those having more than two (usually three to five) are called multifunctional. The functionality of the molecules, along with the relative size of the molecule (molecular weight), in a large part determines the cross-link density of the cured polymer. Higher cross-link density results in a more rigid polymer that is more resistant to higher-temperature exposure. The higher cross-link density will also provide increased chemical and moisture resistance. Low-end difunctional (Tg 100 to 130°C), tetrafunctional modified or blended difunctional/multifunctional (Tg 135 to 160°C), and the now more common multifunctional epoxy systems (Tg 160 to 190°C) have been developed in an effort to preserve the ease of processing that these epoxy resins provide while taking into account the need for enhanced thermal properties. Tetrafunctional modified epoxy systems offer a somewhat higher Tg and better resistance to many chemicals and solvents that are used in circuit board fabrication. Properties of the currently available epoxies cover a broad range of Tg’s from 100 to 190°C.

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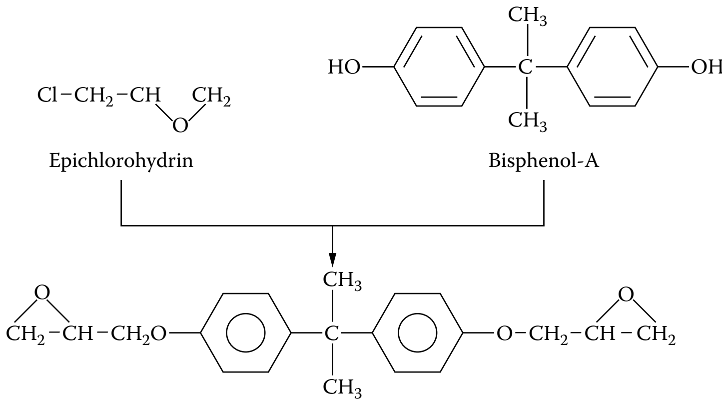

FIGURE 2.1
Synthesis of diglycidyl ether and bisphenol-A.

2.2.1 Difunctional Epoxy

The simplest form of an epoxy resin system is a difunctional epoxy. In the printed circuit industry, the term *epoxy* normally refers to diglycidyl ether of bisphenol-A. The basic monomer of epoxy chemistry is synthesized by reacting epichlorohydrin and bisphenol-A as shown in Figure 2.1. The three-ring or epoxide monomer provides the reactive chemistry of the resin.

To generate an epoxy resin system suitable for impregnation, the base monomer is either further reacted with additional bisphenol-A to yield a non-fire-retardant resin or reacted with tetrabromobisphenol-A to yield a flame-retardant resin (Figure 2.2). The bromine content of these resins is approximately 18 to 21% weight. At this percentage, the resin should meet the flammability requirements of UL 94 V-O without further additives. The brominated resin consists of bromine bonded to the epoxy molecule in such a manner that no free bromine is present. The major disadvantage of this type of resin is poorer adhesion between the epoxy and copper foil, which leads to lower copper peel strength and poorer adhesion of the copper in the plated through holes. Difunctional resins have adequate properties especially for simple single- and double-sided circuit applications, but in general these systems are not adequate for higher-layer-count multilayer boards or the more critical double-sided boards, due to a low Tg leading to a high z-axis expansion, low chemical resistance, and a higher moisture absorption. These properties can be improved by adding more cross-linking to the system.

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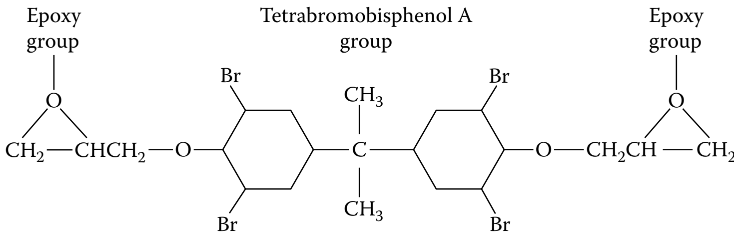

FIGURE 2.2
Difunctional epoxy with tetrabromobisphenol-A additive.

2.2.2 Multifunctional Epoxy

Multifunctional epoxies have become the workhorse of the printed wiring industry. "Multifunctional" generally carries the connotation of higher-performance material. However, properties of currently available multifunctional epoxies cover a broad range, with Tg's ranging from 130 to 190°C.

Multifunctional epoxies that have a Tg rating of 135 to 145°C are composed of the standard difunctional epoxy resins with a minimal amount of either multifunctional or tetrafunctional epoxy resin added to yield marginal improvements in thermal performance (i.e., higher Tg). In these systems, 1 to 4% tetrafunctional epoxy resin or a corresponding amount of fluorescent dye is normally added to improve the automatic optical inspection (AOI) process and prevent shoot-through when curing solder mask on both sides of the board. The tetrafunctional resin is what makes the laminate yellow in color. Cross-linked epoxies are more brittle than the difunctional resins, and this may cause some problems, especially in drilling. Another concern is that if the epoxy novolac is added to the resin, it may lower the levels of flame resistance. For this reason, more highly brominated epoxies or additions of tetrabromobisphenol-A may be required with effects on other properties as already noted.

As epoxy resins have evolved, multifunctional additives have been used to generate a higher cross-linked density in the cured matrix, which affords anywhere from a slight to a substantial improvement in

- Glass transition temperature
- Chemical resistance
- *Z*-axis expansion
- Thermal shock resistance

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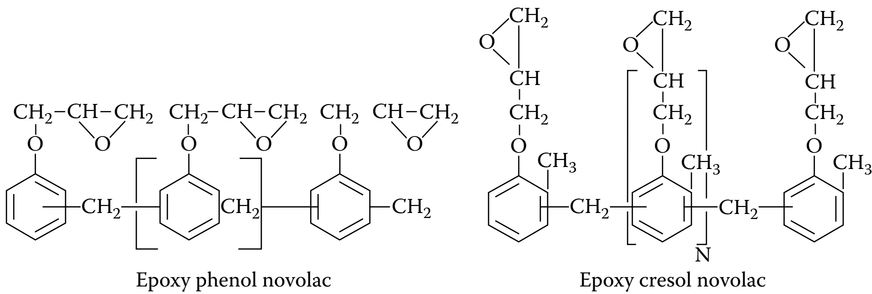

FIGURE 2.3
Epoxy novolac.

The most commonly used multifunctional additives are tetrafunctional epoxy, cresol novolac epoxy, and epoxy phenol novolac (Figure 2.3). These resins can range from low-molecular-weight liquids to very high-molecular-weight solids. Epoxy novolacs are added to enhance certain properties such as increased heat and chemical resistance. Laminates made with novolac will meet UL 94 V-O. Epoxy resins are cured by chemical reaction between the epoxy groups and the curing agent. The curing agents are added to convert the resin into an insoluble, infusible, cross-linked C-stage final product.

Some properties of these resins are not adequate for multilayer boards or the more critical double-sided boards. These shortcomings include a low Tg that can lead to a high *z*-axis expansion with low chemical and moisture resistance. These properties can be improved by adding more cross-linking to the system.

Multifunctional epoxies can be broken down into three categories.

2.2.2.1 General-Purpose Systems Having a Tg between 135 and 145°C

These systems provide improvement in chemical, solvent, and moisture resistance as compared to difunctional epoxy resins. There is little change in thermal resistance and *z*-axis expansion. These materials tend to be compatible with fabrication processes designed for difunctional epoxy.

2.2.2.2 Higher-Performance Multifunctional Epoxies with a Tg between 150 and 165°C

Multifunctional epoxy resin systems provide additional improvement in chemical, solvent, and moisture resistance. The improvement in *z*-axis expansion allows these materials to perform well on thicker boards up to 0.090 in. (2.286 mm) thick without lifted pads. The resin matrix is stiffer and harder and may be more difficult to drill. The improved chemical

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resistance usually requires increased activity of chemical hole cleaning process or the use of plasma hole wall preparation.

2.2.2.3 High-Temperature Multifunctional Epoxy with a Tg between 170 and 185°C

These systems provide very high chemical, solvent, and moisture resistance. The improvement in *z*-axis expansion allows these materials to perform well on boards up to 0.150 in. (3.81 mm) without resulting in lifted pads. Boards built with these materials will usually pass tests requiring up to five solder float tests without evidence of lifted pads. Due to the hardness of these materials, drill wear will be increased.

Currently, high-temperature multifunctional materials are utilized in applications where the boards are extremely thick or subjected to multiple solder assembly operations. The growing trend is to design most high-layer-count printed wiring boards with these resins to ensure that they will not be destroyed at assembly level. The high-temperature epoxies are chosen over other high-temperature materials such as polyimide or bismaleimide-triazine because of material cost and ease of processability.

2.2.3 Tetrafunctional Epoxy

The combination of blends of tetrafunctional and difunctional epoxy resins reinforced with woven glass fabric meets the requirements of an FR-4 laminate. The tetrafunctional resin is added to the base difunctional epoxy with a loading of 6 to 20% by weight. The enhancement of the properties is directly proportional to the amount of tetrafunctional resin added. The addition of the tetrafunctional resin offers a material with better thermal, chemical, and moisture resistance as well as improved electrical properties; however, it is still compatible with normal FR-4 processing technology (Figure 2.4). Today, competitively priced multifunctional systems are replacing tetrafunctional modified FR-4 for almost all applications.

2.2.4 Curing Agent

Dicyandiamide (DICY [Figure 2.5]) cures through all four nitrogen-containing functional groups and consumes both the epoxy and hydroxyl groups in the resin. The final cross-linking reaction yields guanylurea groups (-C=O-NH-R).

Dicyandiamide has been used as a curing agent with epoxy resins (for laminate applications) because it provides latency at room temperature and cures rapidly at elevated temperatures (302 to 329°F [150 to 165°C]). However, dicyandiamide is not soluble in the ketone solvents commonly

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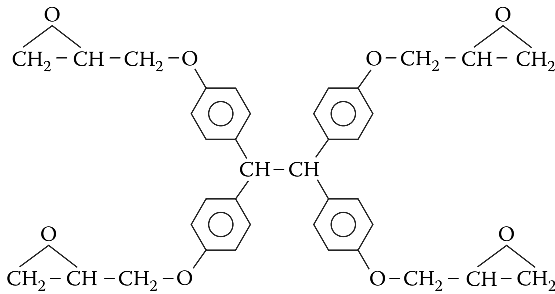

FIGURE 2.4
Tetrafunctional epoxy.

FIGURE 2.5
Dicyandiamide.

used in epoxy formulations. To obtain homogeneous solutions, the dicyandiamide is dissolved in a mixture of dimethylformamide (DMF) and glycol ether. Undissolved dicyandiamide will absorb or complex with the accelerator benzyldimethylamine (BMDA) or absorb dimethylformamide from the epoxy resin. Any of the dimethylformamide held in the prepreg would act as an inhibitor during final cure. Birefringence properties of DICY under polarized light permit determination of the form of dicyandiamide (Figure 2.6). In epoxy prepregs manufactured from a resin solution in which all of the DICY has been dissolved, the DICY structure will be present as long, needlelike crystals (Figure 2.7). However, in prepregs where all the DICY has not been dissolved, poorly formed crystal structures can be observed (Figure 2.8).

It has been established that undissolved DICY, or DICY that has precipitated from the solution, can present numerous problems in the final epoxy laminate. DICY begins to degrade at 347°F (175°C) and, in so doing, produces nitrogen and water vapor. These degradation products have been shown to produce voids in the laminate (Figure 2.9), and a number of other failures have been attributed to the presence of these by-products. Also, undissolved DICY in contact with the copper foil surface will break down into ammonia gas. Some of this ammonia gas, being freer to move than the solid DICY, dissociates into the surrounding areas and aids in curing the epoxy. The balance of this ammonia gas can react with the copper oxide to produce nitrogen gas and water vapor.

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FIGURE 2.6
Dicyandiamide (DICY) under polarized light.

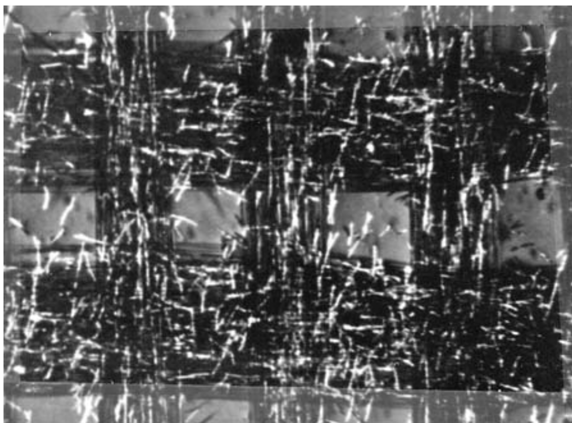

FIGURE 2.7
Dicyandiamide (DICY) (needle life crystals).

In forming epoxy laminates, varying degrees of cross-linking can take place between the epoxy and the DICY. The degree of cross-linking affects many of the properties of the finished laminate. The Tg of the laminate provides an indication of the degree of cross-linking. In general, a higher Tg indicates a higher degree of cross-linking in the laminate. The higher the Tg, the less *z*-axis expansion in the laminate and the less chance of barrel cracking.

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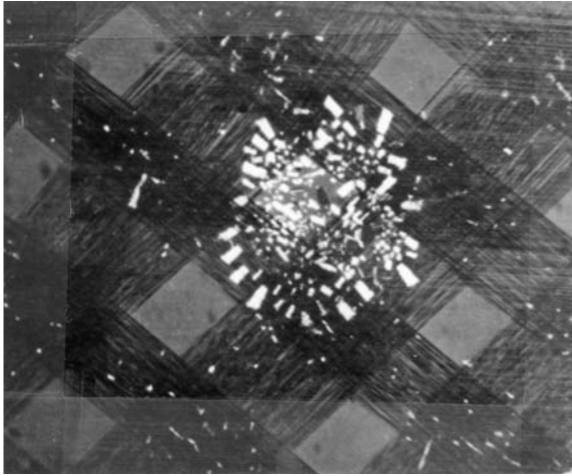

FIGURE 2.8
Dicyandiamide (DICY) (poor crystal formation).

FIGURE 2.9
Dicyandiamide (DICY) (causing laminate voids).

2.2.5 High-Tg Epoxy

A highly crossed-linked epoxy system can achieve Tg values above 180°C. Such materials are more difficult to work with and are usually modified to improve processability. These highly cross-linked materials may be brittle, causing drilling problems. These systems presently compete with high-Tg non-epoxy materials at the high end of the multilayer market.

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2.3 Polyimide

The primary asset of polyimide resins is their high Tg and thermal stability. These enhanced high-temperature properties virtually eliminate the drill smear caused by heat developed during the drilling process, enable the printed wiring board to withstand numerous solder rework cycles, and help maintain copper bond strength at elevated temperatures. The *z*-axis dimensional stability is excellent, which minimizes through-hole copper cracking. Polyimide resins usually have values of Dk and Df that are lower than those for epoxies. One of the disadvantages of polyimide is its tendency to absorb water, which can lead to variable dielectric properties and minimizes their advantage as a material for high-speed applications. The polyimide system has the best long-term thermal characteristics of any currently available material. Its short-term thermal stress performance has in the past been limited by residual high-boiling solvents entrapped during processing. Interply bond strength is not as good as that of triazine.

The polyimide resins were originally used for military applications where multilayer printed wiring board reliability was critical. The high Tg (260 to 300°C), long-term thermal resistance, a low CTE (lower than epoxy), and the high thermal degradation temperature result in excellent reworkability and long plated-through-hole life for the polyimide resin system.

This resin should be specified for systems that must operate with high reliability in an extreme environment such as high ambient temperatures or extremes in thermal cycling for thick multilayer boards where its high Tg minimizes the risk of latent plated-through-hole defects, or for boards that may require high-temperature "field repairability" where the risk of delamination or pad lifting is undesirable.

Laminates made today that use polyimide resins generally use the Kermid 701 resin system. The solvent system used for this resin is very flexible and is not limited to *N*-methyl prylidione (NMP) and methoxy propanol acetate (PMA). Lower-boiling solvents such as ketones can be used as the diluents. The risks of short-term thermal stress failures are correspondingly reduced. The lower melt viscosity of the resin allows the flexibility of making high-resin-flow prepreg for those difficult printed wiring board applications requiring surface leveling and filling in the printed wiring board topography.

Kermid 701 is a two-component liquid resin system that does not require a methylene dianiline (MDA) hardener (Figure 2.10). The latter types of polyimide resins utilize a Diels–Alder reaction, with diallyl bisphenol-A to achieve a toughened cross-link.

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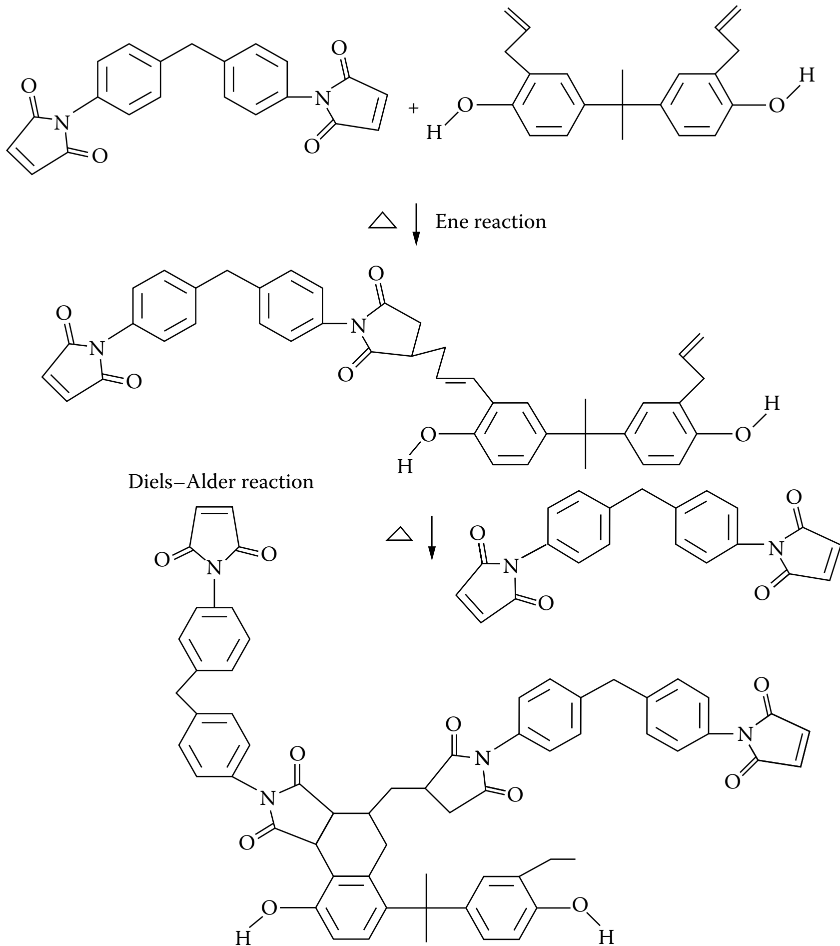

FIGURE 2.10
Polyimide resin.

2.3.1 Epoxy-Blended Polyimide

An epoxy-blended polyimide resin system is a combination of epoxy and polyimide resin. The polyimide resin provides a much higher thermal resistance, while the epoxy resin maintains the mechanical processing advantages. The addition of the polyimide resin raises the Tg of the system to as high as 220°C.

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2.4 Cyanate Ester and Cyanate Ester Blends (BT Resin)

2.4.1 Cyanate Ester Resins

Cyanate ester resins are finding their way into a variety of high-speed applications, where the application of surface mount technology requires both high-speed signal processing and direct surface mounting of leadless chip components. These resins have a comparatively low Dk and a low Df over a large frequency range and temperature. With their low Dk (2.8), a CTE of 10 to 12 ppm/°C, and a high Tg (235°C), cyanate ester resins are the material of choice for high-complexity, high-layer-count multilayer boards. The lower-Dk materials help reduce "cross-talk" between closely spaced signal lines, which minimizes the requirement for extra shielding lines.

Cyanate ester resins are bisphenol derivates containing the ring-forming cyanate (–O–C≡N) functional groups (Figure 2.11). Cyanate ester is a cyclotrimer of dicyanate. The trifunctional cyanate ester cross-links to form a high-temperature polymer (Tg 235°C or higher). In their purest form, these resins are very brittle and have low peel strength. To overcome this, these resins are blended with either epoxy or a small amount of polyimide resins. This blend is called "BT," named after its two major components: bismaleimide and triazine. By varying the ratio of either of the two components, you can handpick the desired Dk. The composition of 10% by weight bismaleimide and 90% by weight triazine results in a similar curing temperature as that of epoxy resin. In most cases, BT resins can be substituted for polyimide resins.

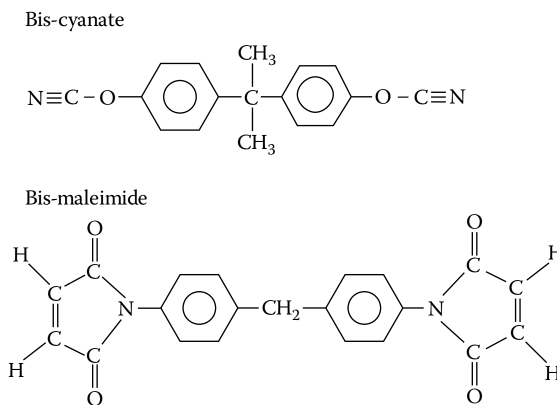

FIGURE 2.11
Cyanate ester resin.

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This material exhibits desirable electrical performance in the microwave frequencies. Laminates made with cyanate ester resins are difficult to manufacture compared to other materials systems and may be very brittle, resulting in cracking during cool-down cycles and drilling unless care is taken in handling. Cyanate ester and BT resins can be made flame-retardant by the addition of brominated epoxy, antimony trioxide, or fluorine compounds to meet the UL 94 V-O flammability rating.

The prime feature of this resin is that, unlike other resins capable of heat curing at a temperature of 347°F (175°C), the high heat resistance of BT resin is a function of the ring structure of the functional groups, rather than the increased cross-linking density, which results from curing.

Resin systems consisting of BT/epoxy are used when higher operating temperatures are required. This resin system is a combination of bismaleimide triazine and epoxy resin. The BT resin provides the good electrical and thermal properties (356°F [180°C]). The epoxy resin is blended with BT resin to improve the system mechanically. Another feature of BT resin is its low Dk and Df, which is the result of the low content of polar groups such as OH^- in the cured resin, again a favorable property for high-frequency and high-speed circuit boards. This resin also exhibits excellent electrical insulation resistance after moisture absorption.

Generally, when a voltage is applied across metallic electrodes and the insulation material between them absorbs moisture, the metal is ionized and moves between the electrodes, causing insulation failure (CAF phenomena). The use of BT resin minimizes such failures, which is another feature that is important in materials for high-density boards. However, as hole spacing gets closer and closer, even BT resin is known to fail.

BT resins are nontoxic to humans and soluble in general-use solvents, and the viscosity is controllable over a wide range, providing a total processability that matches diversified manufacturing processes.

For many temperature applications, BT resin is a direct substitute for polyimide; it has the added advantage that the moisture sensitivity and processability of BT is much closer to conventional epoxy than polyimide. Other than a high-temperature postlamination bake required for full cure, the BT processes are the same as those for epoxy. The major drawback to BT resin is cost. Although BT is much less expensive than polyimide, it is more costly (~1.5 times) than epoxy.

2.5 Polyphenylene Oxide (PPO) Epoxy Blends

One of the more cost-effective resins today is a material based on a blend of PPO and epoxy resin. This resin system is composed of polyphenylene

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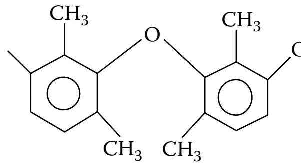

FIGURE 2.12
Polyphenylene oxide epoxy blend (PPO).

oxide and epoxy (Figure 2.12), which when reacted together form a thermoset resin that has a Tg of 180˚C. When coated on glass, the PPO blend processes like epoxy with the exception of a high-temperature bake to obtain a full cure. The major advantage of the resin is very low moisture absorption and a cost that is only 20 to 50% more than epoxy. The disadvantage of this resin is that it has a broad glass transition temperature with softening beginning well below 302˚F (150˚C). This has an adverse effect on the ultimate fatigue life of high-aspect-ratio holes.

PPO blends are an excellent candidate for any application requiring high operating temperatures or low moisture absorption. Care should be taken when using this material in applications where the system must operate over a very large number of thermal cycles that include temperatures in excess of 266˚F (130˚C). The Dk is typically 3.8 to 4.2 at 1 MHz and has a significantly lower Df (0.008 to 0.009). The fact that these materials have half the moisture absorption of standard epoxy makes this an ideal material for backpanels for cellular-based stations and many other wireless applications.

2.5.1 Getek® Resins

Getek resins are a proprietary blend of 70% high-Tg epoxy resin and 30% thermoplastic polyphenylene oxide. This combination of resins has good electrical characteristics, a low Dk of 3.8 to 4.2 at 1 MHz, a Df of 0.008 to 0.009, a low Tg, and a low CTE. The Tg can only be determined by dynamic mechanical analysis (DMA). Getek is UL-approved for operating at 302˚F (150˚C).

2.6 Polytetrafluoroethylene Resin (PTFE)

Polytetrafluoroethylene is an ultra-high-molecular-weight polymer. The DuPont trade name Teflon® is generally applied to this family of fluorocarbons that also includes PTFE.

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The mechanical properties of thermosetting materials are derived from the cross-linking of the reactive groups on the precursors to form rigid, glasslike three-dimensional polymeric matrices during their cure cycle. By contrast, the mechanical properties of PTFE are derived from its high molecular weight. There are no reactive groups attached to the molecule, and no cross-linking or cure takes place during laminate manufacture. The term *Tg* is not strictly applicable to PTFE resin, as it maintains its plastic properties throughout its entire useful range (from well below zero to its very high melting point (620°F [327°C]).

Polytetrafluoroethylene is a high-molecular-weight polymer. Several features of this molecule explain most of its electrical, chemical, and physical properties and therefore the properties of the composite made with this compound:

- Symmetrical orientation of the fluorine atoms about the carbon backbone, thus reducing dissipation loss — "nonpolar nature"
- Molecular size of the fluorine atoms — chemical inertness
- Strong primary chemical bonds — chemically stable
- Weak secondary valence forces/high molecular weight — thermoplastic and chemical properties

The nonpolar nature and unique molecular structure are responsible for the low Dk and Df of PTFE as well as the high volume and surface resistivity, high dielectric strength, and arc resistance. This is in sharp contrast to the highly polar thermoset resins such as epoxies and polyimide resins. The Dk and Df of PTFE are very stable and predictable under various conditions of frequency, humidity, and temperature when contrasted with other resins that are used for electronic purposes. The Dk response of PTFE to frequency is relatively flat. PTFE resins are not hydroscopic; therefore, the Dk and Df are essentially unchanged under varying humidity conditions. The dielectric response of PTFE versus temperature is well characterized and predictable even when a slight hysteresis at 66°F (19°C), caused by crystalline phase change, is considered.

The Dk of PTFE is 2.06. This low Dk reduces the propagation delay by approximately 30% when compared to FR-4. Additionally, cross-talk and board thickness are substantially reduced. The Df of 0.00012 at frequencies of 10 GHz improves signal rise time and attenuation. Normally when the lowest Dk or Df is required, as in microwave applications, PTFE resins are used.

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References

Arlon, *Materials for Electronics,* Arlon Technical Data.
Bright, J.P. and Going, T.J., Polyetherimide laminates for high performance circuitry, *Insulation Circuits,* Oct. 1982.
Deckert, C.A., Epoxy resin chemistry and laminates, *PC Fab,* Apr. 1985.
Dupriest, D., Non-FR-4 materials, *The Board Authority,* June 2001.
Ehrler, S., A review of epoxy materials and reinforcements, *PC Fab,* Apr. 2002.
Engineering Fact File, Cyanate ester, *Electronic Packaging and Production,* June 1997.
Guiles, C.L., *Everything You Wanted to Know about Laminates but Were Afraid to Ask,* Arlon Materials for Electronics.
Guka, M., Ikeguchi, N., and Ayano, S., BT resin widens the choice of laminate materials, *Electronic Packaging and Production,* Dec. 1985.
Homan, G., Aramids, E.I. DuPont de Nemours, private correspondence.
Iguchi, D., Clearing up the confusion about multifunctional epoxy, *Circuitree,* Nov. 1993.
Jorgensen, C., FR-4 dead as Dillinger, *PC Fab,* Apr. 1999.
Ludwig, C.T., Johnson, P., and Lane, S., Polymeric Design of a Polyester Resin for High Frequency PCB Application, IPC Printed Circuit EXPO, Mar. 1996.
Powell, D., Kirayoglu, B., and Weinhold, M., *New Applications for Non-Woven Aramid Reinforcement Which Demand Advanced Physical Fibers,* E.I. DuPont de Nemours & Co.
Tiez, R. and Bhall, P., New Generation of Kermid Polyimide Resin, IPC Meeting.
Vaughan, D.J., *Effects of Varying Dicyandiamide Concentrations in Epoxy Resin,* Clark-Schwebel.

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3

Flexible Films

3.0 Introduction

Materials that are used for finished printed circuit laminates were designed primarily to replace bundles and cables of conventional round insulated wire to both reduce weight and save space. Flexible printed circuits are made on thin flexible based materials usually from a nonreinforced polymeric material. The ability to bend these laminates allows them to be used as interconnects in place of wire harnesses or in places where connections are needed to a moving part. There are two distinct advantages of using flexible circuits:

- Once the flexible circuit layout has been proven, it is almost impossible to make a wrong connection.
- The thinness of the flex circuit allows it to be used in locations where the thickness of even a ribbon cable cannot be accommodated.

Flexible printed wiring consists of layers of insulation, adhesives, and conductive materials put together in a sequence as required by a particular design. In flexible printed wiring, the dielectric serves both electrical and mechanical purposes. Conventional flexible printed wiring consists of five distinct layers of material: base dielectric film, a conductor layer, a cover layer, and two distinct adhesive layers. One of the adhesive layers is used to bond the conductor layer to the base dielectric to form a base laminate. The second adhesive layer joins the cover layer to the etched pattern. It is a good practice to have matching properties in both the base and the cover layer; for this reason, flexible printed wiring is almost always built with identical adhesives and dielectric films in these layers.

The original flexible materials were made from thermoplastic dielectric insulating films that were laminated to copper foil with the use of heat and pressure. The dielectric substrate of the flex laminate has a significant effect on the manufacturing cost and the performance of the finished circuit. Polyimide films offer the best combination of cost and properties for this application. Polyester films are a close second, falling short only on thermal resistance. Aramid fibers (nonwoven) have unique properties

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that suggest their use in applications where cost is important and slight imperfections can be overlooked. Fluorocarbons have superior dielectric properties and are suitable for use in demanding controlled impedance applications. Every laminate consists of a conductor foil and a dielectric substrate. Copper is the typical foil of choice while virtually all flexible circuits are built on either polyimide or polyester substrates. For special purposes, aramid and fluorocarbons are used. The reasons for choosing a particular film are as follows:

- Military and high-performance flexible circuits are currently manufactured with polyimide films, as they offer the best overall performance at an acceptable cost.
- Commercial, cost-sensitive circuits are built on polyester (similar properties to polyimide films, but with a reduced thermal resistance).
- Aramid fibers (nonwoven) are inexpensive and have excellent electrical and mechanical properties but exhibit excessive moisture absorption, which limits their use in some hot, humid environments.
- Fluorocarbons, although expensive and hard to handle, have superior dielectric properties that suit them for controlled impedance boards.

To determine the best materials for a given application, one must first understand the major performance characteristics of each material. A good reference knowledge of the mechanical, electrical, thermal, and chemical properties will allow an effective material choice for each flexible printed circuit board application.

Mechanical properties such as flexibility, tensile strength, tear propagation strength, dimensional stability, electrical strength, Dk, and volume resistivity; thermal properties such as Tg, CTE, and service temperature range; and chemical considerations such as moisture absorption and resistance to acids and alkali must be matched to the design requirements. Table 3.1 shows the adhesives that are most commonly used to laminate the conductive materials (copper) to the dielectric material. If adhesives are used, their properties must be compatible with the environment and operating parameters.

3.1 Types of Flexible Materials

3.1.1 Polyethylene Terephthalate ([PET] Polyester)

Polyester films are made from polyethylene terephthalate polymers. This polymer is the product formed by the condensation reaction of ethylene

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TABLE 3.1

Flexible Base Dielectric Materials and Adhesives

Dielectric Material	Adhesive
Polyester	Polyester
Polyester	Flame-resistant polyester
Polyester	Modified epoxy
Polyester	Butyl phenolic
Polyimide	Acrylic
Polyimide	Flame-retardant acrylic
Polyimide	Modified epoxy
Polyimide	Polyester
Polyimide	Polyimide
Polyimide	Adhesiveless
Aramid	Acrylic
Aramid	Modified epoxy
Composite	Modified epoxy
Composite	Polyester

glycol with either terephthalic acid or dimethyl terephthalate. The filming process consists of feeding the polymer through an extruder onto the casting drum. The resulting amorphous web is subjected to a forward draw through a series of preheated rollers into a stenter where it is drawn sideways and crystallized at elevated temperatures. The resulting biaxially oriented film is then cooled, and the film is wound up onto a core. Polyester is a low-cost cast film containing plasticizers that under normal operating conditions do not become brittle. It is very resistant to solvents, has a tensile strength of 25,000 psi (73,160 kg/cm^2), and has a good dielectric strength. The plastic memory of the polyester films could be used for retractiles, which are long strip circuits folded in half and then coiled so that the ends can be pulled apart; when the ends are released, the circuits coil up again. The center fold gave the tracts a noninductive bifilar coil, which made excellent connections for side-out drawer-type units.

Polyester laminates are built with thermoplastic adhesives that facilitate high lamination temperatures. Although polyester films will burn, adhesives are available with sufficient flame suppression properties to yield laminates that are usable even in sensitive applications,

Commercial and cost-sensitive circuits are generally built on polyester films (approximately 20% of U.S. products are polyester laminates and cover layers). These films have similar mechanical properties to polyimide films, are electrically superior, and absorb far less moisture. However, their resistance to heat is only fair. This film provides excellent thermal and mechanical properties and can be roll-to-roll processed with thermoplastic adhesives. The primary factor limiting the usage of polyethylene terephthalate is its low melting point of 482˚F (250˚C) and low Tg (80˚C).

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However, polyester films will stiffen at low temperatures. Adhesives that are used on polyester substrates have a low resistance to heat. Typical adhesives used with polyester films are polyester, modified polyester, modified epoxy, and butyl phenolic, as shown in Table 3.1.

Maximum use temperature for most polyester films is 257°F (125°C). Even so, with a careful termination process (preferably crimp or pressure), polyester films can reduce flex cost without lowering installed circuit performance and quality.

3.1.1.1 Polyester/Epoxy

This material is manufactured using a nonwoven mat of polyester and glass fibers saturated with a B-stage epoxy resin system. This saturated mat is then combined with copper foil and laminated into either a single- or double-sided clad material without the aid of an adhesive layer. A unique property of this material is that once it is formed or bent, it can retain that shape due to the low and broad Tg temperature of the fully cured material.

3.1.2 Polyethylene Naphthalate (PEN)

Polyethylene naphthalate is a close cousin to polyester. It is the reaction product of dimethyl-2,6-naphthalene dicarboxylate with ethylene glycol to form polyethylene-2,6-naphthalate. The polymer is subsequently formed into a film using the same process as that for polyester but requiring a higher final cure temperature. The resulting film is produced in a highly crystalline form through biaxial orientation. Its performance is similar to PET's but with improved thermal properties including a Tg of 120°C and melting temperature 54°F (12°C) higher than that of polyester. Typical properties of polyethylene naphthalate are shown in Table 3.2.

3.1.3 Fluorocarbons (FEP)

The first flexible circuits were supported and insulated by fusion bonding foils to high-performance fluorocarbons, 15 years before the polyimide films came on the scene. Unmatched chemical inertness, high thermal resistance, and outstanding dielectric properties combined with tough mechanical properties suggest that fluorocarbons would be an ideal material for flexible printed wiring boards. The early experience with the fusion bonding process quickly identified dimensional stability as a fatal flaw in the fusion-bonded fluorocarbon dielectric. Lamination at the required temperature of ~572°F (~300°C) created stresses on the semimolten dielectric that could destroy the dielectric conductor patterns (causing the conductive patterns to move or "swim").

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TABLE 3.2

Typical Properties of Polyethylene Terephthalate (Polyester [PET]) and Polyethylene Naphthalate (PEN)

Property	Min/Max	Units	Polyethylene Terephthalate Requirements	Polyethylene Naphthalate Requirements
Tensile strength	Min	psi	20.02 E+3.	24.95 E+3
		Pa	(13.8 E+7)	17.3 E+7
Elongation	Min	%	50	60
Initiation tear strength	Min	oz(g)	28.22 (800)	35.27 (1000)
Propagation tear strength[a]	Min	oz/(g)	0.28 (8)	—
Propagation tear strength[b]			—	0.14 (4)
Propagation tear strength[c]			0.71 (20)	—
Propagation tear strength[d]			—	0.28 (8)
Propagation tear strength[e]			—	0.705 (20)
Propagation tear strength[f]			1.76 (50)	1.41 (40)
Dimensional stability		%	1	0.3
Chemical resistance				
Tensile strength	Min	psi (Pa)	23.9 E+3 (13.8E+7)	24.95 E+3 (17.2 E+7)
Elongation	Min	%	50	60
Dielectric constant	Max	60 Hz	3.3	—
		1 MHz	3.5	4
Dissipation factor	Max	60 Hz	0.002	—
		1 MHz	0.022	0.01
Dielectric strength	Min	volts/mil	2,000	2000
Volume resistivity	Min	ohm-cm	—	$\times 10^6$
Surface resistance	Min	1 MHz	—	$\times 10^5$
Moisture absorption	Max	%	0.8	1
Fungus resistance			Non-nutrient	Non-nutrient
Relative temperature index	Min	UL 746B	105	160
Flammability	Min	UL 94	VTM-2	VTM-2

[a] Flexible base dielectric materials with thickness < 1.50 mil (<0.038 mm).
[b] Flexible base dielectric materials with thickness < 0.984 mil (<0.025 mm).
[c] Flexible base dielectric materials with 1.50 mil < thickness < 4.016 (0.038 mm < thickness < 0.102 mm).
[d] Flexible base dielectric materials with 0.984 mil < thickness < 1.97 mil (0.025 mm < thickness < 0.050 mm).
[e] Flexible base dielectric materials with 1.97 mil < thickness < 4.016 mil (0.050 mm < thickness < 0.102 mm).
[f] Flexible base dielectric materials with thickness > 4.016 mil (>0.102 mm).

Fluorocarbons have superior characteristics for flexible circuits. Their tear resistance values are very good, so good that fluorocarbon patches are sometimes used to reinforce weak corners on polyimide circuits. Inert to all common chemistries and inherently incombustible, fluorocarbon laminates do not require pampering to survive production or usage.

On the downside, this film is dimensionally unstable at elevated temperatures, has memory, and requires a special copper foil treatment for

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TABLE 3.3

Typical Properties of Fluorocarbons (FEP)

Property	Min/Max	Units	Requirements
Tensile strength	Min	psi	2.459 E+3
		Pa	(17.2 E+6)
Elongation	Min	%	175
Propagation tear strength[a]	Min	oz (g)	2.64 (75)
Propagation tear strength[b]			3.17 (90)
Propagation tear strength[c]			3.17 (90)
Dimensional stability	Max	%	5
Chemical resistance			
Tensile strength	Min	psi	2.495 E+3
		Pa	(17.2 E+6)
Elongation	Min	%	175
Dielectric constant	Max	60 Hz	2.1
		1 MHz	2.2
Dissipation factor	Max	60 Hz	0.0003
		1 MHz	0.0007
Volume resistivity	Min	megohms-cm	$\times 10^7$
Surface resistance	Min	megohms	$\times 10^7$
Dielectric strength	Min	volts/mil	2,500
Moisture absorption	Max	%	0.1
Fungus resistance	—	—	Non-nutrient
Flammability	Min	UL 94	VTM-0

[a] Flexible base dielectric materials with thickness < 1.50 mil (0.038 mm).
[b] Flexible base dielectric materials with thickness < 0.102 mil (0.038 mm).
[c] Flexible base dielectric materials with thickness > 4.016 mil (0.102 mm).

bondability. It also has a low modulus of elasticity. Fluorocarbons do not readily lend themselves to the plated-through-hole process as a result of their excellent resistance to most chemicals.

Adhesion of electroless copper to the drilled hole wall is very poor, requiring additional processing steps. Today, for ease of circuit and laminate manufacturing, fluorocarbons can be assembled with adhesives instead of using the fusion-bonding process. Dimensional stability is much improved, although not at the level of polyimide films. Provided that the adhesive is kept as thin as possible, a circuit so constructed will display some of the excellent electrical characteristics of a fusion-bonded circuit but at a lower cost. Typical properties of fluorocarbons are shown in Table 3.3.

3.1.4 Polyimide

The first polyimide film that was used as a laminate for flexible printed circuitry was known as Kapton®, soon to be followed by Upilex® and

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Apical®. All are marketed in several derivatives with chemistries and mechanical properties custom-engineered for flexible circuit usage.

These films are inherently nonburning and, when combined with specially compounded fire-retardant adhesives, produce laminates that are UL 94-VO rated. However, many flexible circuit adhesives have a much lower resistance. Although they are able to stand up briefly to soldering temperatures, these adhesives are the weak link in the polyimide film laminate.

Some polyimide films absorb a great deal of moisture. Prior to any exposure at elevated temperatures (such as soldering), the polyimide film must be baked at a minimum of 212˚F (100˚C). Because moisture reabsorption is very rapid, the laminate should be stored in a dry box if not ready for immediate use.

3.1.4.1 Tear Resistance

Flexible circuits usually have complex outlines with multiple stress concentration points, making tear resistance an important property. Tear resistance is a characteristic in which an adhesive can enhance laminate performance, since most flexible adhesives have better tear resistance than the polyimide films. These films are hard to surpass as insulators and high-voltage barriers. However, in the flex laminates, the primary insulation (material controlling the conductor runs) is the adhesive, with its own resistance and dielectric strength; thus the designer has to look carefully at all the properties of the laminate and not at the base film when laying out a circuit design.

Polyimide films and adhesives have relatively poor electrical properties for use in controlled impedance application due to the high dielectric constant of 3.7 or greater. That plus a Df greater than 0.03 suggest that another laminate material should be used where controlled impedance is critical.

3.1.4.2 Dimensional Stability

Dimensional stability is crucial in flexible circuit manufacturing. The primary difference between flexible and rigid circuits is that the flexible film-based laminates are used in place of glass-cloth-reinforced rigid systems. The major consequence of this difference is that flexible laminates inherently expand and shrink more during exposure to various processing conditions.

The stability of the flexible laminate is a complex composite of film properties, degraded by the properties of the cured adhesive and the process conditions used to form the laminate. Careful laminate manufacturing,

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using low web tension, vacuum-assisted lamination, and thermally stabilized films, can minimize shrinkage.

Polyimide films with high tensile strength and high modulus improve stability, while after etch shrinkage of 0.1% is achievable with high-performance films. Shrinkage for laminates made with conventional (woven-glass-reinforced) polyimide is more commonly 0.015%. These shrinkage factors may seem trivial, but economical manufacturing of flexible circuits requires the use of large panels (18 x 24 in. [45.7 x 60.96 cm]). The distances from tooling pin to etch features can be as great as 9 in. (22.9 cm) (assuming that the tooling pins are at the border of an 18-in. [45.7-cm] panel) across this span; 0.1% shrinkage translates to 9 mils (22.9 cm) of shift, tolerable and predicable if not accompanied by other errors but undesirable and costly. Typical properties of polyimide films are shown in Table 3.4.

3.1.5 Aramid

Although polyimide and polyester films are the two most common insulating materials used to fabricate flexible circuits, there are other films that could be used, such as the random-fiber aramids and Dacron® epoxies. The random-fiber aramid fibers are a high-temperature material that can withstand soldering temperatures very well. Its main drawback is that it is a very hygroscopic material and readily absorbs processing chemicals, which must be carefully removed after each wet-processing step before going on to the next step. The aramid paper has a very low initiating and propagation tear strength, but it also has a low Dk (about half that of polyimide).

Aramid fibers (nonwoven) are inexpensive and have excellent electrical, mechanical, and thermal properties but feature excessive moisture and residual chemistry absorption. Aramid papers are not films in the strict sense, but they function as a mechanical backbone and adhesive carrier just as do the polymer films. One advantage is their extremely good electrical performance (Dk of 1.6 to 2.0 and Df of 0.0015). They have good dimensional stability, are inexpensive, and are available in a wide range of thicknesses. This film is rated for continuous use at 428˚F (220˚C) and is nonburning. Aramid films have good tensile and tear strength values as well as dimensional stability and only fall short in the area of high moisture absorption and a tendency to stain. Aramid fibers are very hydroscopic (~3.7%). Both surfaces of the aramid paper should be thoroughly coated before the aramid laminate is exposed to any liquid processing. Otherwise the processing chemicals may wick into the aramid fibers, leaving a permanent stain and potential insulation resistance problem.

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TABLE 3.4

Typical Properties of Polyimide and Aramid Films

Property	Min/ Max	Units	Requirements Polyimide	Aramid
Tensile strength[a]		psi	20.02 E+3	—
		(Pa)	(13.8 E+7)	—
Tensile strength[b]		psi	23.93 E+3	—
		(Pa)	(16.5 E+7)	—
Tensile strength		psi	—	4.003 E+3
		(Pa)	—	(27.6 E+6)
Elongation	Min	%	25	4
Initiation Tear strength[a]	Min	oz (g)	3.527 (100)	—
Initiation Tear strength[b]			17.64 (500)	—
Propagation Tear Strength[a]	Min	oz (g)	0.035 (1)	
Propagation Tear Strength[b]			0.141 (4)	—
Propagation tear strength[c]			0.529 (15)	—
Propagation tear strength[d]			0.882 (25)	
Propagation tear strength[e]			—	1.76 (50)
Propagation tear strength[f]			—	2.47 (70)
Dimensional stability[a]	Max	%	0.1	
Chemical resistance				
Tensile strength[a]	Min	psi	20.02 E+7	—
		(Pa)	(13.8 E+7)	—
Tensile strength[b]		psi	23.93 E+3	—
		(Pa)	(16.5 E+3)	—
		psi	—	4.003 E+3
		(Pa)	—	(27.6 E+6)
Elongation	Min	%	25	4
Dielectric constant	Max	1 MHz	4	3
Dissipation factor	Max	60 Hz	0.003	—
		1MHz	0.012	0.013
Volume resistivity	Min	megohm-cm	$\times 10^6$	$\times 10^6$
Surface resistivity	Min	megohm	$\times 10^5$	$\times 10^6$
Dielectric strength	Min	volts/mil	2,500	400
Moisture absorption	Max	percent	3.9	13
Fungus resistance	—	—	Non-nutrient	Non-nutrient
Relative temperature index	Min	UL746B	200	220
Flammability	Min	UL 94	VTM-O	V-O

[a] Flexible base dielectric materials with thickness < 0.984 mil (<0.025 mm).
[b] Flexible base dielectric materials with thickness > 0.984 mil (>0.025 mm).
[c] Flexible base dielectric materials with 0.984 mil < thickness < 1.97 mil (0.025 mm < thickness < 0.050 mm).
[d] Flexible base dielectric materials with 1.97 mil < thickness < 4.016 mil (0.050 mm < thickness < 0.102 mm).
[e] Flexible base dielectric materials with thickness > 4.016 mil (>0.102 mm).
[f] Flexible base dielectric materials with thickness <1.97 mil (<0.050 mm).
[g] Flexible base dielectric materials with thickness >1.97 mil (>0.050 mm).

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Aramids have many desirable properties and are inexpensive, but their shortcomings make them difficult to use in volume flex applications. Typical properties of aramid film are shown in Table 3.4.

3.2 Adhesives

Adhesives are the weakest link in flexible printed wiring laminate, but something must hold the structure together. Adhesives largely determine flexible printed wiring boards' electrical, thermal, and chemical performance and are a critical factor in controlled impedance circuitry, as the adhesive is the dielectric that surrounds the conductive layer and, in a typical construction, contributes up to 50% (or more) of the thickness. The dielectric films that are used classify the temperature rating of the flexible printed wiring (polyimide, polyester, etc.), but it is the adhesive that dominates the performance. Because the adhesive surrounds the conductor, it is the primary insulation in flexible printed wiring that determines the electrical properties such as volume and surface resistivity, Dk, and Df. The dielectric films' properties are secondary. The properties of the adhesive determine the following:

- Most adhesives support combustion unless they are formulated to include flame suppressors.
- Adhesives are the controlling factor in critical conditions such as elevated temperatures.
- Bond strength is an adhesive property. Selection of the proper adhesive can prevent assembly damage especially during soldering and termination.
- Chemical resistance is also an adhesive effect.

The function of adhesives in flexible circuits is to bond cover layers or copper foils to the dielectric substrate and, in multilayer flexes, to bond the inner layers together. A flexible laminate's performance depends on the combination of properties from the adhesive and supporting dielectric film. Adhesives such as acrylic, polyimide, epoxy, modified polyester, and butyl phenolics have been used with varying degrees of success.

There are two mechanical properties to consider in selecting an adhesive system: tensile strength and elongation. A high tensile strength suggests good mechanical stability and resistance to handling stresses of repeated connecting and disconnecting. A high elongation suggests the ability to

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flex repeatedly and move easily. However, these two properties tend to oppose each other. A laminate with high tensile strength will have a low elongation, resulting in a stiffer substrate without the capability of dynamic flexing. A laminate with high elongation would be excellent for dynamic flexing but may not be mechanically durable.

3.2.1 Types and Use of Adhesive

Flexible printed wiring adhesives are used in several forms:

- Base and cover coat are identical in composition if not in thickness. Consists of a single-sided adhesive coating on a dielectric film and together form the dielectric system of a single-sided flexible printed wiring.
- Bond-ply and cast-film adhesives are used to join layers of flexible printed wiring together to form a multilayer structure. Bond plies provide a cast adhesive film that allows for a thinner construction.
- Dielectric barrier between facing etched circuits, acting as a cover coat for both.

Adhesive coatings must be as tack-free as possible so as to minimize foreign material pickup and also to allow for ease of registration and alignment of cover coat and bond plies for lamination.

- Cast films 0.001 to 0.002 in. (0.025 to 0.05 mm) thick must be sufficiently cohesive (while not brittle) to be lifted from the carrier and positioned in a layup without distortion. Most cast films are limp and weak, making accurate alignment of drilled or punched holes with an etched pattern extremely difficult and labor-intensive.
- Coatings must have low residual volatile content (less than 1%) to minimize lamination voids and poor adhesion.
- Cured adhesive must be resistant to attack by processing chemicals; as a conflicting requirement, drilling residue must be removed from pad edges for the plated-through-hole process.
- Because they are all thermosetting to some degree, it is a good practice to protect them from elevated temperature; refrigeration or freezer storage is preferred. Complete cure in a reasonable time at moderate temperatures aids production.
- All have a limited shelf life and must be monitored to ensure freshness and expected performance.

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3.2.2 Coating Process (Adhesive)

Flexible printed wiring adhesives are produced from solutions of solvents, polymers, and curing agents. This mixture is then machine-coated on one or both sides of a substrate to form a base, a cover layer, or a bond ply. The solvent is removed in a drying oven, leaving a tack-free coating that is protected by the release film. The release film is introduced at the last rewind stage and remains on the adhesive coating until layup. Prior to drilling, the release film may be removed to release any stresses that may affect dimensions. The sheet is then put back on the substrate after the drilling operations. Stripping off this film creates a large static charge, which contributes to foreign material buildup.

3.2.2.1 Major Adhesive Types

There are five major types of adhesives that can be used to make a flexible circuit.

3.2.2.1.1 Epoxy Adhesive

Epoxy resins have good high-temperature property retention and remain in good condition after soldering. They also have good long-term stability at elevated temperatures in environmental conditions up to 250°F (121°C). Physical properties of epoxy adhesive are shown in Table 3.5.

3.2.2.1.2 Polyester Adhesive

The only material that should be used as an adhesive for polyester base laminates and cover film is the polyester adhesive. The major drawback to this adhesive is its low heat resistance. Polyester adhesives have excellent electrical properties and flexibility but only a fair resistance to heat. If required, the heat resistance can be improved by partial cross-linking. Physical properties of the polyester adhesive are shown in Table 3.5.

3.2.2.1.3 Acrylic Adhesive

The acrylic adhesives are most often used when the completed circuits are subjected to high soldering temperature. They offer the best heat to short-term high heat exposure. They also have good electrical properties and have been used successfully on polyimide film substrates for many years. The modulus of the polyimide/acrylic laminate has made it the preferred choice for dynamic flex applications. However, due to the acrylic adhesive thickness and high *z*-axis expansion, this combination is finding less and less interest among flex users. Some of the problems that the fabricators and users have encountered are as follows:

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TABLE 3.5

Typical Properties of Adhesives

Property	Min/ Max	Units	Epoxy	Polyester	Polyimide	Acrylic
Peel strength[a]	Min	lb/in.				
as received		(N/m)				
as received[b]			3.997 (700)	2.501 (438)	—	3.997 (700)
as received[c]			7.9942 (1400)	4.996 (875)	6.2812 (1100	7.9942 (1400)
after solder float[b]			3.495 (612)	—		3.495 (612)
after solder float[c]			6.9949 (1225)	—	6.5667 (1150)	6.9949 (1225)
after solder float[b]			3.997 (700)	2.501 (438)	—	3.997 (700)
after temp. cycling[c]			7.9942 (1400)	4.996 (438)	7.1377 (1250)	7.9942 (1400)
Flow	Min		5:01	10:01	8:01	5:01
Volatile content	Max	%	4	1.5	0.2	4
Dimensional stability	Max	%	—	1	—	—
Solder float			Pass	—	Pass	Pass
Chemical resistance	Min	%	80	90	85	80
Dielectric constant	Max	1 MHz	4	4.6	3.5	4
Dissipation factor	Max	1 MHz	0.06	0.13	0.02	0.05
Volume resistivity	Min	1 MHz	$\times 10^6$	$\times 10^6$	$\times 10^7$	$\times 10^6$
Surface resistivity	Min	megohms	$\times 10^4$	$\times 10^4$	$\times 10^6$	$\times 10^5$
Dielectric strength	Min	volts/mil	500	1,000	3,000	1,000
Moisture and insulation resistance	Min	megohms	$\times 10^3$	$\times 10^4$	$\times 10^3$	—
Moisture absorption	Max	%	4	2	1	6
Fungus resistance			Non-nutrient	Non-nutrient	Non-nutrient	Non-nutrient

[a] Represents values for peel with bonding to treated side of copper. Values are half when bonding to untreated surfaces.
[b] Adhesive thickness < 0.984 mil (<0.025 mm).
[c] Adhesive thickness > 0.984 mil (>0.025 mm).

- They are vulnerable to attack by some solvents in the photoresist process.
- They are vulnerable to attack by some alkaline solutions that are used in the plating and etching process.
- Absorbed solvents are especially difficult to remove prior to multilayer lamination. Delamination or blistering can occur if these volatiles are not removed.

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- In high-density design, dimensional stability and small hole drilling problems (drill smear) can decrease yields.
- Plasma desmearing that is used to clean out small drilled holes will show higher etchback rates for the acrylic adhesive than for the polyimide film. If not controlled, plated-through-hole failures may occur.

Physical properties of acrylic adhesives are shown in Table 3.5.

3.2.2.1.4 Polyimide Adhesive

Polyimide films can be coated with a polyimide adhesive. Polyimide adhesives' chemical resistance and electrical properties are at least as good as or better than the acrylic adhesive. Additionally, they offer better heat resistance than any other flexible system due to the resins' cross-linking during cure. The reduced dynamic flexing ability of the polyimide adhesive is not a serious limitation, as the majority of flexible circuits produced are used in static flexing applications. The trade-off for this increased laminate stiffness is better dimensional stability, better processability, and lower overall adhesive thickness. Physical properties of polyimide adhesive are given in Table 3.5.

3.2.2.1.5 Butyl Phenolic

Butyl phenolics are more heat-resistant than polyester adhesive, but their electrical properties are not as good or as flexible. The addition of additives to the butyl phenolic adhesive can increase its flexibility.

3.2.3 Adhesiveless Systems

Traditionally, plastic films laminated with a metal foil have been utilized for the manufacturing of flexible printed wiring laminates. Metal-clad laminates prepared from a heat-resistant polyimide film, using a variety of adhesives (e.g., acrylic, epoxy, polyesters), have been the most commonly used materials. These films are generally chosen as the dielectric substrate because of their high temperature stability, good dielectric behavior, and properties. The nonpolyimide adhesive that bonds the substrate and conductor together is often the weakest link in the system. Because of the poor thermal stability and higher CTE, they often fail at the bondline either during fabrication or during the assembly process.

Over the years, researchers have come up with several improved adhesive systems but have not provided a satisfactory solution to the functional issues. The latest approach to this problem was to develop an adhesiveless system made with polyimide film and metal that is devoid

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of any adhesive. This results in an adhesiveless clad laminate that is thinner due to the absence of one or two mils of adhesive required to adhere the copper foil to the dielectric film. Adhesiveless copper-clad laminates offer improved operating characteristics for single- and double-sided circuits as well as rigid flex and multilayer boards. In the adhesiveless clad copper laminates, the copper is bonded to the polyimide film without the aid of an adhesive. Compared to adhesive-based laminates, adhesiveless laminates provide a thinner circuit, greater flexibility, and better thermal conductivity. Additionally, the thermal stress performance of the higher-layer-count rigid flex is significantly better.

Adhesiveless laminates can be characterized into four manufacturing technologies.

3.2.3.1 Cast to Foil

Cast to foil involves casting a liquid solution of polyamic acid onto the surface of a metal foil. The entire composition is then heated to a temperature that will evaporate the solvent and imidize the polyamic acid. This process forms a polyimide or polyamide-modified polyimide film. Cast to foil is an efficient method of producing single-sided laminates. However, producing a double-sided laminate requires an additional step. In this step, thermal compression is used to bond two single-sided cast laminates together with a compatible adhesive. Although the adhesion of the copper to the film is good, this process is limited to copper foils 1 oz (28.349 g) or greater. Cast-to-foil laminates with the thinner copper (less than 1 oz [28.349 g]) is much more difficult to handle. It also creates a problem in processing the laminate in such processes as drilling and routing. These problems are the result of the high temperatures involved in making the cast-to-foil laminate.

3.2.3.2 Vapor Deposition on Film

In the vapor deposition on film method, copper is vaporized in a vacuum chamber, causing the metal vapors to be deposited on the film. A surface treatment on the film enhances copper adhesion. It is a relatively fast process usually limited to a copper thickness of about 0.2 µm. Additional copper thickness can be achieved through electrolytic plating.

3.2.3.3 Direct Vapor/Sputter Metallization onto Polyimide Film

The sputtering method involves placing the film in a large vacuum chamber that has a copper cathode. The cathode is bombarded with positive ions, causing small charged particles to be deposited on the film. This results in an ultrathin copper coating, which must be followed by a

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buildup of electrolytic copper plating. The copper adhesion is not as good as the cast or plated method, nor does the dimensional stability compare favorably with the adhesive-based materials. A base coating of either chrome or nickel must be applied prior to performing the sputter process. It is also a slow process compared to the vapor deposition method.

3.2.3.4 Plated on Film

The process begins with a surface treatment to the roll of film, followed by an ultrathin coating of a barrier metal to promote good copper adhesion. The copper is then continuously plated onto the barrier metal to a desired thickness. The electrodeposited copper thickness can be controlled to provide very thin copper foils. When compared to other adhesiveless laminates, plated to film does not induce thermal stresses due to its low processing temperature.

3.2.4 Adhesiveless Properties

An important feature of adhesiveless circuits is their ability to maintain a uniform thickness. Copper conductors will not deform into the base film due to the film's high Tg. In contrast, conductors are set into an adhesive in a relatively uncontrolled manner.

Adhesiveless technology offers certain electrical advantages that are not instantly obvious. This results from a range of thinner conductive coatings that are typically available. Thinner coatings are possible because adhesiveless materials are metallized using the roll processing technique. Time is a major controlling factor for metal thickness, so creating a thinner foil can be as simple as increasing roll speed or reducing amperage to the plating rectifier.

3.2.4.1 Electrical Advantage

From an electrical standpoint, thinner conductive coatings offer greater latitude to the electrical engineer who is designing controlled impedance boards. Consider a micro-strip or stripline design with adhesiveless material: the dielectric spacing is reduced, which usually necessitates a narrower conductor to achieve the desired impedance factor. This may make the design less producible and subsequently cost-prohibitive, but with the option of using 0.25 oz copper (6.687 g; 0.5 oz [5.27 g] finished), the cross-sectional area of the conductor can be reduced by 50% without impacting the line width. This coupled with a lower Dk allows for higher impedance values without seriously affecting the image or etch yields. A beneficial side effect of using adhesiveless materials for controlled impedance

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boards is a narrowing of the impedance range as noted on the time domain reflectometer (TDR). Acrylic adhesive has a tendency to allow embossing (conductor settling into the adhesive); this can result in a variation in dielectric separation, which is somewhat determined by the density of the conductive pattern. This is seen on the TDR curve as a greater delta (tolerance) between the minimum and maximum of impedance values.

3.2.4.2 Mechanical Advantage

A reduction in the dielectric spacing, which is typically one half that of traditional acrylic-based materials, means that the metal foil layers are significantly closer to the neutral axis and therefore subjected to less stress and straining during flexing. This is especially important during dynamic (continual) flexing applications where increased life performance and reliability can be achieved.

3.2.4.3 Thermal Advantage

In high-layer-count multilayer and rigid flex applications, the advantages are well-known. Acrylic adhesive with a *z*-axis CTE of 500 to 600 ppm/°C and a Tg of 30 to 40°C is the known weak link from a reliability standpoint. The more acrylic adhesive in the construction, the greater the chance of barrel cracking or pad lifting either during thermal cycling or during soldering. By using adhesiveless inner layers with polyimide cap layers, a high reliability (all-polyimide construction) rigid flex capable of 20 plus layers can be produced without plated-through-hole reliability problems.

These constructions are excellent for military/aerospace and other high-reliability applications, but material costs could be prohibitive for commercial applications. By removing the adhesive layer, the thermal dissipation characteristics are improved by a factor of two (due to the reduction in thickness) and the resulting laminates are inexpensive, but their shortcomings make them difficult to use in volume flex applications. Properties of some adhesiveless laminates are given in Table 3.6.

3.3 Cover Coat/Cover Layer

The etched conductive traces on the flexible circuits are usually protected from damage (either mechanical or environmental) by covering these traces with a protective film. These materials are generally the same polymer as the base material. The cover coat serves five distinct purposes:

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TABLE 3.6

Typical Properties of Some Adhesiveless Laminates

Type Property	Min/ Max	Units	Copper-Clad Adhesiveless Polyimide Requirements	Deposited Copper-Clad Adhesiveless Polyimide Requirements
Dimensional stability	Max	%	0.2	0.15
Peel strength	Min	lb/in. (N/m)		
as received[a]			2.998 (525)	2.998 (525)
as received[b]			5.9957 (1050)	5.9957 (1050
after solder float[a]			2.998 (5250	2.501 (438)
after solder float[b]			5.9957 (1050)	3.9997 (700)
after temp. cycling[a]			2.998 (525)	2.501 (438)
after temp. cycling[b]			5.9957 (1050)	3.997 (700)
Initiation tear strength[c]	Min	oz (g)	3.527 (100)	3.527 (100)
Initiation tear strength[d]			17.64 (500)	—
Propagation tear strength[c]	Min	lb/in. (N/m)	0.035 (1)	0.035 (1)
Propagation tear strength[d]			0.014 (4)	0.14 (4)
Propagation tear strength[a]			0.529 (15)	0.529 (15)
Propagation tear strength[b]			0.882 (25)	0.882 (25)
Flexural endurance[e]	Min	cycle	1000	1000
Low-temp. flexibility		5 cycles	Pass	—
Chemical resistance	Min	%	80	80
Solder float			Pass	Pass
Solderability			Pass	Pass
Dielectric constant	Max	1 MHz	4	4
Dissipation factor	Max	1 MHz	0.01	0.012
Volume resistivity	Min	megohm-cm	$\times 10^6$	$\times 10^6$
Surface resistance	Min	megohm	$\times 10^5$	$\times 10^5$
Dielectric strength	Min	V/mil	2000	2000
Fungus resistance			Non-nutrient	Non-nutrient
Moisture absorption	Max	%	3	4
Moisture and insulation resistance	Min	megohm	$\times 10^3$	$\times 10^2$

[a] Flexible metal-clad dielectric materials with the following thickness: metal < 1.38 mil (0.035 mm), base < 0.984 mil (<0.025 mm), adhesive thickness < 0.984 (<0.025 mm).
[b] Flexible metal-clad dielectric materials with the following thickness: metal > 1.38 mil (>0.035 mm), base > 0.984 mil (>0.025 mm), adhesive thickness > 0.984 mil (>0.025 mm).
[c] Flexible metal-clad dielectric materials with thickness < 0.984 mil (0.025 mm).
[d] Flexible metal-clad dielectric materials with 0.984 mil < thickness < 1.97 mil (0.025 mm < thickness < 0.050 mm).
[e] Flexible metal-clad dielectric materials with thickness < 1.97mil (<0.050 mm).

- It protects the conductors against the environment.
- It defines the solder coating areas for component assembly.
- It affords protection against mechanical damage that might occur if a moving flexible circuit touches another part of the equipment.

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- It puts the copper on a single-sided flexible circuit on the neutral bending axis.
- It helps to anchor the terminal pads to the base film.

Repeated bending of an unclad flexible circuit will impose stresses on the copper conductor. The addition of the cover coat of equal thickness to the base material will balance the build and significantly increase the flexing life of the circuit. Cover coat materials can be either a liquid or film product that is applied over the etched pattern to insulate it against unintended contact or to limit the flow of solder during the soldering operation. This is similar to solder masks in rigid printed wiring boards; cover coats provide a well-defined termination area.

The adhesive is mandatory for building a multilayer flexible printed wiring board and is likewise unavoidable in the use of cover layers and laminated metal clads. Although their presence is largely overlooked, flexible printed wiring conductors are surrounded by adhesives, and the adhesive, not the dielectric, is the primary dielectric in the flexible printed wiring system. The dielectric film and the adhesive form the dielectric system for the flexible printed wiring and neither performs well without the other. Flexible printed wiring boards with thick dielectric films will not survive solder attachment if the adhesive that holds the conductors in place melts.

3.4 Bond Plies

Bond plies are like double-sided adhesive tape. A bond ply is a cover layer with an adhesive on both sides and could be used as a cover layer or as a joiner in multilayer stack-ups, bonding stiffeners, or heat sinks onto flexible printed wiring. This material is simply a layer of adhesive on a release sheet that can be cut into any shape or size, lifted from the release paper, and inserted into the stack-up. Properties of the various bond plies are shown in Table 3.7.

3.5 Conductive Materials

Copper foil is far and away the leading choice of conductor material for flexible printed wiring boards. Although aluminum is superior in conductivity, it is chemically more active and therefore presents corrosion problems when joined to other metals. Copper is the standard material for conductivity and current-carrying capacity. It is easily etched to create

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TABLE 3.7

Typical Properties of Various Bond Plies

Property	Min/ Max	Units	Requirements			
			Epoxy	Acrylic	Polyester	Polyimide
Peel strength	Min					
as received		lb/in. (N/m)	8.0 (1400)	8 (1400)	5 (875)	6 (1100)
after solder float		lb/in. (N/m)	7.0 (1225)	7.0 (1225)	—	6 (1150)
after temp. cycling		lb/in. (N/m)	8.0 (1400)	8.0 (1400)	5.0 (875)	7.0 (1250)
Flow	Max		<5:1	<5:1	<10:1	<5:1
Volatile content	Max	%	2	2	1.5	—
Dimensional stability	Max	%	0.15	—	—	0.2
Solder float			Pass	Pass	—	Pass
Chemical resistance	Min	%	80	80	90	85
Dielectric constant	Max	1 MHz	4	3	3	3.4
Dissipation factor	Max	1 MHz	0.04	0.05	0.13	0.02
Coefficient of thermal expansion		ppm/°C	100–200	400–600	100–200	220–260
Tg		°F	194-329	86–104	194–230	428–500
		°C	90–165	30–40	90–110	220–260
Volume resistivity	Min	megohm-cm	$\times 10^6$	$\times 10^6$	$\times 10^6$	$\times 10^7$
Surface resistance	Min	megohm	$\times 10^4$	$\times 10^5$	$\times 10^5$	$\times 10^6$
Dielectric strength	Min	volts/mil	750	1,000	1,000	2,500
Moisture and insulation resistance	Min	megohm	$\times 10^6$	—	$\times 10^4$	$\times 10^3$
Moisture absorption	Max	%	<4	<6	<2	<1
Fungus resistance			Non-nutrient	Non-nutrient	Non-nutrient	Non-nutrient

high-density patterns and can be deposited from solutions in multilayer or three-dimensional circuitry manufacturing processes.

3.5.1 Electrodeposited Copper

The electrodeposited (ED) copper process starts from an ionic solution and builds foil at a high deposition rate on a steel drum. The thickness of the foil is dependent on both the current density and the time in the plating tank. After the required foil thickness is obtained, the foil is removed from the drum as one continuous coil. It produces foil that is very smooth and shiny on one surface (called "drum side"), whereas the outside or dull side of the foil has a "tooth" that provides a very good surface for adhesion. The grain structure of ED copper has a vertical orientation and high yield and tensile strength. The vertical grain structure provides smooth, even etching properties as to aid in the production of narrow conductor runs on close centers. Because of their inherently rough surfaces, conventional ED copper foils bond very well to the flexible dielectric film, where their flexural properties are irrelevant. ED copper is basically

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used in commercial industries (automotive, etc.) where repeated flexing is not a requirement. See Chapter 4 for more details on ED copper.

Modern electrodeposition technology has altered the logic for choosing rolled annealed foils for flexible printed circuitry. Through careful adjustments of current density and bath chemistries and by the use of unique equipment, high-quality ED foils can be produced that have competitive, if not superior, properties compared with rolled annealed copper foils.

3.5.2 Rolled Annealed Copper (RA)

Rolled foils are different in every way from ED copper. This foil is very flexible and should be used in dynamic applications that require constant flexing. RA copper is manufactured by melting the cathode copper (which is produced electrolytically) and then formed into large ingots. This direct chill casting method allows for controlled solidification that provides continuous purity, monitoring, and grain size selection and also eliminates existing defects such as voids that would influence the quality of the foil when it is rolled into the final form. Because this process starts with copper ingots and has longer production cycles with incremental approaches to the final thickness, rolling results in a foil with horizontal grain orientation and smooth surfaces on both sides. Roll reduction quickly causes work hardening, with the result that rolled foils must be periodically annealed. They are sold in several degrees of hardness from "as rolled" to dead "soft." Rolled annealed is the standard anneal condition that provides good flexural endurance and resistance to fracturing in dynamic use, which is typical of flexible printed wiring boards.

Because of the brittleness of the early ED foils, it has long been customary to use RA foils for flexible printed wiring boards. RA metallurgy provides good flexural endurance but is also complicated as a result of handling during manufacturing because it is soft and easily distorted. An alternative form of rolled foil that offers better handling and flexural properties is a version called low-temperature anneal (LTA) foil. LTA foils are sold with high levels of residual rolling stresses (the grain structure has an unusual elongation). High residual stress means quicker annealing when the foil is heated. (See Chapter 4 for more details.)

3.6 Copper-Clad Laminates

Up to now we have discussed the various properties of materials that go into making a flexible laminate. Listed on pages 60–62 (Table 3.8 to Table 3.10) are the properties of the copper-clad laminates. The properties listed in these tables are for the most commonly used films and adhesives.

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TABLE 3.8

Typical Properties of Copper-Clad Dielectric Films (Polyimide)

			Requirements		
Property	**Min/ Max**	**Units**	**Polyimide/ Butyral Phenolic**	**Polyimide/ Acrylic**	**Polyimide/ Epoxy**
Peel strength	Min	lb/in. (N/m)			
as received[a]			1.999 (350)	3.997 (700)	3.997 (700)
as received[b]			3.997 (700)	7.994 (1400)	7.994 (1400)
after solder float[a]			1.496 (262)	3.495 (612)	2.998 ((525)
after solder float[b]			3.495 (612)	6.9949 (1225)	6.9949 (1225)
after temp. cycling[a]			1.999 (350)	3.997(700)	3.997(700)
after temp. cycling[b]			3.997 (700)	7.9942 (1400)	7.994 (1400)
Initiation tear strength[c]	Min	oz(g)	3.527 (100)	3.527 (100)	3.527 (100)
Initiation tear strength[d]			17.64 (500)	17.64 (500)	17.64 (500)
Propagation tear strength[c]	Min	oz(g)	0.035 (1)	0.035 (1)	0.035 (1)
Propagation tear strength[e]			0.14 (4)	0.423 (12)	0.423 (12)
Propagation tear strength[a]			0.529 (15)	0.529 (15)	0.529 (15)
Propagation tear strength[b]			0.882 (25)	0.882 (25)	0.882 (25)
Flexural endurance	Min	cycle	1000	1000	1000
Low-temp. flexibility		5 cycle	Pass	Pass	Pass
Dimensional stability	Max	percent	—	0.15	0.15
Solder float			Pass	Pass	Pass
Chemical resistance	Min	percent	80	80	80
Dielectric constant	Max	1 MHz	4	4	4
Dissipation factor	Max	1 MHz	0.03	0.04	0.04
Volume resistivity	Min	megohm-cm	$\times 10^5$	$\times 10^6$	$\times 10^6$
Surface resistance	Min	megohms	$\times 10^5$	$\times 10^5$	$\times 10^5$
Dielectric strength	Min	volts/mil	1199	2000	2000
Moisture and insulation resistance	Min	megohm	$\times 10^3$	$\times 10^2$	$\times 10^3$
Moisture absorption	Max	percent	4	4	4
Fungus resistance			Non-nutrient	Non-nutrient	Non-nutrient

[a] Flexible metal-clad dielectric materials with the following thickness: metal < 1.38 mmil (<0.035 mm), base < 0.984 mil (0.025 mm), adhesive < 0.984 mil (<0.025 mm).

[b] Flexible metal-clad dielectric materials with the following thickness: metal > 1.38 mil (>0.035 mm), base > 0.984 mil (>0.025 mm), adhesive > 0.984 mil (0.025 mm).

[c] Flexible metal-clad dielectric materials with thickness < 0.984 mil (<0.025 mm).

[d] Flexible metal-clad dielectric materials with thickness > 0.984 mil (0.025 mm).

[e] Flexible metal-clad dielectric materials with 0.984 mil < thickness < 1.97 mil (0.025 mm < thickness < 0.050 mm).

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TABLE 3.9

Copper-Clad Dielectric Films (Polyethylene Terephthalate and Polyethylene Naphthalate)

			Requirements	
Property	**Min/ Max**	**Units**	**Polyethylene Terephthalate/ Polyester**	**Polyethylene Naphthalate/ Modified Epoxy**
Peel strength	Min	lb/in. (N/m)		
as received[a]		width	3.997 (700)	1.999 (350)
as received[b]			4.996 (875)	3.997 (700)
after solder float[a]			—	—
after solder float[b]			—	—
after temp. cycle[a]			3.997 (700)	1.999 (350)
after temp. cycle[b]			3.997 (700)	3.997 (700)
Dimensional stability	Max	percent	0.3	0.3
Initiation tear strength	Min	oz (g)	28.22 (800)	35.270 (1000)
Propagation tear strength[c]		oz (g)	0.353 (10)	20
Propagation tear strength[d]			0.705 (20)	
Propagation tear strength[b]			1.760 (50)	
Flexural endurance[e]	Min	cycle	1,000	—
Low-temp. flexibility		5 cycles	Pass	—
Chemical resistance	Min	percent	80	70
Solder float			Pass	—
Solderability			Pass	pass
Dielectric constant	Max	1 MHz	4	3.5
Dissipation factor	Max	1 MHz	0.02	0.02
Volume resistivity	Min	megohm-cm	x106	x107
Surface resistance	Min	megohm	x104	x105
Dielectric strength	Min	V/mil	2500	2000
Fungus resistance			Non-nutrient	Non-nutrient
Moisture absorption	Max	percent	2	2
Moisture and insulation resistance	Min	megohm	x104	x104

[a] Flexible metal-clad dielectric materials with the following thickness: metal < 1.38 mil (0.035 mm), base < 0.984 mil (0.025 mm), adhesive < 0.984 (0.025 mm).

[b] Flexible metal-clad dielectric materials with the following thickness: metal > 1.38 mil (>0.035 mm), base > 0.984 mil (>0.025 mm), adhesive > 0.984 mil (>0.025 mm).

[c] Flexible metal-clad dielectric material with thickness < 1.50 mil (<0.038 mm).

[d] Flexible metal-clad dielectric materials with 1.50 mil < thickness < 4.016 mil (0.038 mm < thickness < 0.0102 mm).

[e] Flexible metal-clad dielectric materials with thickness < 1.97 mil (0.050 mm).

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TABLE 3.10

Typical Properties of Fluorocarbon and Aramid Laminates

			Requirements		
Property	**Min/ Max**	**Units**	**Fluorocarbon/ Acrylic**	**Fluorocarbon/ Epoxy**	**Aramid/ Fluorocarbon**
Dimensional stability	Max	percent	1	1	
Peel strength					
as received[a]			—	3.997 (700)	3.997 (700)
as received[b]			2.495 (437)	7.9942 (1400)	7.942 (1400)
after solder float[a]			—	2.998 (525)	2.998 (525)
after solder float[b]			1.999 (350)	6.9949 (1225)	6.9949 (1225)
after temp. cycling[a]				3.997 (700)	—
after temp. cycling[b]			2.495 (437)	7.9942 (1400)	—
Propagation tear strength[c]	Min	oz (g)	2.65 (75)	2.65 (75)	3.17 (90)
Propagation tear strength[d]			3.17 (90)	3.17 (90)	—
Flexural endurance[e]	Min	cycle	1000	1000	400
Low-temp. flexibility		5 cycles	Pass	Pass	pass
Chemical resistance	Min	percent	80	80	90
Solder float			Pass	Pass	pass
Solderability			Pass	Pass	pass
Dielectric constant	Max	1 MHz	3	3	2.3
Dissipation factor	Max	1 MHz	0.025	0.025	0.004
Volume resistivity	Min	megohm-cm	x106	x106	x109
Surface resistance	Min	megohm	X105	x104	x108
Dielectric strength	Min	V/mil	2000	2000	1500
Fungus resistance			Non-nutrient	Non-nutrient	Non-nutrient
Moisture absorption	Max	percent	4	4	0.5
Moisture and insulation resistance	Min	megohm	x103	x103	x107

[a] Flexible metal-clad dielectric materials with the following thickness: metal < 1.38 mil (<0.035 mm), base < 0.984 mil (0.025 mm), adhesive < 0.984 mil (<0.025 mm).

[b] Flexible metal-clad dielectric materials with the following thickness: metal > 1.38 mil (>0.35 mm), base > 0.984 mil (0.025 mm), adhesive > 0.984 mil (>0.025 mm).

[c] Flexible metal-clad dielectric materials with thickness < 1.50 mil (0.038 mm).

[d] Flexible metal-clad dielectric materials with thickness > 1.50 mil (0.038 mm).

[e] Flexible metal-clad dielectric materials with thickness < 1.97 mil (<0.050 mm).

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References

Combs, C., *Printed Circuit Handbook,* 4th ed., McGraw-Hill.

Dean, S.E., Flexible Circuits Dielectric Base Materials Option, IPC Technical Meeting, 1995.

Dean, S.E., Flexible covercoating techniques, *IPC Tech Review,* 1995.

Gardeski, T., Polyethylene terephthalate (PET) and polyethylene naphthalate (PEN) films for printed circuitry applications, in *Printed Circuit Board Materials Handbook,* Jawitz, M., Ed., McGraw-Hill.

Holland, D.L., *Composite Dielectric Films for Flexible Printed Circuits.*

IPC-4202, Flexible Base Dielectric for Use in Flexible Printed Circuitry.

IPC-4203, Adhesive Coated Dielectric Films for Use as Coversheets for Flexible Printed Circuitry and Flexible Adhesive Bonding Film.

IPC-4204, Flexible Metal-Clad Dielectric for Use in Fabrication of Flexible Printed Circuitry.

Kanakarajan, L.K., *New Adhesiveless Substrate for Flexible Printed Circuits and Multichip Modules,* E.I. DuPont.

Pollack, H. and Jacques, R.C., Adhesiveless Laminates Improve Flex Performance.

Scarlette, T.C., *Introduction to Printed Circuit Board Technology.*

Stearns, T., Dielectrics influence circuit performance and laminate processing, *Electronic Processing and Packaging,* 1992.

Stearns, T., Flex materials: Part 2, *PC Fabrication,* Dec. 1998.

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4

Copper Foils

4.0 Introduction

The use of copper foils as a conductive material for either rigid or flexible printed wiring boards is well-known. Two types of foils in use today are either electrodeposited (ED) or wrought (sometimes called rolled annealed [RA]) copper foils. Specific foil properties and end user applications have led to a further categorization of these two types into grade classification (IPC-4562). Over the years, particular types and grades have been specific for consumer, commercial, or military markets. As a general rule, electrodeposited foils, identified as grades 1 to 4, are utilized on rigid boards (single, double, composite, and multilayer boards). Flexible circuitry, on the other hand, utilizes both electrodeposited and wrought copper foils (grades 2, 5–8) for their applications. Although the IPC lists grades 4, 6, 10, and 11, these foils are not readily available for commercial use.

4.1 Electrodeposited Copper Foil (also called ED foil)

The most widely used type of conductive material for printed wiring is electrodeposited copper foil. Copper plating by electrodeposition is theoretically quite simple. The process consists of a plating cell with a conforming anode, a cathode, and a chemical plating cell (Figure 4.1). The acid sulfate copper solution is pumped into the electroforming cell where the application of current between the anode and cathode causes copper ions from the plating cell to plate on the cathode surface. The cathode is a highly polished cylindrical drum that rotates partially submerged in the solution. As the drum enters the solution, copper begins to deposit on the surface of the drum and continues to plate until it exits the plating solution. Due to the copper's poor adhesion to the stainless steel drum, the copper can easily be peeled from the drum. The copper foil is stripped

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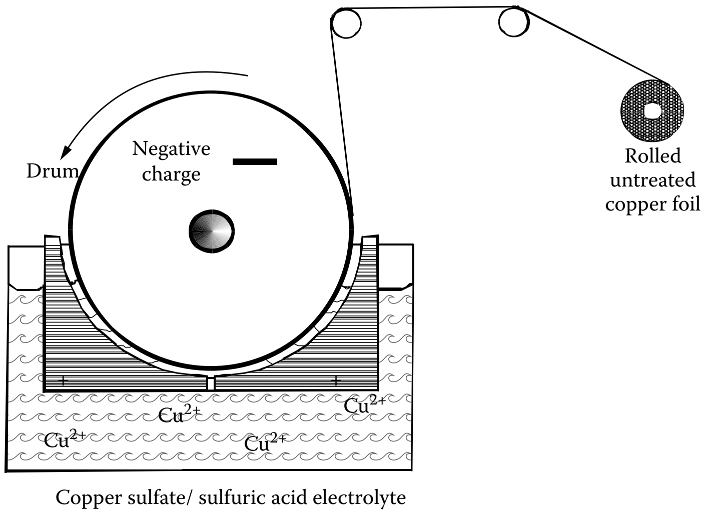

FIGURE 4.1
Plating cell for electroplated copper.

from the cathode as it continues to rotate and produce more foils. For practical purposes, the thickness of the foil is determined by the rotational speed of the drum and the current density. The anodes conform to the contour of the drum so that consistent plating takes place. This is important for thickness control both across and within the manufactured roll. Accuracies of ±5% are readily attainable in thickness required for circuit board applications.

The electrodeposited copper foils produced by this process usually are shiny on one side and have a matte finish on the reverse side. The smooth shiny side represents the initiation of the copper plating and the smoothness of the finish mirrors the drum's cathode surface. The matte side represents the copper grain growth (columnar grains or dendrites) of the process, which contributes a microscopically roughened structure (Figure 4.2) that aids in adhesion. The matte side is the side that is laminated or bonded to the dielectric materials.

Typically, foils produced by the electrodeposition process have a higher tensile strength than those manufactured by the rolling process. This is caused by the differences in the manufacturing process for the two types of foil. The annealing process associated with the rolled foil causes the foil to become ductile, which results in the foil having a reduced tensile strength. The physical properties of electrodeposited foils are given in Table 4.1.

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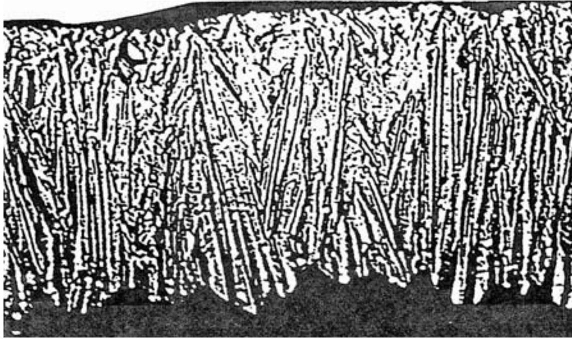

FIGURE 4.2
Electroplated copper with columnar grains.

4.2 Rolled Copper Foils (also called RA foil)

Rolled or wrought copper foils have been and still are basically used for flexible printed wiring boards. In comparison to electrodeposited foils, there are some advantages and disadvantages to the rolled copper foils. The disadvantage is that the equipment required to produce rolled foils is very cost-intensive and therefore there are very few suppliers. Also the width of the foils (mostly 24 in. [610 mm] wide) is constrained by the equipment, which often prohibits rolled copper usage by many laminators who have scaled their equipment to sizes common with electrodeposited foils (48 to 60 in. [1219 to 1524 mm]).

In the "as rolled" condition, the grains are distorted in the longitudinal direction and copper that is formed has a high tensile strength, is fairly hard, and has a relatively low elongation. Once the foil is annealed, the grains relax and reform into smaller grains that are relatively equiaxial (Figure 4.3). This product has a significantly lower tensile strength and hardness, and the elongation has been increased considerably.

The advantage of the rolled copper foils is that once they are either annealed or heat-treated, they are still the most ductile foils available. This advantage can be important for applications that require continuous flexing.

4.2.1 Fabricating Rolled Copper Foils

The fabrication process begins with a highly pure copper ingot. The purity of the ingot can be varied to conform to the end item copper chemical

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TABLE 4.1

Properties of Electrodeposited Copper Foils

Property	Units	Grades 1	2	3	4
Properties at 23°C					
Tensile strength					
1/2 oz	kpsi/	30 (207)	15 (103)	30 (207)	15 (103)
1 oz	(Mpa)	40 (276)	30 (207)	40 (276)	20 (138)
2 oz		40 (276)	30 (207)	40 (276)	25 (172)
Fatigue ductility					
1/2 oz	%	n/a	n/a	n/a	65
1 oz		n/a	n/a	n/a	65
2 oz		n/a	n/a	n/a	65
Elongation					
1/2 oz	%	2	5	2	5
1 oz		3	10	3	10
2 oz		3	15	3	20
Properties at 180°C					
Tensile strength					
1/2 oz	kpsi/	n/a	n/a	15 103	—
1 oz	(Mpa)	n/a	n/a	20 (138)	14 (97)
2 oz		n/a	n/a	20 (138)	22 (152)
Fatigue ductility					
1/2 oz	%	n/a	n/a	n/a	n/a
1 oz		n/a	n/a	n/a	n/a
2 oz		n/a	n/a	n/a	n/a
Elongation					
1/2 oz	%	n/a	n/a	2	—
1 oz		n/a	n/a	2	6
2 oz		n/a	n/a	3	11
IPC Designation — IPC-4562		/1 CU-E1	/2 CU-E2	/3 CU-E3	/4 CU-E4

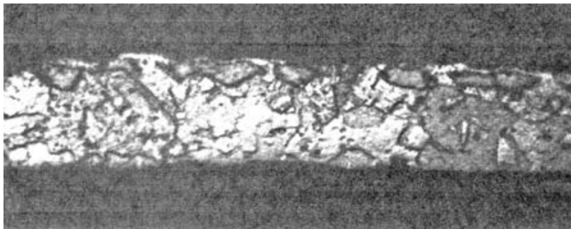

FIGURE 4.3
Rolled annealed foil with equiaxed grains.

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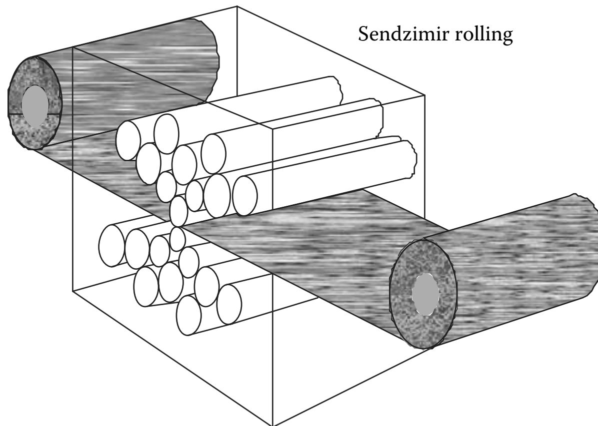

FIGURE 4.4
Rollling reduction process for copper foil.

composition requirements. The next step involves a series of ingot reductions, by passing the material many times between successively smaller and smaller gaps in the rolling mill (Figure 4.4) until it reaches the desired thickness. Both temperature and pressure are important in the reduction processes, as copper metal is work-hardened into certain metal characteristics. The resultant grain structure of rolled copper foil is different from that of electrodeposited foil. The structure of rolled copper foils is random or equiaxed grains (Figure 4.3), whereas electrodeposited foils are usually columnar (Figure 4.2). The grain structure, size, shape, and location are the major contributors to the foils' mechanical properties such as ductility and tensile strength. The physical properties of the rolled copper foils are given in Table 4.2.

4.2.2 Foil Treatment

4.2.2.1 Heat Treatment

One additional manufacturing step is available and it provides additional performance characteristics to both electrodeposited and rolled copper foils. Heat treatment or annealing of the copper foils changes the grain structure of the copper and, thus, the mechanical properties. By doing this (annealing), you can produce foils that are more ductile.

4.2.2.2 Foil Processing

Following base foil production, both wrought and electrodeposited foils are processed or treated through a serpentine machine (Figure 4.5). Purified

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TABLE 4.2

Properties of Wrought Copper Foils

Grades		Grades			
Property	**Units**	**5**	**6**	**7**	**8**
Properties at 23°C					
Tensile strength					
1/2/oz	kpsi/	50 (345)	—	15 (103)	15 (103)
1 oz	(Mpa)	50 (345)	25–50 (177–345)	20 (138)	20 (138)
2 oz		50 (345)	25–50 (177–345)	25 (172)	20 (138)
Ductility					
1/2 oz	%	30	—	65	25
1 oz		30	65–30	65	25
2 oz		30	65–30	65	25
Elongation					
1/2 oz	%	0.5	—	5	5
1 oz		0.5	10–0.5	10	10
2 oz		1	20–1	20	10
Properties at 180°C					
Tensile strength					
1/2 oz	Kpsi/	—	n/a	—	n/a
1 o/z	(Mpa)	20 138	n/a	14 (97)	n/a
2 oz		40 (276)	n/a	22 (152)	n/a
Elongation					
1/2 oz	%	—	n/a	—	n/a
1 oz		2	n/a	6	n/a
2 oz		3	n/a	11	n/a
IPC designation	IPC 4562	/5 CU-W5	/6 CU-W6	/7 CU-W7	/8 CU-W8

rinsing steps occur between each treatment stage. The treated foil can now adhere to a variety of adhesives or other dielectric materials. Typically there are three treatment stages: bonding, thermal barrier, and stabilization. These treatments are usually applied to the base copper foil and each has its own distinct purpose. The bonding treatment consists of a copper metal and copper oxide treatment, which increases the copper surface area for better wetting of the adhesive or resin.

Thermal barrier treatments, usually using either brass, zinc, or nickel, allow the adhesion of the clad laminate to be maintained in spite of the thermal processing conditions involved in PCB manufacturing. Most of the copper foils supplied to the flex market do not require this treatment. Thermal processing conditions for flex circuits are not as severe as those for conventional multilayer boards.

The foil stabilization treatment (sometimes called passivation or anti-oxidation) is applied on both sides of the copper to prevent oxidation and staining. Although all stabilization treatments are chrome-based, some

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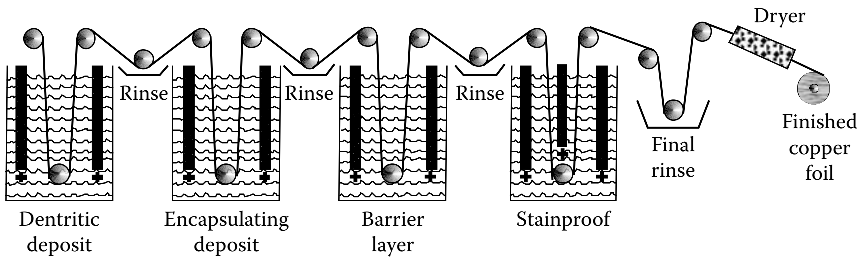

FIGURE 4.5
Copper foil processing final treatment.

manufacturers use nickel, zinc, and other metals in combination with the chrome.

4.3 Grades

Generally, electrodeposited foils identified as grades 1 to 4 are used for rigid printed wiring boards. Flexible circuits use both electrodeposited and wrought copper foils (grades 2, 5–8). The physical properties of grades 1 to 4 are shown in Table 4.1 and those for grades 5 to 8 are shown in Table 4.2. The properties for nickel foil are shown in Table 4.3.

The mechanical properties for all grades are given in Table 4.4 with foil weights and thickness given in Table 4.5.

4.3.1 Electrodeposited

4.3.1.1 Grade-1 or Standard Electrodeposited (STD-Type E)

Copper foils (grade 1) are basically used by laminate manufacturers in the United States for laminates that require heavier copper foils (>3 oz [65 g] by weight). This foil is often called "standard electrodeposited copper" and is still used in Asia for single- and double-sided rigid laminates.

4.3.1.2 Grade-2 or High-Ductility Electrodeposited Foils (HDE-Type E)

High-ductility copper is specifically used in the rigid and flexible laminate industry. The ductility of this grade of copper, at room temperature, allows the foil to be used for flex to install applications. The main users of grade-2 copper (as a flex material) are the consumer and automotive industries, which require lower cost and good flexibility for flex-to-install circuit boards. High-ductility copper is very cost-competitive to rolled copper

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TABLE 4.3
Foils

Property	Units	Grades 9	10	11
Properties at 23°C				
Tensile strength				
1/2 oz		n/a	15 (103)	40 (276)
1 oz	kpsi (Mpa)	80 (550)	20 (138)	40 (276)
2 oz		70/489	20 (138)	40 (276)
Fatigue ductility				
1/2 oz		n/a	25	n/a
1 oz	%	n/a	25	n/a
2 oz		n/a	25	n/a
Elongation				
1/2 oz		—	5	5
1 oz	%	4	10	10
2 oz		7	10	10
Properties at 180°C				
Tensile strength				
1/2 oz	kpsi/Mpa	n/a	n/a	20 (138)
1 oz		n/a	n/a	20 (138)
2 oz		n/a	n/a	20 (138)
Elongation				
1/2 oz		n/a	n/a	15
1 oz	%	n/a	n/a	20
2 oz		n/a	n/a	20
IPC designation	IPC-4562	/9 Ni/E1	/10 CU-E10	/11 CU-E11

foil if the intended application does not warrant the extreme ductility often required in continuous flexing applications. Compared with the wrought foils, the grade-2 copper foils are lower in cost, are higher in laminate copper peel strength, and retain columnar structure for superior etch characteristics.

4.3.1.3 Grade-3 or High-Temperature Elongation Foil (HTE-Type E)

By far the most common or popular grade of copper used in both rigid and thin laminate applications is grade-3 copper foil, also known as HTE. Most multilayer boards today utilize high-temperature elongation copper foils in their inner-layer construction. This is especially true of multilayer boards of six or more layers. This foil has a greater elongation at elevated temperature than the standard ED copper foil with typical values of 2 to 3% vs. 1.5% or less. This correlates to reduced cracking of inner-layer foils at the interface of the plated through hole during thermal cycling. Grade-3

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TABLE 4.4

Mechanical Properties of Copper Foils

	Copper Weight in oz/ft²				Copper Weight in g/m²		
	Grade	1/2	1	2 and over	157	305	610 and over
Foil Type	Minimum Tensile Strength (psi)				Minimum Tensile Strength (kg/mm²)		
E.D. standard		15,000	30,000	30,000	105,500	219,900	210,900
E.D. high ductility		15,000	30,000	30,000	105,500	210,900	210,900
Rolled, as rolled		50,000	50,000	50,000	352,000	352,000	352,000
Rolled, lt. cold rolled		—	—	32,000	—	—	225,000
Rolled, annealed		150,000	20,000	20,000	105,500	140,700	175,800
	Minimum Elongation (%) Based on 2 in. (50.8 mm) Gauge Length						
E.D. standard		2	3	3	2	3	3
E.D. high ductility		5	10	20	5	10	20
Rolled, lt. cold rolled		—	—	5	—	—	5
Rolled, annealed		10	10	20	10	10	20

foils may not always be necessary for polyimide multilayer boards (although most suppliers use them anyway). The primary source of innerlayer foil cracking is stresses caused by high *z*-axis expansion during thermal excursion, in processing, or during repair. The high Tg of polyimide (464 to 500°F [240 to 260°C]) greatly reduces the magnitude of these stresses because the total *z*-axis expansion at any given temperature range is less.

4.3.1.4 Grade-4 Annealed Electrodeposited or "Super High Duct" (ANN-Type E)

Although this grade is listed in IPC-4652, there is no known source to obtain this material.

4.3.2 Rolled Copper Foil

4.3.2.1 Grade-5 "As Rolled" Wrought Copper (AR-Type W)

Along with grade 8, this copper foil is used mainly in the production of flex laminates. Some of the physical properties change for the better during lamination, which makes this foil ideal for flexible circuits.

4.3.2.2 Grade-6 or Light Cold Rolled Wrought (LCR-Type W Special Temper)

Like grade 4, this material is also unavailable even though it is listed in IPC-4652.

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TABLE 4.5

Properties of Electrodeposited Nickel Foils

Property	Units	Values
Chemical	%	
Nickel (including cobalt)		99.5 min
Carbon		0.01 max
Silicon		0.004 max
Boron		0.005 max
Aluminum		0.003 max
Magnesium		0.001 max
Sulfur		0.005 max
Chromium		0.005 max
Zinc		0.005 max
Copper		0.005 max
Lead		0.005 max
Iron		0.015 max
Manganese		0.004 max
Mechanical Properties		
Tensile strength	psi	100,000
Yield strength	psi	75,000
Hardness	DPH	200
Elongation	%	6–8 (2" gage)
Physical Properties		
Coefficient of thermal expansion	cm/cm/°C $\times 10^6$	14.2
Resistivity	Microhm-cm	7.75
Thermal conductivity	BTU/ft²/Hr/°F/in.	420
Peel Strength (Treated Foil) to Epoxy Glass		
0.001" foil	lb/in.	9.0–10.0
0.002" foil		12.0–14.0
0.003" foil		14.0–18.0

Note: Ductility, as measured by elongation, can be increased to 23% by annealing at 1400°F in a hydrogen atmosphere. This will result in a corresponding decrease in ultimate tensile strength values.

4.3.2.3 Grade-7 or Rolled Annealed Wrought (ANN-Type W)

Rolled annealed copper foils are the most easily recognized in the flex industry because of their almost exclusive use in producing flexible circuits. In comparable thickness, this grade is the most expensive to purchase. It is used in most continuous flex applications or others in which

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ductility is an essential component for continual operation. This grade is the most ductile of all the grades and types. Even though it has very good properties, it is gradually being replaced by grades 5 and 8.

4.3.2.4 Grade-8 or "As Rolled" Wrought Low-Temperature Annealable (Type LTA)

Grade 8 is equivalent to grade 5 in requirements and usage. Grade-8 flexes are basically used for commercial flex applications where continuous flexing is not a requirement. Low-temperature annealable foils are unique in that the foil is manufactured to soften or anneal during normal laminating conditions. Like grade 5, this foil is used in the production of flex laminates. During lamination, some properties change (for the better), which makes this material ideal for flex application.

4.3.3 Properties

Depending on the properties required by the particular design, foils can be ordered "as rolled," "light annealed," or "full annealed" (recrystallized). A comparison of resulting properties is shown in Table 4.4.

4.3.4 Application

Most rolled copper foils used in the laminate industry are used in flexible circuitry and are typically bonded to a flexible material with the aid of an organic adhesive where the ductility of the foil is essential to the application. Another significant application of rolled foils is in critical microwave applications where the foil's very smooth surface permits the production of fluoropolymer (Teflon®) laminates with a very low df (dissipation factor). The df is lower with rolled foil than with ED foil because of a phenomenon called the "surface effect," which in effect says that the electrical signal traveling at higher microwave frequencies follows the path of the copper at the interface with the dielectric. The rough ED copper has a much longer pathway than the smooth rolled foil.

4.4 Nickel Foil

The development of electrodeposited nickel foils has helped eliminate some of the etching problems experienced with rolled foils. These problems resulted from limited purity, grain orientation, and rolling lubricant inclusions.

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Continuously plating on and stripping produce electrodeposited nickel foils from a rotating drum in a manner similar to the way that electrodeposited copper foils (Figure 4.1) are produced. The thickness is established by current density and drum speed. ED nickel foils are 99.5% pure (minimum). Standard thicknesses are 1 to 7 mils, with 1 to 3 mils most commonly used. Table 4.3 shows the physical properties of electrodeposited nickel and Table 4.4 shows the chemical properties. Table 4.5 gives additional physical properties of nickel. Availability and use of nickel foil are very limited.

References

Gould, P., Metal foils — Understanding them is basic to PC assembly and joining technology, *Insulation Circuits,* Oct. 1975.

Guiles, C., *Everything You Wanted to Know about Laminates but Were Afraid to Ask,* Arlon Inc., Materials for Electronics Div.

IPC -4562, Metal Foil for Printed Wiring Applications.

Savage, R., *Copper Foils,* chapter 7.

Savage, R., Manufacturing copper foil for flexible circuits, *Electronic Packaging and Production,* May 1992.

Savage, R., private correspondence, June 6, 2004.

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5

Laminates, Rigid

5.0 Introduction

A wide variety of materials have been developed for use in the fabrication of printed wiring boards. Each material and each process has a targeted area and application. When used within the prescribed area, the printed wiring board will have the lowest cost possible while satisfying the performance and cost goals of the application. Due to confusion about material needs for specific applications, materials are often chosen without proper regard to the cost-benefit trade-off. This may result in a product that costs more than it should without any compensating benefit. Choose your materials wisely.

5.1 NEMA Grades

One of the first attempts to classify base materials that are used as laminates for printed wiring boards was completed by the National Electrical Manufacturing Association (NEMA). Their "Industrial Laminating Thermosetting Products Standard Publication LI-1" documents many of the materials that could be used as laminates for printed wiring boards.

Copper-clad laminates are composed of three basic materials: a copper foil, resin, and reinforcement. Some laminates require an adhesive to bond the foil to the reinforcement.

5.1.1 Paper-Based Laminates

In the mid-1950s, manufacturers (e.g., General Electric, Westinghouse, Formica) started producing paper-based laminates that are still being produced by Pacific Rim nations for high-volume, low-cost consumer electronics.

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Paper-based laminates are produced using layers of a phenolic-, polyester-, or epoxy-impregnated paper that have been laminated together under high pressure and temperatures to produce a flat sheet of electrical-grade laminates. These laminates may have copper foil on one or both sides of the dielectric and may or may not be flame-retardant. Today there are several grades of paper-based laminates (as defined by NEMA Publications L1-1) that can be used for producing printed wiring boards (XPC, XXXPC, FR-1, FR-2, and FR-3). These materials are the least expensive and are generally used in low-cost consumer products (e.g., calculators, consumer electronics, telecommunications equipment, radios TVs, video games, controllers), as opposed to the military, aerospace, or high-reliability medical fields.

Due to the high z-axis expansion of the paper-grade materials, plating of through holes is not recommended. This can result in frequent cracking of the plated through hole. In forming a laminate with paper-based material, an adhesive coating on the copper foil is used to bond the coated paper to the foil.

The main drawbacks of these laminates are lack of physical strength, poor impact resistance, poor dimensional stability, unstable electrical characteristics, and breakage. The chief asset of paper-grade materials is their punchability, low price, and electrical characteristics that are adequate for many noncritical applications.

One of the benefits of paper-based laminate materials is that they can be punched rather than drilled, which results in processing economics for long runs. Copper-clad materials that can be easily punched fall into two categories: the paper grades (i.e., XPC, XXXPC, FR-1, FR-2, and FR-3) and the composite grades (i.e., CEM-1, CEM-3, CRM-5, and FR-6). The properties of each material will determine whether it should be punched at room temperature, warm, or hot.

5.1.2 Types of Laminates

5.1.2.1 XPC

The XPC laminate is made from a cellulose-based material that is impregnated with a single coating of a plasticized phenolic resin. The adhesive coating on the copper foil is used to bond the foil to the coated paper. The XPC laminates are normally brown in color and can be easily punched or sheared at room temperature, but they produce cleaner holes when warmed (100°F [38°C]) prior to punching. XPC laminate shows excellent punching properties and excellent dimensional stability.

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5.1.2.2 XXXPC

The XXXPC laminate is also made from a cellulose-based paper but is impregnated with two coats of a modified plasticized resin. This laminate is also opaque brown in color and can be readily punched or sheared at room temperature (73°F [23°C]), but, like the XPC laminates, better results are obtained when this material is punched warm.

The XXXPC laminate is a low-cost, low-performance material that is recommended for applications that require a higher insulation resistance and a lower dielectric loss than XPC. However, this laminate has poor flexural strength and electrical properties when wet.

5.1.2.3 FR-1

This laminate is also made from a cellulose-based paper but is impregnated with a plasticized, flame-retardant phenolic resin. The adhesive on the copper foil is used to adhere the copper foil to the coated paper. FR-1 laminates are normally brown in color and can be punched at room temperature but produce cleaner holes and edges if punched or sheared at slightly elevated temperatures. These laminates are used to fabricate single-sided printed wiring boards but have extremely poor electrical properties when wet. The FR-1 laminate can be manufactured with "green" variants that are halogen-, dioxin-, and antimony-free. FR-1 laminate has a comparative tracking index (CTI) of over 600 V.

5.1.2.4 FR-2

FR-2 laminate is produced from multiple plies of cellulose-based paper impregnated with an upgraded high-temperature, flame-retardant, plasticized phenolic resin. In manufacturing the FR-2 laminates, each sheet of cellulose paper is coated twice with the resin. These laminates are generally medium to dark opaque brown in color and should be punched or sheared at slightly elevated temperatures (100°F [38°C]). The FR-2 and XXXPC laminates have similar properties except that the FR-2 is flame-retardant.

This laminate performs better than FR-1 when tested for moisture and insulation resistance (MIR) and has a comparative tracking index (CTI) of over 600 V. FR-2 laminates are mostly used to fabricate single-sided boards; however, some double-sided, non-plated-through-hole boards have been produced. This material can also be supplied in "green" variations — halogen-, dioxin-, and antimony-free. FR-2 is typically used where dimensional stability and high performance are not requirements. Like other paper-based products, FR-2 is a low-cost laminate.

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5.1.2.5 FR-3

FR-3 laminate is also made from multiple plies of cotton linter, impregnated with two coats of a modified flame-retardant epoxy resin. The laminates can be light yellow to cream or white in color and are somewhat translucent. This material is very brittle and should be punched or sheared only at elevated temperature (100°F [38°C]). FR-3 laminate has better wet electrical properties than FR-2 laminate and is generally used where high insulation resistance is a requirement. This laminate is mostly used in the fabrication of single-sided boards; however, some success has been achieved in producing relatively thin double-sided boards with plated through holes.

5.1.3 Properties, Construction, and Specifications (Paper-Based Laminates)

The physical properties of paper-based laminates are given in Table 5.1 while the construction is shown in Figure 5.1 (except FR-3, which is shown in Figure 5.2). Paper-based laminates are approved to the specifications shown in Table 5.2.

5.1.4 Processing Paper-Grade Laminates

One of the major differences between fabricating paper-based laminates and fabricating laminates made with reinforced fiberglass is in the hole-forming and routing process. With paper-based laminates, all the holes, slots, and contours are usually punched at one time. Glass-based laminates require that each hole be drilled individually and then routed. Punching of paper-based laminates is much easier, produces cleaner holes, and is less troublesome if the part is preheated to approximately 100°F (38°C) even if the laminate is classified as "cold punch." Since punch tooling is relatively expensive, punched boards are usually used in high-volume applications where tooling costs can be amortized over long, or multiple, product runs.

5.2 Composite Laminates

A composite laminate, by the adopted IPC definition, "consists of two or more forms of reinforcing materials bonded together with a suitable resin." The resin type is not specified and may be any type that will do the job. The emphasis is solely on what type of reinforcements is used.

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TABLE 5.1

Typical Properties of Paper-Based Laminates

	Laminate					
Property	**XPC**	**XXXPC**	**XXXP**	**FR-1**	**FR-2**	**FR-3**
Electrical						
Dielectric breakdown	Kv	15	15	5	15	300
Electric strength	v/m	425	450	400	450	450
Dielectric constant	1 MHz	5.6	4.1	6	4.3	4.3
Dissipation factor	1 MHz	0.07	0.04	0.06	0.045	0.04
Volume resistivity	Megohm-cm	$\times 10^4$	$\times 10^4$	$\times 10^3$	$\times 10^4$	$\times 10^4$
Surface resistivity	Megohm	$\times 10^3$	$\times 10^3$	$\times 10^2$	$\times 10^3$	$\times 10^3$
Physical						
Moisture absorption	%	1.3	1.3	2	1.3	1.0
Peel strength	lb/in.	—	—	6.7–7.0	6.0–7.0	8.0–9.0
Flammability (UL)	UL 94	V-1	HB	V-1	V-1	V-1
Flexural strength						
LD	psi	19,300	12,000	12,000	12,000	20,000
CD		16,600	10,500	10,000	10,500	16,000
Izod impact strength						
LD	—	—	—	2.4	2.4	2.5
CD	—	—	—	2.1	2.0	2.2
Tensile strength						
LD	psi	10,500	12,400	12,000	12,500	14,000
CD		850	9,500	9,000	12,000	12,000
Maximum operating temperature	0C	130	125	75	105	140
Arc resistance	sec	—	—	20	30	20
Modulus of elasticity in flexure						
LD	—	1,000	1,000	1,200	1,000	1,200
CD	—	800	800	900	800	1,000
Thermal						
Thermal conductivity		—	1.7	1.8	1.8	1.6
Tg range	°C	—	—	95–125	80–100	90–110

Note: Br = bromine; Cl = chlorine; SbO = antimony oxide; Al_2O_3 = aluminum oxide.

The reinforcement materials may be a combination of paper, glass mat, glass felt, and reinforced woven glass as its core and reinforced woven glass as its outer layer. Some grades of composite laminates may have through holes punched or drilled and successfully plated. Composite laminates are designated CEM-1, CEM-3, CRM-5, and FR-6. Composite laminates are used extensively as circuit boards in radios, automotive applications, industrial controls, appliances, TV games, calculators, higher-technology television sets, printers, smoke detectors, and boards for several types of

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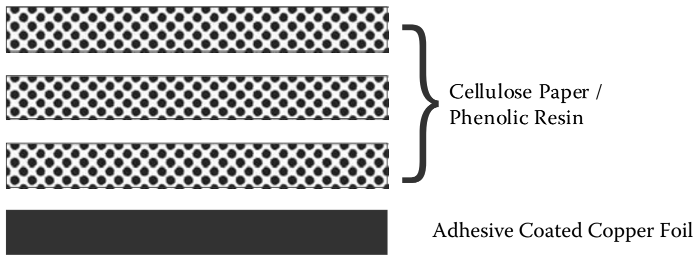

FIGURE 5.1
Cross-sectional view of XPC, XXXPC, FR-1 and FR-2.

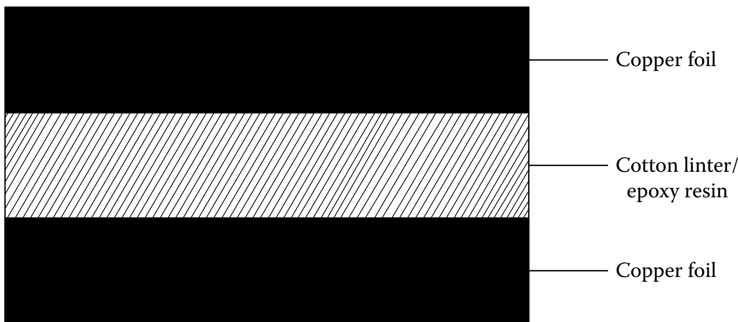

FIGURE 5.2
Cross-sectional view of FR-3.

power sources. Approximately 7% of all printed wiring boards made worldwide are made from composite-grade laminates.

5.2.1 Reinforcing Mats

The reinforcing mats are composed of chopped or continuous strands in nonwoven random matting and are usually held together by resinous binders. They have been popular as polyester-based laminates. All the glass materials exhibit excellent electrical properties due to their low moisture absorption. Glass mat is rated superior to glass felt in thermal properties due to the binders that are used to hold the felt together. These binders are not the coupling agents normally used to coat glass to maximize the resin-to-glass bonding.

The punching and drilling properties of the felt tend to be better, as the glass fibers are not concentrated into lightly packed and more-difficult-to-cut bundles. The mat performs nearly as well in this regard because the mat bundles are not as dense or as tightly packed as in woven fabric.

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TABLE 5.2

Specification Sheets for Laminates and Prepregs

Specifications			Resin System				
IPC 4101	ANSI	Reinforcement Type	Primary	Secondary	Flame Retardant	Fillers	Tg
/00	XPC/00	Cellulose paper	Phenolic	None	N/A	N/A	N/A
/01	XXXPC	Cellulose paper	Modified phenolic non–flame resistance	None	N/A	N/A	N/A
/02	FR-1/02	Cellulose paper	Phenolic flame resistance	None	Br, Cl	N/A	N/A
/03	FR-2/03	Cellulose paper	Modified phenolic flame resistance	None	Br, Cl	N/A	N/A
/04	FR-3/04	Cellulose paper	Modified epoxy flame resistance	None	Br, Cl SbO	N/A	N/A
/10	CEM-1	Woven E-glass/surface cellulose paper core	Modified epoxy flame resistance	Phenolic	Br, SbO	N/A	N/A
/11	CRM-5/11	Woven E-glass/surface/ E-glass felt core	Polyester flame resistance	Vinyl ester	Br	Inorganic fillers	80°C
/12	CEM-3/12	Woven E-glass/surface nonwoven E-glass core	Epoxy	none	Br	With or without fillers	N/A
/13	4101/13	Woven E-glass	Polyester	Vinyl ester	Br	Inorganic fillers	N/A
/20	G-10/20	Woven E-glass	Epoxy non-flame resistance	none	N/A	N/A	100°C (min)
/21	FR-4/21	Woven E-glass	Difunctional epoxy flame resistance	Multifunctional epoxy	Br	N/A	100–150°C
/22	G11/22	Woven E-glass	Epoxy hot strength retention flame resistance	None	N/A	N/A	135–175°C
/23	FR-5/23	Woven E-glass	Epoxy hot strength retention flame resistance	None	Br	N/A	135–185°C
/24	FR-4/24	Woven E-glass	Epoxy flame resistance	Multifunctional epoxy	Br	N/A	150–200°C

(continued)

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TABLE 5.2 (continued)

Specification Sheets for Laminates and Prepregs

Specifications			Resin System		Flame		
IPC 4101	ANSI	Reinforcement Type	Primary	Secondary	Retardant	Fillers	Tg
/25	FR-4/25	Woven E-glass	Epoxy flame resistance	Multifunctional oxide	Br	N/A	150–200°C
/26	FR-4/26	Woven E-glass	Epoxy flame resistance	Multifunctional epoxy	Br	N/A	170–200°C
/27	FR-4/27	Unidirectional E-glass, cross-plied	Epoxy flame resistance	Multifunctional epoxy	Br	N/A	110°C (min)
/28	FR-4/28	Woven E-glass	Epoxy flame resistance	Non-epoxy	Br	N/A	170–220°C
/29	FR-4/29	Woven E-glass	Epoxy flame resistance	Triazine	Br	N/A	170–220°C
/30	GPY/30	Woven E-glass		Epoxy	Br	N/A	170–220°C
/40	GPY/40	Woven E-glass	Polyimide	None	N/A	N/A	200°C (min)
/41	GPY/41	Woven E-glass	Polyimide	None	N/A	With or without inorganic fillers	250°C (min)
/42	GPY/42	Woven E-glass	Polyimide	Epoxy	N/A	With or without inorganic fillers	200–250°C
/50	4101/50	Woven aramid		Multifunctional epoxy	Br	None	150–200°C
/53	4101/53	Nonwoven aramid paper	Polyimide	Epoxy	N/A	N/A	220°C (min)
/54	4101/54	Unidirectional aramid fiber cross-plied	Cyanate ester	None	Br	N/A	230°C (min)
/55	4101/55	Nonwoven aramid paper	Epoxy	Multifunctional epoxy	Br	None	150–200°C

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/56	4101/56	Nonwoven aramid paper	Polyimide	None	N/A	N/A	250°C (min)
/60	4101/60	Woven quartz fiber	Polyimide	None	Br	N/A	250°C (min)
/70	4101/70	Woven S-2 glass	Cyanate ester	None	Br	None	230°C (min)
/71	4101/71	Woven E-glass	Cyanate ester	None	Br	None	230°C (min)
/80	CEM-1/80	Woven E-glass/ cellulose Paper	Epoxy flame resistance	Phenolic	Br, SbO	Kaolin and/or inorganic catalyst	100°C (min)
/81	CEM-1/83		Epoxy flame resistance	Multifunctional epoxy	Br	Kaolin and/or inorganic catalyst	N/A
/82	FR-4/82	Woven E-glass Chopped Felt	Epoxy flame resistance	Multifunctional epoxy	Br	Kaolin and/or inorganic catalyst	110°C (min)
/83	FR-4/83	Woven E-glass	Epoxy	Multifunctional epoxy	Br	Kaolin and/or inorganic catalyst	150–200°C
/90	4101/90	Woven E-glass	Polyphenylene ether	None	Br, SbO	N/A	175°C (min)
/91	4101/91	Woven E-glass	Polyphenylene ether	None	Br	N/A	175°C (min)
/92	4101/92	Woven E-glass	Epoxy	Multifunctional epoxy	P	N/A	110–150°C
/93	4101/93	Woven E-glass	Epoxy	Multifunctional epoxy	Al2O3	N/A	110–150°C
/94	4101/94	Woven E-glass	Epoxy	Multifunctional epoxy	P	N/A	150–200°C
/95	4101/95	Woven E-glass	Epoxy	Multifunctional epoxy	Al2O3	N/A	150–200°C
/96	4101/96	Woven E-glass	Polyphenylene ether	None	Non-Br Non-Sb	N/A	175°C (min)

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In the composite approach, different materials are blended together to get the best performance. CEM-1 demonstrates this in that the glass surface provides the adequate flexural strength while the paper core keeps the price down.

5.2.1.1 Surfacing Mats, Paper, or Veil

Originally these types were used to cover reinforcing mat and fabric to even out underlying fiber patterns and impart a smooth finish. More recently, this type of mat has been used to replace cellulose paper in various laminates as the core substrate. CEM-3 and CRM-5 composite materials are composed of various layers of surfacing mat sandwiched between woven fabric layers.

5.2.1.2 Glass Fiber "Paper"

In the technique for manufacturing glass fiber mat or "paper" using the basic technology of paper-making, chopped fibers of glass are suspended in a water slurry and then collected on a forming screen. The wet formed mat is saturated with binders, dried, and cured into a mat or paper product. Wet-processed glass fibers are treated with a chemical size to enhance processing and improve the physical characteristics.

A particular advantage of the wet process is the ease with which glass fibers can be blended with other fiberglass or nonglass products to combine the advantage of the different materials.

As a core material for printed circuit board laminates, the glass fiber wet-formed mat improves punchability of the laminate and gives increased dimensional stability and strength.

5.2.1.3 Polyester Glass Mat

The other member in the low-cost, low-performance category of laminates is the polyester glass mat (FR-6). The main attributes of this grade are its good electrical properties and reasonable price. There are, however, certain deficiencies that prevent its more extensive use as printed wiring laminates. Flexural strength is no better than that of paper grades, erratic and low copper peel strengths are not unusual, and thickness variation is twice that of paper. Although it is a punching material, there were a number of problems associated with it. Die wear is excessive and hole-to-hole cracking is a potential problem. The glass/resin dust that is produced in machining may be a source of irritation for manufacturing personnel.

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5.2.2 Types of Composite Laminate

5.2.2.1 CEM-1

CEM-1 laminate is a composite-grade laminate that is composed internally of either unbleached cellulose paper or cotton linter and impregnated with a plasticized flame-retardant epoxy resin. The outer layers are composed of woven fiberglass impregnated with epoxy resin. The epoxy resin that is used in making the CEM-1 internal cores may differ from the formulation that is used to coat the woven glass because the core resin is specifically formulated to treat the cellulose fibers rather than the glass fibers. The CEM-1 laminate is usually opaque tan in color. This laminate is a good all-around material with excellent mechanical strength. The construction and resin system employed in making the CEM-1 laminate gives it the punching properties of FR-2 and FR-3 and electrical properties approaching those of FR-4. This combination of materials enables the laminate to still be cold-punched while realizing the improved physical and electrical properties of the woven glass. CEM-1 was developed for single-sided applications that require higher strength and stiffness than can be achieved by all other paper laminates. The CEM-1 laminates are basically used to produce single-sided boards; however, some success has been made in producing double-sided boards with plated through holes. This laminate has better moisture absorption and electrical properties than FR-2. CEM-1 has been used in both consumer and industrial products. This laminate can be obtained halogen- and antimony-free. The CTI value is over 600 V.

5.2.2.2 CEM-3

CEM-3 is a composite laminate made up of dissimilar materials. The internal layers are composed of a nonwoven glass core (also called fiberglass felt), while the outer layers are composed of a woven fiberglass cloth. Both the internal and external layers are impregnated with the same epoxy resin (which is close to the formulation used to coat FR-4 laminates). The CEM-3 laminate is translucent in color and can be readily punched at room temperature. These laminates are mostly used to produce double-sided boards with plated through holes.

5.2.2.3 CRM-5

CRM-5 laminate is also a composite-grade laminate. The internal layers are composed of a fiberglass-paper core (also called glass mat) impregnated with a flame-retardant modified polyester resin. This is the same basic resin that is used to coat the FR-6 laminate. The outer layers are a

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woven fiberglass coated with the same polyester resin. The CRM-5 laminates are normally white in color and can be easily punched at room temperature. This composite laminate can be used to produce a double-sided printed wiring board with plated through holes. The CRM-5 laminate has excellent electrical properties especially under humid conditions. It has a CTI of over 600 V and a lower Dk (3.7) and Df (0.018) than competing paper or composite laminates, which makes it an excellent material for high-frequency or high-voltage applications.

5.2.2.4 FR-6

The FR-6 laminate is composed of a random fiberglass mat core that is saturated with a modified flame-retardant polyester resin. This resin is normally opaque white in color. The FR-6 laminate is basically used to produce single-sided boards, and even though it is basically constructed from all glass, it can be readily punched at room temperature. This laminate has good electrical insulation properties and dielectric properties, especially under humid conditions. With a CTI index of over 600 V, a Dk of 3.6, and a Df of 0.016, this material allows the board designer maximum flexibility for safety and protection for frequency-sensitive applications. There are certain limitations that prevent its more extensive usage as a laminate for printed wiring boards. Flexural strength is no better than that of paper grades, erratic and low copper peel strengths are not unusual, and thickness variation is about twice that of paper. Although it is listed as a punchable-grade material, there are a number of problems associated with it. Die wear is excessive and hole-to-hole cracking could be a problem. It has lower mechanical properties than the CEM-1 or CEM-3 laminates. FR-6 material is designed for low-capacitance or high-impact applications and is designed for the consumer electronics market.

5.2.2.5 Properties, Construction, and Specifications (Composite Laminates)

The physical properties of composite laminates are shown in Table 5.3, and their construction is shown in Figure 5.5 to Figure 5.8. These materials are approved to the specifications shown in Table 5.2.

5.2.3 Storage

Laminates of all types are a fully cured product, and when a copper foil is clad on one or both sides, these materials do not require any special storage conditions other than ambient temperature and humidity (50 to 70%). These laminates can be stored for many months with no harmful effects.

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TABLE 5.3

Typical Physical Properties of Composite-Grade Laminates

Property	Units	Laminates			
		CEM-1	CRM-5	CEM-3	FR-6
Electrical					
Dielectric breakdown	Kv	40	40	40	40
Electric strength	v/m	450	500	500	—
Dielectric constant	1 MHz	4.3	3.7	4.2	3.6
Dissipation factor	1 MHz	0.035	0.022	0.035	0.018
Volume resistivity	Megohm-cm	$\times 10^6$	$\times 10^3$	$\times 10^6$	$\times 10^6$
Surface resistivity	Megohm	$\times 10^4$	$\times 10^4$	$\times 10^4$	$\times 10^4$
Physical					
Moisture absorption	%	0.5	0.5	0.5	0.5
Peel strength	1 oz/2 oz lb/in.	7.0/9.0	6.0/7.5	8.0/10.0	7.0/8.0
Flammability (UL)	UL 94	V-0	V-0	V-0	V-0
Flexural strength					
LD	psi	50,000	45,000	50,000	22,000
CD		40,000	36,000	40,000	20,000
Maximum operating temperature	0C	140	130	130	130
Arc resistance	sec	60	60	60	100
Thermal					
Thermal conductivity	—	1.8	1.8	1.8	—
Tg Range	0C	85–115	95–125	95–125	85–115

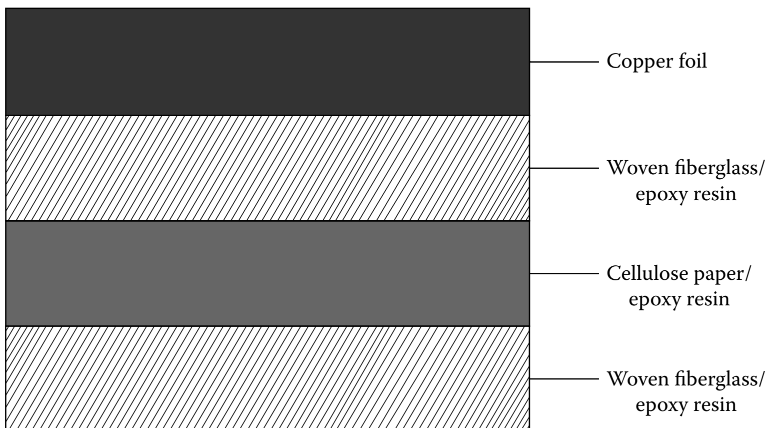

FIGURE 5.3
Cross-sectional view CEM-1 and CEM-3.

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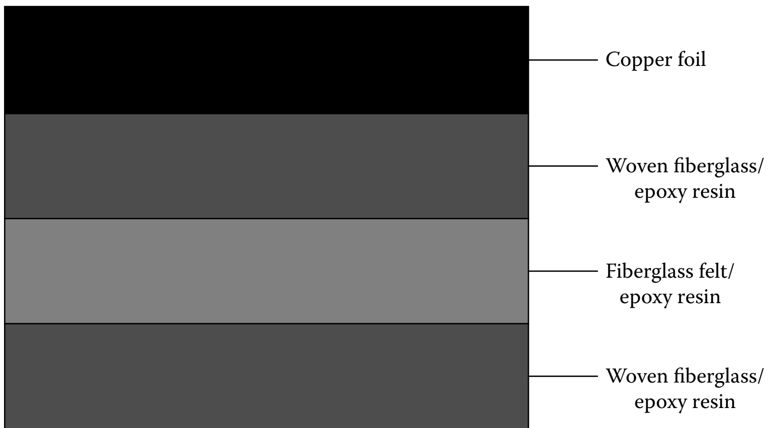

FIGURE 5.4
Cross-sectional view CRM-5.

FIGURE 5.5
Cross-sectional view FR-6.

FIGURE 5.6
Cross-sectional view FR-4.

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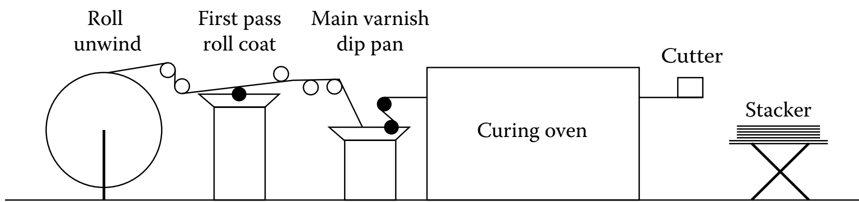

FIGURE 5.7
Horizontal coating machine.

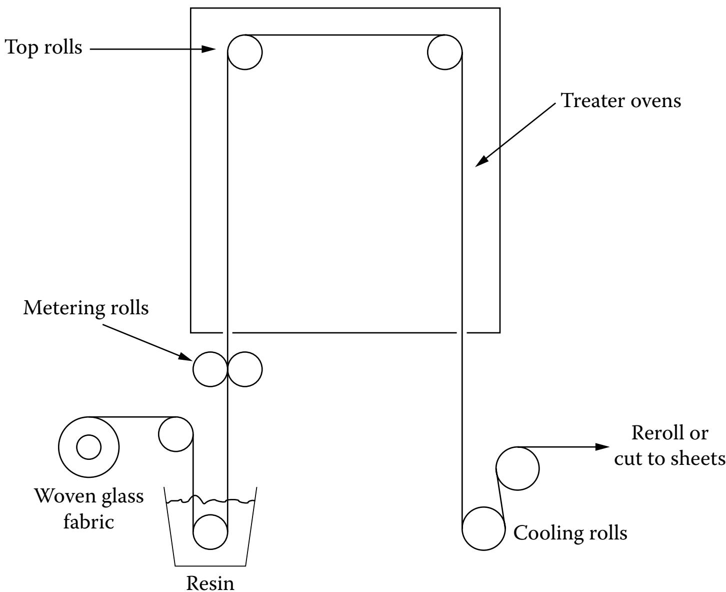

FIGURE 5.8
Vertical coating tower.

However, some laminates, especially epoxy glass, do absorb moisture over time, and therefore baking these laminates (after prolonged storage) is recommended. When moisture is absorbed into the laminate, it can result in defects such as measling and delamination, especially during the solder leveling process or hot oil fusing process.

Caution should be exercised in the storage of laminates that are unclad or clad on one side only. Single-sided laminates should be stored under conditions similar to those under which prepregs are stored (low humidity and temperature). Laminates should be stored flat, so as to prevent warpage from being introduced into the sheets or panels.

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5.2.4 Material Recommendation

Factors that influence the choosing of proper paper or composite type laminates are processing considerations and intended end use:

- For single-sided boards, using punch-through-hole applications, use FR-6, CEM-1, or CRM-5.
- For plated through holes and single-sided boards, consider CEM-3, CRM-5, or FR-6.
- Where electrical characteristics are not paramount, use FR-2 or FR-6.
- Where electrical characteristics are important, use CRM-5.
- If tool wear is a major factor, use FR-2 or CEM-1.
- For large or heavy loaded boards, consider CEM-1, CEM-3, or CRM-5.

Table 5.4 lists the various paper- and composite-grade papers, their composition, their applications, and alternative materials that could be used in place of the recommended materials.

5.3 Rigid Laminates (Glass-Reinforced)

Almost any solid insulating resin and glass reinforcement materials can be combined to produce a laminate. The selection of the proper resin and reinforcement material depends on the performance requirements of the printed wiring boards. Copper-clad laminates and prepregs are available with a variety of resin systems and reinforcements. The standard copper-clad laminate and prepreg (i.e., FR-4 epoxy/E-glass) has been available for many years and functions well, but there are some applications in which FR-4/E-glass does not perform well. In these applications, multifunctional epoxies, higher-temperature epoxies, bismaleimide/epoxy, cyanate esters, polyimide, and polytetrafluoroethylene are being used. Along with the higher-performance resins, higher-performance reinforcements (i.e., S-glass, D-glass, quartz, and aramids) are finding applications. These resins and reinforcements are being used when higher thermal performance, reduced Dk, lower loss, or controlled CTE are requirements.

A rigid printed circuit board consists of a thin copper foil (for the conductors) and a suitable dielectric material. The latter is basically a reinforced resin. The characteristics of the laminate (essentially the dielectric

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TABLE 5.4

Typical Copper-Clad Laminates (Paper- and Composite-Grade) Cross-Reference

Grade	Composition	General Properties	Application	Alternative
XPC	Plasticized phenolic resin/cellulose based	Good flexibility, intended for cold punching and shearing	Radio TV Video games Calculators	XXXPC
XXXPC	Phenolic resin/kraft paper	Excellent punching at room temp., low flexural strength, poor wet electrical strength	Automotive Video games Calculators	FR-1 FR-2 FR-6
FR-1	Phenolic resin/kraft paper	Punchable at room temp., poor wet electrical properties	Automotive Consumer electronics	FR-2 FR-6
FR-2	Epoxy resin/kraft paper	Brittle, but punchable with heat; similar physical/electrical properties as XXPC	Automotive Video game controls Calculators	FR-6 CEM-1
FR-3	Phenolic resin/kraft paper	Brittle, but punchable with heat; good electrical properties for paper	Telephone sets	FR-6 CEM-1 CEM-3
FR-6	Polyester resin/kraft paper	Punchable at room temp., good wet electrical properties, better flexural strength than paper	Automotive, Telecommunications	CEM-1 CRM-5
CEM-1	Epoxy glass fabric on surface, epoxy cotton paper core	Punchable at room temp., good electrical properties but less than polyester, good flexural and impact strength	Consumer electronics	FR-6 CEM-1
CEM-3	Epoxy glass fabric on surface, epoxy glass paper core	Punchable at room temp but harder than CEM-1, good electrical properties, suitable for PTH	Computers Peripherals Keyboards	CRM-5 FR-4
CRM-5	Polyester resin/glass fabric on surface, glass paper core	Good electrical properties, punchable at room temp., good flexural strength	Consumer electronics Automotive Telecommunications	CEM-3 FR-4 FR-6
FR-4	Epoxy resin/glass fabric on surface	High flexural and impact strength, good electrical properties, excellent for PTH	Automotive Telecommunications Military	CEM-3 CRM-5

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material of the resin and reinforcement) are typically divided into two main categories: electrical and mechanical.

To achieve a low CTE value without constraining cores, low resin content is required. If the resin content is too low, then a dry laminate, weave exposure, etc. are possible. Prepreg without enough resin can result in inadequate fill of inner-layer circuitry.

5.3.1 Electrical Characteristics

The electrical characteristics are mainly the Dk and the frequency-dependent Df. Consideration is given to these electrical characteristics when the application is signal- or frequency-sensitive. If the Dk is important, then raising the resin content will normally lower the Dk. However, it will have an opposite effect on the CTE. The major thermomechanical characteristics are the Tg and the CTE. The Tg is the temperature at which the material begins to soften and the mechanical properties (CTE) increase. Higher-Tg materials therefore have increased resistance to thermal processing. A reduced CTE yields a more stable material during solder reflow or wave soldering.

There are always trade-offs in terms of resin content vs. physical, electrical, and chemical properties. High resin contents result in low dielectric constants, improved dielectric strength, and, in the case of many systems, improved resistance to stripping of resin by process chemistries. Lower resin contents (which are typical of heavier-weight glass fabrics) result in more rigidity and flatter laminates but a higher dielectric constant (which is driven by the glass fabric) and the risk of dryness or "measling" when thermally stressed. Each resin system has its own unique properties that will determine the "right" level of resin content.

5.3.2 Laminate Thickness

The thickness of a laminate is a function of the number of layers, or plies, that it contains. Each style of fabric — when it is coated with a resin to a particular weight, that weight largely confined to a narrow range by the glass style and thickness — has a characteristic thickness, which can be determined mathematically based on the fabric weight and density and the resin weight and density.

Buildup is the term used to describe a combination of plies of prepreg that goes into the construction of a laminate. Common laminate buildup thickness per ply can be given roughly, but the actual thickness yield depends on the processing as well as resin content or the ply's weight.

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Fabric Style	Typical Thickness per Ply
106 E-glass	0.0018–0.0022 in.
1080 E-glass	0.0025–0.0033 in.
2313 E-glass	0.0032–0.0040 in.
2116 E-glass	0.0042–0.0050 in.
7628 E-glass	0.0060–0.0078 in.
503 Quartz	0.0050–0.0055 in.
120 Kevlar®	0.0040–0.0050 in.
E-210 Thermount®	0.0017–0.0020 in.
E-220 Thermount®	0.0030–0.0032 in.
E-230 Thermount®	0.0037–0.0039 in.

5.4 Laminates, Rigid Glass Reinforcement

5.4.1 Epoxy Laminate (FR-4)

Epoxy is the most successful and commonly used resin system that is used with glass reinforcement for printed wiring applications. The general term *epoxy* actually encompasses a wide range of material types, even though they share certain properties and are primary epoxy based from a chemical reactivity point of view. As a result of the wide range of available epoxy materials and modifiers, there are numerous epoxy products that can be selected for specific applications.

For many nondemanding applications, 130 to 140°C Tg (so-called tetrafunctional modified) epoxies have become the material of choice. In higher-layer-count multilayer boards, very thick circuits, and circuits requiring improved thermal properties, the 170 to 180°C Tg "multifunctional" epoxies have become the material of choice. In circuits requiring improved electrical properties, epoxy resins with a low Dk and Df are also available.

As the range of end-use applications has grown, so has the range of available epoxy materials. In addition, the components in FR-4 materials, particularly woven fiberglass fabric and resin, provide a very good combination of performance, processability, and cost characteristics. The range of woven fiberglass fabric styles available makes it easy to control dielectric and overall laminate thickness. The resins are either straight thermoset epoxy resin systems (including cross-linking agent, accelerators, and certain fillers) or, more commonly, epoxy blends.

FR-4 epoxy resin laminates with Tg 130°C are cost-effective materials for printed wiring boards. The Dk of these materials is nominally ~4.4 and the Df is ~0.019. (The Dk is higher for rigid boards with low resin contents, being as high as 4.8 in many cases.) Higher-temperature epoxy

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materials provide more thermal resistance than standard FR-4 laminates because of the enhancement of the resin system and increased cross-link density. These materials have a typical Tg of 175°C and a slightly lower CTE. Because they are based on a resin system similar to FR-4, the electrical characteristics are similar and they process like FR-4. Typical uses for higher-Tg resin systems include backplanes, BGAs, TAB, wire bonding, COB, and when multiple thermal cycles are required during assembly, such as double-sided SMT. The FR-4 epoxy, dicyandiamide-cured resins have been in use for so long that their processability is considered a standard by laminate and printed board producers.

As can be seen from Table 5.2, there are several materials that are considered an NEMA-grade FR-4. They are flame-retardant, use woven fiberglass reinforcement, and are primarily epoxy based, although there is one type specifically designated as an epoxy polyphenylene oxide (PPO®) blend, which results in somewhat enhanced dielectric and loss properties.

The primary differentiator between epoxy materials is the Tg value. Table 5.2 specification /21 refers to an FR-4 resin with a minimum Tg of 110°C (pure difunctional epoxy). More common are FR-4 materials with a Tg value of 130 to 140°C (tetrafunctional modified) and 170 to 180°C (multifunctional). Obviously there are many different types of epoxy resins that will yield different Tg values as well as differences in other properties. In addition, as the epoxy/PPO blend makes obvious, the resin system can include resins other than epoxies. Finally, in Table 5.2, specification /82 covers an FR-4 material catalyzed for an additive copper-plating process. A catalyst for this material is kaolin clay filler coated with palladium. Materials with filler can also be classified as FR-4.

High-Tg FR-4 materials have better dimensional stability, which is important for complex printed wiring boards because the cores do not require heating much above the Tg, as conventional FR-4 would require.

Rigid FR-4 laminates are copper-clad epoxy-glass laminates with high mechanical strength, excellent machinability, and consistent drilling properties; they are approved to UL 94-VO flame retardancy and have good dimensional stability, good electrical and mechanical properties, and good adhesive strength between layers. The outstanding electrical, mechanical, and thermal properties make FR-4 an excellent material for a wide range of applications including computers and peripherals, servers, telecommunications, aerospace and industrial controls, VCRs, and TV and electronic toys.

5.4.1.1 Difunctional Epoxies

Difunctional epoxies are a combination of brominated bisphenol-A epoxy resin using 2-methylimidizole as the accelerator and dicyandiamide

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(DICY) as the hardener. In some cases a filler such as talc is added. Difunctional epoxies cured with DICY hardener result in an epoxy with a Tg between 100 and 120°C. These resins, the least expensive of the FR-4's, are often used to blend down multifunctional epoxies to obtain a mid-range Tg system.

There are a variety of epoxy resins; they are grouped together by their Tg and fall into three categories.

5.4.1.1.1 Low-End Modified Difunctionals with a Tg of 135 to 150°C

These systems provide improvement in chemical, solvent, and moisture resistance when compared to standard difunctional epoxies. There is little change in thermal resistance and *z*-axis expansion. Printed wiring boards as thick as 0.075 in. (1.90 mm) are commonly produced without lifted pads. These materials tend to be compatible with fabrication processes designed for difunctional epoxy.

Difunctional systems can be blended with a minimal amount of multifunctional epoxy resins to yield an incremental improvement in thermal performance. In these systems, 2% tetrafunctional resins are also added to enhance optical inspection. A Tg of this range can also be achieved via higher loading of tetrafunctional resin.

5.4.1.1.2 High-Temperature Multifunctional Epoxy, Tg between 150 and 165°C

In these systems, 1 to 4% tetrafunctional epoxy resin or a corresponding amount of fluorescent dye is normally added to improve the optical inspection process and prevent shoot-through when curing solder mask on both sides of the board. The tetrafunctional resin is what makes the laminate yellow. This system provides additional improvement in chemical, solvent, and moisture resistance. The improvement in *z*-axis CTE allows these materials to perform well on thicker boards up to 0.090 in. (2.29 mm) thick without resulting in lifted pads. The more highly cross-linked resin matrix is stiffer and harder and may be more difficult to drill, resulting in increased drill wear. The improved chemical resistance requires increased activity in the hole-cleaning process, but surface resin does not tend to be attacked by process chemistries as in the case of straight difunctional.

5.4.1.1.3 High-Temperature Multifunctional Epoxy, Tg between 170 and 190°C

These systems provide very good resistance to chemical, solvent, and moisture attack. The improvement in total *z*-axis expansion allows these materials to perform well on boards up to 0.150 in. (3.8 mm) thick without

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resulting in lifted pads. Boards built using these materials will usually pass tests requiring up to five separate solder float tests, without any evidence of lifted pads. Due to the hardness of these materials, the drill wear will be increased.

Specialty resins are designed to yield significant improvements in thermal performance, decomposition temperature, and chemical resistance. High-performance epoxies can be used where higher continuous operating temperatures are required. These systems are often patent protected.

Currently, high-temperature multifunctional materials are utilized in applications where the boards are extremely thick or are subjected to multiple solder assembly operations. The current trend is to design most high-layer-count printed wiring boards with these resins to ensure that these boards will not be destroyed at assembly. The high-temperature epoxies are chosen over other high-temperature materials such as bismaleimide-triazine or polyimide resins because of material costs and ease of processability and can pass multiple solder applications.

Table 5.5 shows the typical properties of the epoxy resins (difunctional, multifunctional, and tetrafunctional) reinforced with E-glass.

5.4.2 Cyanate Ester

The trifunctional cyanate ester cross-links to form a high-temperature polymer (Tg 230 to 240°C or higher) with dielectric properties, which makes it of special interest in the high-frequency (RF) printed wiring marketplace. However, there are a number of issues with this system, including high rates of moisture pickup, extreme sensitivity to processing caustics, and brittleness under suboptimal processing conditions.

A low Dk (2.8 for the neat resin) is the main feature of the cyanate ester resin system. In applications requiring high Tg combined with low Dk and Df, quartz fabric can be used. S-2 glass offers a compromise in both cost and performance, providing reduced Dk and CTE values compared to standard E-glass without the high cost associated with quartz. Cyanate ester resin systems have potential application in a variety of high-speed applications, where the application of surface mount technology requires both high signal speed processing and direct mounting of leadless components. In certain cases, it has been determined that the use of standard E-glass, even at a low resin content, does not give a sufficiently low CTE to accommodate devices with I/O counts over about 48. In those cases, the use of S-2 glass offers a reasonable alternative. At 50% resin content, a CTE of 10.5 to 11 ppm/°C can be achieved using S-2 glass and cyanate ester resin vs. about 15 ppm/°C for the E-glass equivalent.

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TABLE 5.5

Typical Properties Epoxy Resin Reinforced with E-Glass

Property	Units	Difunctional Epoxy	Multifunctional Epoxy	Tetrafunctional Epoxy
Electrical				
Dielectric breakdown	Kv	40	40	40
Electric strength (min)	v/m	2900	1000–2000	1500
Dielectric constant	1 MHz	4.5	3.7	4.2
Dissipation factor	1 MHz	0.02	0.022	0.035
Volume resistivity	Megohm-cm	5.1×10^7	$\times 10^3$	$\times 10^6$
Surface resistivity	Megohm	$\times 10^4$	$\times 10^4$	$\times 10^4$
Physical				
Moisture absorption	%	0.35	0.1	0.1
Peel strength	lb/in.			
Low-profile copper	(Kg/M)	3.9 (70)	10 (180)	8 (145)
Standard copper				
After thermal stress		4.5 (80)	8 (145)	5.9 (105)
At 125°C		3.9 (70)	5 (90)	3.9 (70)
After process solution		4.5 (80)	5 (90)	4.5 (80)
Dimensional stability	in./in.	—	0.0005	0.0002
Flammability (UL)	UL 94	V-0	V-0	V-0
Average burn time (max)	sec	5	5	5
Individual burn time (max)	sec	10	10	10
Flexural modulus				
LD	psi	—	3×10^3	—
CD		—	2.5×10^6	—
Flexural strength				
LD	psi	60,000	85,000	70,000
CD		50,000	60,000	60,000
Coefficient of thermal expansion				
X	x106	15	15	15
Y		15	15	15
Z		60	55	60
Maximum operating temperature	0C	—	130	—
Arc resistance	sec	60	120	60
Thermal		—	—	—
Tg range	°C	100	130	180

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TABLE 5.6

Typical Properties of Triazine and Bismaleimide-Modified Epoxy Flame Retardant

Property	Units	E-Glass	Quartz
Peel strength	Kg/M		
After thermal stress		90	90
At elevated temperature		35	35
Volume resistivity	Megohm-cm		
After moisture resistance		$\times 10^6$	$\times 10^6$
At elevated temperature		$\times 10^5$	$\times 10^3$
Surface resistance	Megohm		
After moisture resistance		$\times 10^6$	$\times 10^4$
At elevated temperature		$\times 10^5$	$\times 10^3$
Moisture absorption	%	0.35	0.3
Dielectric breakdown (max)	Kv	40	40
Dielectric constant	1 MHz	4.8	4.3
Dissipation factor	1 MHz	0.02	0.015
Flexural strength at elevated temperature			
LD	Kg/M2	2.11×10^7	2.11×10^7
CD			
Arc resistance	sec	60	60
Thermal stress	10 sec @ 288°C	Pass	Pass
Electric strength (min)	v/m	2900	2900
Flammability (UL)	sec	5	5

Cyanate ester is a good option for high-complexity, high-layer-count multilayer boards, where its low Dk is of value for two reasons:

- Lower-Dk materials permit impedance requirements to be met with thinner individual spacing than would be possible with higher-Dk materials such as FR-4.
- Lower-Dk materials help reduce "cross-talk" between closely spaced signal lines and minimize the requirement for extra shielding lines.

The properties of triazine- and bismaleimide-modified epoxy with either E-glass or S-2 reinforcement are shown in Table 5.6.

5.4.3 Polyimide Laminates

5.4.3.1 Polyimide/Glass

The base resin system is a pure polyimide resin that provides a low *z*-axis expansion through the most severe processes and thermal excursions resulting in good plated-through-hole integrity. This laminate is ideal for

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many different applications due to its low *z*-axis expansion. It improves the plated-through-hole reliability on high-layer-count multilayer boards, or where thick (>0.093 in. [>2.36 mm]) finished boards are needed for mechanical purposes. The high copper peel retention at elevated temperature allows multiple soldering or rework cycles and is ideal where field repairs are required. The pure polyimide chemistry provides the ultimate in thermal resistance for long-term high-temperature burn-in applications or in down-hole environments. The low *z*-axis CTE significantly improves via reliability in the thermal cycling environment.

Polyimide glass laminates exhibit relatively low *z*-direction CTE (30 to 50 ppm/°C) as well as moderate water absorption, high flexural and peel strengths, good dimensional stability (*xy*), and a relatively low density. Coupled with this is the ability to process polyimide/quartz using the same equipment and techniques as polyimide/glass laminates.

Without copper foil, the polyimide/glass has a CTE of 15.0 to 15.9 ppm/°C, and with 9.4% copper, the CTE is ~15.6 to 16.1 ppm/°C. At 17 ppm/°C there is a crossover due to copper. This tends to stabilize the CTEs in the range of 55 to 65% resin content. Electrically, polyimide/quartz laminates exhibit a relatively low Dk and Df (4.0–4.2 and 0.015, respectively).

5.4.3.2 Polyimide Glass and Copper-Invar-Copper

Copper-invar-copper (CIC) has a low CTE (~4.6 ppm/°C) and a higher modulus (20,000,000 psi). Laminates containing CIC are significantly lower in CTE than their nonconstrained counterpart. Even at 8% copper, a CTE of 12 to 13 ppm/°C is obtainable at normal resin content range if about 10% by volume of CIC is used.

5.4.3.3 Polyimide Quartz

Polyimide quartz offers the advantage of a low CTE combined with a low Dk (3.65 at 10 GHz) and Df (0.005). A CTE of 11.7 to 12 ppm/°C was achieved without copper and 12.8 to 13.7 ppm/°C with 13% retained copper. Quartz is best selected if its dielectric properties are also important.

Laminates and materials made from quartz fibers exhibit high strength, low expansion, excellent chemical resistance, and attractive electrical properties. Application for this type of material has been in the military and aerospace programs (aircraft, space vehicles, missiles, antennas, heat shields, and nose cones).

Physically, polyimide quartz has a number of excellent properties including a low CTE, low water absorption, high flexural strength, high peel strength, good dimensional stability (*xy*), and a relatively low density. Coupled with this is the ability to process polyimide/quartz using the same equipment and processes as polyimide/E-glass. Another physical

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property that is attractive is a relatively low *z*-axis expansion of 30 to 35 ppm/°C. Because quartz fibers are made of fused silica glass, the same amino-silane coupling agent can be used that is used for E-glass.

On the downside, quartz-based laminates are abrasive and will use drill bits much faster than will glass-reinforced products with the same resin system.

The physical properties of polyimide resin reinforced with either E-glass or quartz are given in Table 5.7.

5.4.4 Polyphenylene Oxide (PPO®)

The combination of epoxy and polyphenylene oxide resin and glass reinforcement yields a low Dk of 3.6 to 4.3 at 1 MHz and a Df of 0.005 at 1 MHz and 0.009 at 1 GHz. Copper-clad laminates made from proprietary unsaturated polyester resins are being used for high-frequency applications. A PPO/epoxy system has a low Dk and is stable over a wide temperature range. These materials are hybrid polyester-based laminates that compare favorably to PTFE but process and assemble like FR-4. They are very suitable for wireless applications. The physical properties of PPO/epoxy laminates are shown in Table 5.8.

5.5 Aramid Laminates

5.5.1 Epoxy Thermount®

Epoxy Thermount consists of a nonwoven aramid reinforcement coated typically with a high-temperature epoxy (or alternatively, polyimide with higher Tg at 250°C resin). The result is a material having a Tg of ~170°C with typical CTE values of 10 to 12 ppm/°C. The Dk at 3.8 to 4.0 is lower than that of FR-4. The absence of woven fiberglass reinforcement allows for the formation of vias by use of lasers. Increased density interconnects are made possible by the material's smooth surface and the laser-formed vias.

The Dk of nonwoven aramid reinforcement is consistent across all constructions and thickness but also over a wide frequency range. This relates to a predictable and stable performance for impedance control for almost any design. Stable Dk also means that there will be no surprises as new designs come along operating at different frequencies, as the Dk is also stable over frequency range. Nonwoven aramid materials provide a low in-plane CTE. The copper content (% by weight) will drive the expansion rate higher.

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TABLE 5.7

Typical Properties of Triazine and/or Bismaleimide-Modified Epoxy

Property	Units	Polyimide/ E-Glass	Modified Polyimide with E-Glass	Non-MDA Polyimide/ E-Glass	Polyimide Quartz
Peel strength	Kg/M				
After thermal stress		70	60	70	—
At elevated temperature		80	70	80	—
Volume resistivity	Megohm-cm				
After moisture resistance		$\times 10^4$	$\times 10^8$	$\times 10^8$	5×10^9
At elevated temperature		6×10^5	$\times 10^6$	—	—
Surface resistance	Megohm				
After moisture resistance		$\times 10^4$	$\times 10^6$	3×10^8	8×10^7
At elevated temperature		6×10^4	$\times 10^6$	$\times 10^8$	$\times 10^7$
Moisture absorption	%	11	1	0.35	0.35
Dielectric breakdown (max)	Kv	40	40	40	40
Dielectric constant	1 MHz	5.4	5.4	4.3	3.6
Dissipation factor	1 MHz	0.035	0.035	0.01	0.01
Flexural strength temperature					
LD	Kg/M^2	4.23×10^7	4.23×10^7	4.23×10^7	4.23×10^7
CD		3.31×10^7	3.17×10^7	3.31×10^7	3.31×10^7
Flexural strength at elevated temperature (LD)	Kg/M^2	3.17×10^7	3.17×10^7	3.17×10^7	3.17×10^7
Arc resistance	sec	120	120	120	120
Thermal stress	10 sec @ 288°C	Pass	Pass	Pass	Pass
Electric strength (min)	v/m	2900	2900	2900	2900
Flammability (UL)	sec	—	—	—	—
Tg range	°C	260	240	250	260

The combination of DICY-free multifunctional epoxy (Tg 180°C) on nonwoven aramid reinforcement and a nominal resin content of 49% is designed for performance reliability with various interconnect packages such as ball grid arrays (BGAs), thin small outline packages (TSOPs), and fine pitch surface mount technology (FP-SMT), where conventional substrates are more prone to solder joint cracking under thermal and power cycling due to CTE mismatch of the mounted devices.

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TABLE 5.8

Typical Properties of Polyphenylene Oxide/Epoxy-Resin-Impregnated E-Glass

Property	Units	Polyimide/ E-Glass
Peel strength	Kg/M	
After thermal stress		80
At elevated temperature		70
Volume resistivity	Megohm-cm	
After moisture resistance		$\times 10^6$
At elevated temperature		$\times 10^5$
Surface resistance	Megohm	
After moisture resistance		$\times 10^4$
At elevated temperature		$\times 10^3$
Moisture absorption	%	0.55
Dielectric breakdown (max)	Kv	40
Dielectric constant	1 MHz	4.4
Dissipation factor	1 MHz	0.035
Flexural strength temperature		
LD	Kg/M^2	4.23×10^6
CD		3.52×10^6
Flexural strength at elevated temperature (LD)	Kg/M^2	—
Arc resistance	sec	60
Thermal stress	10 sec @ 288°C	pass
Electric strength (min)	v/m	2900
Flammability (UL)	sec	5
Tg range	°C	—

5.5.1.1 Multifunctional Epoxy/Nonwoven Aramid Reinforcement

The combination of multifunctional epoxy (Tg 180°C) on nonwoven aramid reinforcement and a nominal resin content of 54% is designed for performance reliability in those applications which use laser or plasma ablation or for filling circuitry that is etched on heavier than 1 oz copper. This type of substrate is also designed for packaging with various interconnect packages where solder joints are prone to cracking under thermal or power cycling due to CTE mismatch of the mounted devices. Typical properties of epoxy/Thermount are given in Table 5.9.

5.5.2 Epoxy on Woven Kevlar®

Kevlar aramid organic fiber was developed by the DuPont Company in the mid-1970 as a high-tensile, high-modulus, low-density reinforcement material. The use of Kevlar cloth impregnated with resin as a printed wiring material can be used as an alternative to glass/epoxy.

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TABLE 5.9

Typical Properties of Resin-Impregnated Nonwoven Aramid Reinforcement

Property	Units	Multifunctional Epoxy	Non-MDA Polyimide
Peel strength	lb/in.	4	3.5
Volume resistivity	Megohm-cm		
After moisture resistance		$\times 10^6$	$\times 10^6$
At elevated temperature		$\times 10^3$	$\times 10^3$
Surface resistance	Megohm		
After moisture resistance		$\times 10^4$	$\times 10^4$
At elevated temperature		$\times 10^3$	$\times 10^3$
Moisture absorption	%	3	3.5
Dielectric breakdown (max)	Kv	1.5	1.3
Dielectric constant	1 MHz	4	4.5
Dissipation factor	1 MHz	0.025	0.035
Flexural strength	psi	37,300	34,000
Flexural modulus	psi	187,000	170,000
Tensile strength	psi	363,000	165,000
Tensile modulus	psi	203,000	226,000
Coefficient of thermal expansion			
Thermal stress			
X	in./in./°C	7.0–9.0	6
Y		7.0–9.0	6
Z		80–90	95
Glass transition temperature	°C	180	220

Lightweight, low-loss Dk, high modulus, and negative CTE make Kevlar an excellent choice for CTE-controlled boards. Within the normal range of resin content (58 to 65%), epoxy Kevlar laminates can achieve CTE of less than 6 ppm/°C and without copper foil between 8 and 10 ppm/°C.

Epoxy Kevlar laminates are most commonly constructed with a multifunctional epoxy resin (CTE 35 to 45 ppm/°C) reinforced with Kevlar aramid fabric (CTE ~–4 ppm/°C). The resulting laminate has an in-plane (*xy*) CTE from 6 to 9 ppm/°C. The Tg of the cured material is 170°C. Given that the resin expands isotropically (the same amount in each direction) to the extent that the reinforced resin system is constrained from moving in the *xy*-plane of the laminate, the resin will expand in the *z*-direction. The resin will expand approximately 60 to 70 ppm/°C below the Tg and 250 ppm/°C above the Tg.

Kevlar reinforcements and many high-performance resin systems are sensitive to humidity. Moisture may be absorbed as a result of uncontrolled storage conditions or during wet processing. The multilayer board may be degraded, causing it to blister or delaminate or causing the electrical properties to be degraded; therefore an oven drying operation is required prior to all high-temperature processing. Typical properties of epoxy/Kevlar are shown in Table 5.10.

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TABLE 5.10

Typical Properties of Woven Aramid Fabric Impregnated with Modified Epoxy Resin

Property	Units	Woven Aramid Modified Epoxy (135–190°C)
Peel strength	Kg/m	
After thermal stress		70
At 125°C		70
Volume resistivity	Megohm-cm	
After moisture resistance		$\times 10^6$
At elevated temperature		$\times 10^3$
Surface resistance	Megohm	
After moisture resistance		$\times 10^4$
At elevated temperature		$\times 10^3$
Moisture absorption	%	2
Dielectric breakdown (max)	Kv	40
Dielectric constant	1 MHz	4.5
Dissipation factor	1 MHz	0.035
Flexural strength		
LD	Kg/m^2	3.52×10^7
CD		2.82×10^7
Flexural strength at elevated temperature (LD)	Kg/m^2	—
Thermal stress	10 sec @ 288°C	Pass
Electric strength	v/m	2900
Flammability (UL)	sec	Pass

5.6 Prepreg

Prepregs (i.e., PRE-imPREGnated glass fabrics) are woven glass fabrics that have been impregnated with a partially reacted resin. The creation of the prepreg is a complex process requiring the selection of the proper glass finish plus the selection of the right resin system for the required physical function, environmental performance, and electrical properties. This process involves impregnating the glass with resin and then applying heat to advance the resin to its partially cured or "B"-stage (as it is commonly called).

5.6.1 Manufacturing Prepreg

The glass fabric is first immersed in a reservoir filled with resin to impregnate it. Once the glass is fully saturated with the resin, care must be taken to meter the exact amount of resin that is to be retained on the glass and

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to control the uniformity of the resin across the web of the glass. From this point, the resin-wet glass moves on to the drying oven section of the treater where solvents are removed and the resin is advanced chemically, or "B-staged." This may be achieved with either horizontal or vertical coaters, although today vertical coaters are most commonly used for woven glass products while horizontal coaters are still used for paper-based products. The B-stage material is cooled as it leaves the oven and is rolled onto a core at the dry end of the treater.

There are specific storage requirements for prepregs. Prepregs should be stored at or below 50% relative humidity and below 70°F (21°C). Exposure to humidity can cause moisture absorption that can lead to excessive flow, voids, measling, delamination, frothy beads, and, in some epoxies, reduced Tg values due to hydrolysis of the epoxy during cure. Exposure to higher temperatures can cause premature advancement of the B-stage resin, which can result in dryness, weave exposure, delamination, laminate voids, and, in extremis, not enough flow to fill inner-layer features and achieve proper wetting of surfaces for bonding.

Prepregs in rolls should be racked and not stood on end. Standing on end will cause telescoping of rolls with subsequent problems. Rolls of prepreg should not normally be stacked on top of one another, as the bottom rolls may be damaged by the weight of the material on top. Once sheeted, prepregs can be stored in sheet form on racks or trays in stacks up to 2 in. high.

5.7 Additive Laminates

5.7.1 Additive Circuitry

A technique of building circuit lines on a non-copper-clad substrate can produce high-volume consumer-oriented products on an inexpensive substrate with punched holes or produce a high-quality fine-line board on a glass epoxy substrate with few of the problems associated with the typical copper-clad laminates. Unclad, thin copper-clad, adhesive-coated, or catalytic laminates are all forms of reinforced polymeric sheets that can be processed by additive or semiadditive techniques into printed wiring board laminates.

5.7.2 Semiadditive Laminates

Semiadditive laminates either have a thin copper foil laminated to it or a nonclad surface that has been prepared to accept copper plating. Once

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the board is fully copper-covered, standard subtractive processing techniques, including electroplating, produce the circuit lines while only a thin background remains to be etched. Laminates for this type of application fall into the following categories.

5.7.2.1 Ultrathin Copper Foil Clad

A number of thin foil claddings are available (0.125 oz [5 μm] to 0.25 oz [9 μm]). Copper electrodeposited on an aluminum or copper carrier allows these foils to be handled through typical laminate buildups and provides a shield to protect the foil from scratches and oxidation. Peelable carriers, either copper or aluminum, have a weak bond to the copper and are easily removed by the laminator before shipment, or, for further protection, they can be left on until the hole formation by the fabricator. Etchable aluminum carriers are tightly bonded to the copper foil. This prevents any epoxy resin from bleeding through a pinhole in the copper foil and spreading over the foil surface, resulting in plating and etching problems. The aluminum carrier is etched off typically using a caustic solution. This leaves only the thin copper foil clad to the laminate. The base laminate substrate for ultrathin copper-clad material is the same in every respect as that used for thicker cladding in the subtractive process.

5.7.2.2 Unclad

For some applications, the substrate is purchased without any copper cladding and the major fabrication step in semiadditive manufacturing involves applying a thin conductive copper coating over the entire board surface and in the drilled or punched holes. The unclad laminate must first be prepared for copper plating by producing a surface capable of chemical and mechanical bonding to the copper.

An adhesive, comprising a blend of phenolic resins and natural rubbers, is applied to the laminate surface. The laminate is then put through an adhesive promotion step, which oxidizes the adhesive and creates a porous hydrophilic surface that will accept copper deposition.

Regardless of the method used to create the adhesive coating, certain properties of this coating must be measured and controlled to obtain uniform copper plating with sufficient adhesion. The degree of cure of the adhesive must be within certain limits to allow proper activation of the adhesive surface. The adhesive thickness over the laminate substrate proves critical because if it is low, the resin used in electrical-grade laminates will also be oxidized by the adhesion promotion step. If degraded significantly, this can lead to electrical problems, poor copper peel strength, and absorption of chemicals and moisture, resulting in failures

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during IR fusing or component wave soldering. Typically the adhesive measures 0.6 to 1.3 thousandths of an inch.

The unclad, adhesive-coated semiadditive technique has a distinct advantage in that it can be used on any substrate. The growth of composite materials opens interesting alternatives to the field in that they allow through-hole plating on punched parts. There are no additives to the laminate substrates in these additive-coated materials, so they differ from standard copper-clad laminates only in the surface coating. Additive-coated materials have property requirements similar to the equivalent grade copper-clad laminate with the exception of some surface-related properties. The insulation resistance of the adhesive-coated laminate is low by these test methods and represents a potential problem.

Additive laminates are used only when the circuitry is composed of electroless copper. Laminates used in these processes consist of any of the semiadditive materials capable of being made catalytic, or preseeded catalytic materials. To allow plating of electroless copper, the same hydrophilic and porous surface and hole requirements are necessary for adequate copper adhesion. Laminates for this type of application fall into the following categories.

5.7.2.3 Unclad or Adhesive-Coated

Any semiadditive laminate can serve for the full additive process by using a negative resist, adhesion promoting and catalyzing only the areas to be plated, and building all circuitry with electroless copper.

5.7.2.4 Catalytic or Seeded

These laminates have an electroless copper catalyst dispersed in the resin system. Again, either the surface is resin-rich or an adhesive coating is applied. A negative resist is then applied, the surface is adhesion promoted, and electroless copper is plated on the surface and in the holes to a desired thickness. No seeding step, common to all subtractive and semiadditive manufacture, is required. Laminates manufactured for this process contain only a small percentage of the catalytic agent, and the effect on the laminate properties is minor. Properties of additive circuitry laminates are given in Table 5.11.

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TABLE 5.11

Typical Properties of Additive Laminates

Property	Units	Woven E-Glass Surface/ Cellulose Paper Core Catalyzed (CEM-1)	Woven E-Glass Nonwoven Glass Core Catalyzed (CEM-3)	Woven E-Glass Epoxy Resin Catalyzed (FR-4)
Peel strength	Kg/m			
After thermal stress		70	—	—
At 125°C		70	—	—
Volume resistivity	Megohm-cm			
After moisture resistance		$\times 10^6$	$\times 10^6$	$\times 10^6$
At elevated temperature		$\times 10^3$	$\times 10^3$	$\times 10^4$
Surface resistance	Megohm			
After moisture resistance		$\times 10^4$	$\times 10^4$	$\times 10^4$
At elevated temperature		$\times 10^3$	$\times 10^3$	$\times 10^3$
Moisture absorption	%	0.5	0.5	0.35
Dielectric breakdown (max)	Kv	40	40	40
Dielectric constant	1 MHz	5.4	5.4	5.4
Dissipation factor	1 MHz	0.035	0.035	0.035
Flexural strength				
LD	Kg/m^2	2.11×10^7	2.32×10^7	4.23×10^7
CD		1.76×10^7	1.90×10^7	3.52×10^7
Flexural strength at elevated temperature (LD)	Kg/m^2	—	60	60
Thermal stress	10 sec @ 288°C	Pass	Pass	Pass
Electric strength	v/m	2900	2900	2900
Flammability (UL)	sec	5	5	5

References

Bright, J.P. and Going, T.J., Polyetherimide laminates for high performance circuitry, *Insulation Circuits*, Oct. 1982.

Coombs, C., *Printed Circuit Handbook*, McGraw-Hill.

Data Sheets, Taconic Advanced Dielectric Division.

Ehrler, S., A review of epoxy materials and reinforcement: Part 2, *PC Fab*, April 1999.

Engineering Fact File, *Electronic Packaging and Production*, June 1997.

Grebenkemper, J., Thin PCB laminates, *PC Design*, Mar. 2002.

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Guiles, C., CTE Materials for PWB's, Arlon Electronic Substrate Division.
Iguchi, D., Clearing up the confusion about multifunctional epoxy, *Circuitree Mag.,* Nov. 1993.
IPC-4101, Institute for Packaging Electronic Circuits.
Jawitz, M., *Printed Circuit Board Material Handbook,* McGraw-Hill.
Jorgensen, C., FR-4 dead as Dillinger, *PC Fab,* April 1999.
Laminates, *Circuit Manufacturing,* Jan. 1980.
Lampe, J., *High Frequency Laminates,* IPC.
NEMA Specification L1-1, National Electrical Manufacturing Association.
Sober, D., Fundamentals of Base Materials, IOC Workshop.
Witkins, R.M., *Processing Teflon Boards for Stripline Fabrication,* Transaction of the California Circuit Association.

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6

High-Speed/High-Frequency Laminates

6.0 Introduction

In the past few years increasing clock speeds and the use of higher frequencies in commercial electronics have resulted in a convergence of requirements between what have traditionally been considered "conventional" PWBs and those that were considered as "microwave and RF." As a result, there has been a broad-based effort to optimize the performance and reduce the cost of PTFE-based microwave laminates, concurrent with an effort to develop non-PTFE, cost-effective alternative materials for applications where the full package of properties associated with PTFE can be "designed around." It has become increasingly difficult for lossy (0.025 to 0.03) FR-4 and its derivatives to meet the needs of packaging at frequencies above 1 to 2 GHz where signal-to-noise ratio is critical. In this chapter we will look at PTFE laminates as well as some of the alternatives that have been developed.

6.1 High-Speed/High-Frequency Laminates

High-speed laminates are constructed with materials that will permit circuits to operate at microwave and RF frequencies. Advanced electronics that will contain Very High Speed Integrated Circuits (VHSIC) with pulse rates in a fraction of a nanosecond will have to perform when "clock rates" 20 times those in production today are used. To meet their special end product designs requirements, high-frequency laminates typically have a low dielectric constant (Dk) and a low dissipation factor (Df) over the application's frequency and temperature range. High-speed/high-frequency materials are normally characterized as having a Dk of less than 4.0 and a Df of less than 0.010, although high-Dk materials (4.5, 6, and 10) are available for microwave/RF applications requiring circuit miniaturization.

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Electronic packaging can be divided into two major applications, each of which has its own unique requirements. The differences are sufficiently different that two classes of materials have been developed to meet these demands (RF analog and digital). The major differences between these two areas are the ability of the circuitry involved to tolerate signal losses and the complexity of the circuitry.

6.1.1 RF Analog Circuit Characteristics

RF analog circuits are usually processing signals that are small and precise. The accuracy with which the circuits perform, or the ability of the circuits to process low-level signals successfully, depends on the package having the lowest possible losses to maintain an acceptable signal-to-noise ratio. Losses for this type of product occur as reflections, from impedance changes, or from absorption of some of the signals in the dielectric material.

Losses from reflection are traceable to variations in impedance. These stem from variations in thickness, variations in the Dk of the laminate, or variations in final trace width and thickness. The first two of these are due to variability in the laminate itself, while the last may be attributed to the board fabrication process. RF analog circuits are sufficiently uncomplicated that most can be constructed on a double-sided PWB. As a result, the ability of a material to be laminated into a multilayer structure is less important than are losses and Dk and Df uniformity.

6.1.2 Digital Circuit Characteristics

Digital circuits are designed to tolerate substantial losses and still perform their tasks successfully. As a result, material characteristics other than loss tend to be more important. Digital circuits tend to be more complex and require multiple signal and power layers to house them. This puts a priority on processing characteristics, such as ease of lamination, ease of drilling, etc. Electrical requirements in some designs cause the printed circuit board to be relatively thick. To ensure that the printed circuit board will not fail as a result of rework, material must not soften at rework temperature. (In traditional laminates, Tg is used as an indicator of ability to withstand rework temperature, but in many microwave materials such as PTFE, there is no Tg as such.)

6.1.3 Two Major Classes of Reinforcements

Printed circuit board dielectric materials can be divided into two major classes based on the type of reinforcement used (woven glass and non-woven reinforcement). Because of the amount of glass in the woven glass

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cloth, the Dk of the laminates based on it is higher than that of laminates based on other reinforcements (glass used in laminates has a relative Dk of 6.0).

6.1.4 Goal of Each Application Area

RF analog applications are characterized by the need for low losses, low leakage, low and uniform Dk, and a low layer count. Further, since this type of printed wiring board tends to be small, cost of the dielectric material has less effect on the overall product cost than does the cost of the other components. As a result, using more expensive materials to meet performance goals is acceptable. For this class of printed wiring boards, choosing a material based on Dk and loss characteristics usually dominates over purely cost considerations.

High-layer-count multilayer printed wiring boards with a large number of drilled and plated through holes characterize digital applications. The processing cost associated with registering and laminating many layers, coupled with drilling, usually dominates the choice of materials. The absolute Dk value of the insulating materials is important, but it is less important than processing cost and dimensional stability. As a result, woven-glass-reinforced materials are nearly always required. The choice of a resin system used with the glass reinforcement is usually based on keeping the *z*-axis expansion within acceptable limits. The thicker the printed circuit board is, the lower the total *z*-expansion must be to produce a reliable printed wiring board. Digital applications are almost always subjected to pricing pressure (not so with RF analog), so material choices must be made that achieve performance at minimal cost.

An exception to the above for digital wiring boards occurs when layer counts become extremely high, as often occurs with supercomputers. To keep the overall printed wiring board thickness within reasonable limits and still achieve impedance in the 50-ohm range, it is often necessary to use nonreinforced laminates. This results in a lower Dk and a higher impedance. Dimensional stability is achieved by mating signal layers with power planes on opposite sides of the laminate. The sheet of copper provides the dimensional stability during processing and lamination. The cost of the printed wiring board will be higher using this strategy.

One other area that can require the choice of low-Dk materials is in the fast-switching applications such as gigabit and higher clock systems. In such products, signal propagation speed (which can also be referred to in terms of propagation delay) along the traces required to connect components determines how fast the system can operate. Signal speed in a dielectric medium is determined by dividing the speed of light in a vacuum by the square root of the effective dielectric constant of the medium.

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A material with a Dk lower than conventional FR-4 will often be required. It should be noted that the increase in speed may carry with it a much higher material and process cost per circuit. A designer is advised to try other methods for achieving the desired speed, such as designing with the shortest possible runs between critical devices, before resorting to this solution.

6.2 Thin Laminates

Thin laminates provide a means to reduce high-frequency electrical noise in the power distribution system of a digital system. These laminates are beneficial if they have reduced thickness, increased Dk, or increased Df.

Thinner laminates damp out at a much faster rate than thicker laminates. This occurs because the thinner laminates induce a higher field between the power/ground plane pair. This field causes more current to flow in a copper ground plane, which causes additional energy loss due to RF effects. Utilizing thin laminates on power/ground plane pairs can significantly reduce high-frequency noise on the power distribution network. From an electrical noise viewpoint, using laminates with a higher Dk and Df will also reduce noise.

The switching noise on printed circuit power planes is increasingly becoming an issue in computer designs. Both the switching rates and switching current amplitude are increasing with each new generation of chip designs. The noise is one source of intermittent failures in digital logic. Conventional techniques for reducing noise are becoming increasingly less effective at higher frequencies.

6.3 Resins

6.3.1 Polytetrafluoroethylene Laminates

Polytetrafluoroethylene-based laminates are selected primarily for their low loss characteristics. PTFE resin typically has a dielectric constant of 2.09 and a loss of 0.004 at 10 GHz. The Dk value is relatively flat with frequency. Woven-glass reinforcement provides dimensional and mechanical stability required for cost-effective manufacturing using standard printed wiring board technology. Woven-glass-supported PTFE materials are not new. Since the early 1950s, when the first woven-glass-supported

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copper-clad PTFE laminates were introduced, they have found broad use in the high-speed/high-frequency and RF microwave fields. The desired electrical properties of these materials relate to the high resin content of PTFE, an ultrahigh-molecular-weight, high-temperature thermoplastic. By varying the ratio of glass to resin, and by incorporating carefully selected ceramic fillers to modify Dk and processing characteristics, a family of products has been engineered to suit the requirements for Dk, Df, and mechanical properties unique to each design (see Table 6.1).

Increasing emphasis in the microwave industry on smaller-size, lightweight components for airborne applications, as well as FCC and military requirements for the utilization of higher frequencies to make better use of available bandwidths, have led to the growth in the demand for precision stripline circuitry. Copper-clad glass-reinforced polytetrafluoroethylene is frequently specified as the base material for these applications due to its favorable electrical properties at frequencies above 1 GHz.

TABLE 6.1

Typical Properties of PTFE Woven Fiberglass

Property	Units	Value
Dielectric constant	1 MHz	—
	10 GHz	
Dissipation factor	1 MHz	—
	10 GHz	0.004
Thermal coefficient of Er		
Volume resistivity	Megohm-cm	1×10^6
Surface resistance	Megohm	1×10^4
Arc resistance	sec	>180
Tensile modulus	kpsi	—
Tensile strength	kpsi	—
Compressive strength	kpsi	—
Flexural modulus	kpsi	—
Dielectric breakdown	Kv	20
Specific gravity	g/cm^3	—
Water absorption	%	0.2
Coefficient of thermal expansion		
X	ppm/°C	9.0–12.0
Y		9.0–12.0
Z		120–145
Thermal conductivity	W/mk	0.34
Outgassing		
Total mass loss	%	—
Collected materials	%	—
Condensation materials	%	—
Water vapor recovered	%	—
Flammability (UL)	UL 94	V-O

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Lowering the Dk reduces the delay propagation and leads to the reduction in cross-talk at a given impedance. A low Df minimizes rise-time degradation by preserving the high-frequency content of short rise-time signals.

PTFE is inherently a low-modulus material, which makes handling neat PTFE difficult and, as mentioned above, is why woven fiberglass is typically used in most PTFE constructions. An alternative to using PTFE with glass reinforcement is to use an expanded PTFE fiber impregnated with conventional resins such as epoxy or cyanate ester to achieve microwave properties. Expanded PTFE fibers have a porosity of 10 to 20% and a Dk of 1.7 to 1.9; however, after impregnation and lamination, these fibers become fully densified (air excluded) and the Dk rises to about 2.0. Dimensional stability may be a problem if this fiber is the sole reinforcement in a laminate. Although PTFE fibers have a relatively high tensile strength, they are compressively weak. During processing, this material will shrink; therefore a small amount of either quartz or E-glass can be added for stabilization (see Table 6.2 and Table 6.3).

TABLE 6.2

Typical Properties of PTFE/Epoxy Woven Fiberglass

Property	Units	Value
Dielectric constant	1 MHz	3.8
	10 GHz	3.5
Dissipation factor	1 MHz	0.0022
	10 GHz	0.0026
Thermal coefficient of Er		–213
Volume resistivity	Megohm-cm	3×10^{12}
Surface resistance	Megohm	4.6×10^{11}
Arc resistance	sec	>180
Tensile modulus	kpsi	154
Tensile strength	kpsi	147
Compressive strength	kpsi	223
Flexural modulus	kpsi	342
Dielectric breakdown	Kv	>45
Specific gravity	g/cm^3	2.39
Water absorption	%	0.08
Coefficient of thermal expansion		
X	ppm/°C	35
Y		35
Z		1115
Thermal conductivity	W/mk	0.032
Outgassing		
Total mass loss	%	0.04
Collected materials	%	0.01
Condensation materials	%	—
Water vapor recovered	%	0.011
Flammability (UL)	UL 94	V-0

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TABLE 6.3

Typical Properties of PTFE/Triazine Woven Fiberglass

Property	Units	Value
Dielectric constant	1 MHz	3.8
	10 GHz	3.7
Dissipation factor	1 MHz	0.001
	10 GHz	0.001
Thermal coefficient of Er		—
Volume resistivity	Megohm-cm	1×10^6
Surface resistance	Megohm	1×10^6
Arc resistance	sec	>180
Tensile modulus	kpsi	—
Tensile strength	kpsi	—
Compressive strength	kpsi	—
Flexural modulus	kpsi	—
Dielectric breakdown	Kv	>45
Specific gravity	g/cm^3	—
Water absorption	%	0.08
Coefficient of thermal expansion		
X	ppm/°C	—
Y		—
Z		—
Thermal conductivity	W/mk	—
Outgassing		
Total mass loss	%	—
Collected materials	%	—
Condensation materials	%	—
Water vapor recovered	%	—
Flammability (UL)	UL 94	V-0

PTFE woven-glass laminates are offered in a wide range of Dk values and thicknesses with an assortment of copper foils and metal cladding to provide optimum match to specific frequencies, losses, and impedance design criteria. PTFE products can be designed and manufactured with Dk values from as low as 2.17 (Df 0.0009) to as high as 10.2 (Df about 0.003) and almost anywhere in between. Product thicknesses are available, depending on the specific products, from as low as 0.002 to over 0.5 in. (0.076 to over 12.7 mm) with many "special" products becoming "standard" as they find broad applicability in the industry.

Standard copper foils include 0.5, 1, and 2 oz, low-profile electrodeposited copper and 0.5, 1, and 2 oz rolled annealed copper foils. Heavy metal backing is also common for ground planes, heat sinks, and packaging, which lends rigidity and dimensional stability to the dielectric through fabrication.

PTFE-coated glass fabric forms the building block for this family of laminate materials. The desired Dk and thickness are achieved by combining the proper number of glass plies and the proper amount of resin.

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The entire package is fusion-bonded with metal foil under high pressure and at a temperature exceeding the melting point of PTFE. Thus no "adhesives" are used to apply the cladding. The Dk and thickness control relate directly to the building block, the PTFE-coated glass. By controlling the resin content to ±1%, a very tight Dk tolerance of ±0.015 about the actual value (not the nominal) can be achieved. Thickness tolerances are likewise very tight because of the uniformity of the very fine woven-glass fabric and tight weight-coating control. Both of these features, tight Dk and thickness control, are critical for optimum frequency response and impedance control.

6.3.2 Ceramic-Filled Polytetrafluoroethylene

The selection of laminates typically available for designers is significantly reduced once the operating frequencies increase to 1 GHz and above. Use of ceramic fillers has also enabled PTFE products to be manufactured with excellent stability of dielectric constant as a function of temperature, with dielectric constants as high as 6 and 10.2 and with higher thermal conductivity, especially valuable in higher-powered applications such as power amps and high-speed switching systems that generate a lot of heat. Ceramic-filled PTFE is also easier to process in many applications, having in most cases lower *x*-*y* and *z* CTE values, and because the ceramic makes drilling easier and cleaner without the risk of resin smearing in "pure" PTFE packages.

An alternative to PTFE, the use of glass-reinforced hydrocarbon/ceramic laminate is designed for performance-sensitive commercial applications. The designer of RF microwave circuits requires stable electrical properties over environmental conditions, allowing for repeatable design of filters, matching networks, and controlled impedance transmission lines. Low dielectric loss allows these materials to be used in many applications where higher operating frequencies limit the use of conventional circuit board materials (see Table 6.4).

6.3.3 New Fluoropolymer Composite Materials

New fluoropolymer composite materials have been developed to meet both the electrical and mechanical demands of the high-density digital boards. They are fluoropolymer-based and filled with ceramic particles. These materials have Dk values ranging from 2.8 to 3.5, which reduces the propagation delay by up to 30% compared to the conventional epoxy/E-glass laminate. Additionally, cross-talk and board thickness are substantially reduced. The Dk can be selected between 3.5 and 3.6. Another approach is to build multilayers with one or two layers of PTFE on the

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TABLE 6.4

Typical Properties of PTFE/Nonwoven Fiberglass/Ceramic Laminates

Property	Units	Value
Dielectric constant	1 MHz	—
	10 GHz	3.5
Dissipation factor	1 MHz	—
	10 GHz	0.0026
Thermal coefficient of Er		–213
Volume resistivity	Megohm-cm	3.3×10^{12}
Surface resistance	Megohm	4.6×10^{11}
Arc resistance	sec	>180
Tensile modulus	kpsi	154
Tensile strength	kpsi	147
Compressive strength	kpsi	223
Flexural modulus	kpsi	342
Dielectric breakdown	Kv	>45
Specific gravity	g/cm^3	2.39
Water absorption	%	0.08
Coefficient of thermal expansion		
X	ppm/°C	35
Y		35
Z		115
Thermal conductivity	W/mk	0.032
Outgassing		
Total mass loss	%	0.04
Collected materials	%	0.01
Condensation materials	%	—
Water vapor recovered	%	0.03
Visible condensate	%	NO
Flammability (UL)	UL 94	V-O

substrate surface. FR-4 is used as the bonding agent. An alternative product developed to meet the needs is a ceramic-filled thermoset resin–based laminate (Table 6.2). These materials have a Dk of 3.8 and a Df of 0.0022, and when a flame retardant is added to this material, the Dk increases to approximately 3.48 and the Df to 0.004.

These high-frequency laminates use the technology of combining the low-loss dielectric properties (Dk of 3.02 and Df of 0.0016) of a thermosetting nonpolar organic resin with the low expansion properties of the ceramic filler. This combination is designed for performance in high-frequency applications (beyond 40 GHz) where conventional materials' Dk and Df are inadequate for the circuitry. These materials are designed for improved mechanical stability. This high-frequency material is ceramic-filled laminate reinforced with a woven fiberglass. These materials are designed to offer exceptional electrical properties and mechanical stability.

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6.3.4 Epoxy Resin

Another low-cost material developed as a replacement for all PTFE laminates is a specific formulation of epoxy resin. This is a homogeneous, flame-retardant, thermosetting epoxy formulated to provide improved dielectric properties. These resins are applied to standard E-glass fabric with standard copper foil. What makes this resin unique is that it contains no dicyandiamide (DICY) as the cross-linking molecule. As a result, this resin provides better thermal, dielectric, and moisture absorption than the higher-performance FR-4.

The Dk of these laminates is about 20% lower than that of the standard FR-4 epoxy, and the Df represent a 50% reduction in signal loss. One of the advantages of this material is in designing controlled impedance boards. With a lower Dk, designers can utilize thinner cores to obtain the same impedance values as FR-4, resulting in thinner laminates and more reliable multilayer circuit boards. This material is qualified to UL as ANSI FR-4.

6.4 High-Frequency Laminate Designations

The following designations (per Mil-S-13949) have been assigned to materials that are used for high-speed/high-frequency laminates:

GRN for dielectric constant from 2.17 to 2.33

GTN for dielectric constant less than 2.8

GXN for dielectric constant from 2.4 to 2.60

GYN for dielectric constant from 2.15 to 2.40 at X-band

6.4.1 GRN Type Laminates with Glass Microfibers

Laminates meeting type GRN (Dk = 2.17–2.33 at 10 MHz) use a low ratio of glass microfibers that are randomly oriented to maximize benefits of fiber reinforcement in the direction most valuable to circuit producers and in the final circuit application. The low Df extends the usefulness to K-band and above. Together, these properties offer faster signal propagation and higher signal-to-noise ratio. Materials with a Dk of 2.33 use a higher fiberglass/PTFE ratio for a more highly reinforced combination, which offers better dimensional stability and increased mechanical

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strength. Typical properties of laminates that meet the requirements of type GRN are shown in Table 6.5.

6.4.1.1 GRN Type Laminates with Nonwoven Fiberglass

These laminates are nonwoven fiberglass/PTFE composites for use as printed wiring board substrates. The nonwoven reinforcement allows these laminates to be used more readily in applications where the final circuit will be bent to shape. Conformal or "wraparound" antennas are a good example. These laminates use longer random fibers and a proprietary process to provide greater stability and better Dk uniformity. Typical properties for these laminates are given in Table 6.5.

TABLE 6.5

Typical Properties of PTFE Woven Glass Type GRN

Property	Units	Values Microfibers	Values Nonwoven Fiberglass
Dielectric constant	1MHz	—	—
	10 GHz	17–2.20	2.33
Dissipation factor	1 MHz	—	—
	10 GHz	0.0009	0.0013
Thermal coefficient of Er		–157	–132
Volume resistivity	Megohm-cm	2.4×10^{14}	1.3×10^{13}
Surface resistance	Megohm	3.2×10^{12}	1.1×10^{11}
Arc resistance	sec	>180	>180
Tensile modulus	kpsi	133	173
Tensile strength	kpsi	120	147
Compressive strength	kpsi	182	197
Flexural modulus	kpsi	213	239
Dielectric breakdown	Kv	>45	>45
Specific gravity	g/cm^3	2.23	2.27
Water absorption	%	0.04	0.05
Coefficient of thermal expansion			
X	ppm/°C	46	31
Y		47	35
Z		311	203
Thermal conductivity	W/mk	0.263	0.263
Outgassing			
Total mass loss	%	0.02	0.03
Collected materials	%	0	0
Condensation materials	%	—	—
Water vapor recovered	%	0.02	0.02
Visible condensate	%	NO	NO
Flammability (UL)	UL 94	V-O	V-O

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TABLE 6.6

Typical Properties of PTFE Woven Fiberglass Laminates Type GTN

Property	Units	Unidirectional Values	Cross-Plied Value
Dielectric constant	1 MHz	2.40–2.65	2.40–2.65
	10 GHz	2.40–2.65	2.40–2.65
Dissipation factor	1 MHz	0.001	0.001
	10 GHz	0.0022	0.0022
Thermal coefficient of Er		–153	–170
Volume resistivity	Megohm-cm	1.2×10^9	1.8×10^9
Surface resistance	Megohm	4.5×10^7	1.5×10^8
Arc resistance	sec	>180	>180
Tensile modulus	kpsi	706	725
Tensile strength	kpsi	517	572
Compressive strength	kpsi	359	342
Flexural modulus	kpsi	537	456
Dielectric breakdown	Kv	>45	>45
Specific gravity	g/cm^3	2.31	2.31
Water absorption	%	0.03	0.03
Coefficient of thermal expansion			
X	ppm/°C	14	18
Y		21	19
Z		182	177
Thermal conductivity	W/mk	0.254	0.254
Outgassing			
Total mass loss	%	0.04	0.01
Collected materials	%	0.01	0
Condensation materials	%	—	—
Water vapor recovered	%	0.03	0
Visible condensate	%	NO	NO
Flammability (UL)	UL 94	V-O	V-O

6.4.2 GTN Type Laminates with E-Glass

Laminates meeting type GTN (Dk = 2.40–2.65 at 1 MHz) use a higher fiberglass/PTFE ratio to provide better mechanical properties approaching conventional substrates. Other advantages include better dimensional stability and lower thermal expansion in all directions. Typical properties of laminates that meet the requirements of type GTN are given in Table 6.6.

6.4.3 Type GXN Laminates with E-Glass

Laminates that meet type GXN (Dk = 2.4–2.6 at 10 MHz) use a higher fiberglass/PTFE ratio. They are designed for high-reliability stripline and microstrip circuit applications. The glass reinforcing fibers are oriented in the *xy*-plane of the laminate. This orientation maximizes dimensional

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TABLE 6.7

Typical Properties of PTFE Woven Fiberglass Laminates Type GXN

Property	Units	Unidirectional Values	Cross-Plied Value
Dielectric constant	1 MHz	2.40–2.65	2.40–2.60
	10 GHz	2.40–2.65	…..
Dissipation factor	1 MHz	0.001	0.001
	10 GHz	0.0022	0.0022
Thermal coefficient of Er		–153	–170
Volume resistivity	Megohm-cm	1.2×10^8	1.8×10^9
Surface resistance	Megohm	4.5×10^7	1.5×10^8
Arc resistance	sec	>180	>180
Tensile modulus	kpsi	706	725
Tensile strength	kpsi	517	572
Compressive strength	kpsi	359	342
Flexural modulus	kpsi	537	456
Dielectric breakdown	Kv	>45	>45
Specific gravity	g/cm^3	2.31	2.31
Water absorption	%	0.03	0.03
Coefficient of thermal expansion			
X	ppm/°C	14	18
Y		21	19
Z		182	177
Thermal conductivity	W/mk	0.254	0.254
Outgassing			
Total mass loss	%	0.01	0.01
Collected materials	%	0	0
Condensation materials	%	—	—
Water vapor recovered	%	0	0
Visible condensate	%	NO	NO
Flammability (UL)	UL 94	V-O	V-O

stability and minimizes etch shrinkage where circuit feature registration is critical. The Dk can be specified anywhere within the range of 2.4 to 2.6 with a tolerance of ±0.04. The Df extends the useful frequency range into K-band (17 to 27 GHz). Laminates meeting type GXN have mechanical properties approaching those of conventional substrates. Typical properties of laminates that meet the requirements of type GXN are given in Table 6.7.

6.4.4 GYN Type Laminates with E-Glass

Laminates meeting type GYN (Dk = 2.17–2.35) use a medium fiberglass/PTFE ratio to lower the Dk and improve the Df without sacrificing mechanical properties. These laminates are manufactured from woven fiberglass fabric coated with PTFE interleaved with thin sheets of pure PTFE. The woven matrix produces a more stable laminate with a more

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TABLE 6.8

Typical Properties of PTFE/Woven Fiberglass Ceramic-Filled Laminate Type GYN

Property	Units	Unidirectional Values	Cross-Plied Value
Dielectric constant	1 MHz	—	—
	10 GHz	2.17–2.33	2.17–2.33
Dissipation factor	1 MHz	—	—
	10 GHz	0.008	0.009
Thermal coefficient of Er		–161	–151
Volume resistivity	Megohm-cm	1.4×10^9	2.3×10^8
Surface resistance	Megohm	2.9×10^8	3.4×10^6
Arc resistance	sec	>180	>180
Tensile modulus	kpsi	267	275
Tensile strength	kpsi	202	219
Compressive strength	kpsi	237	237
Flexural modulus	kpsi	357	357
Dielectric breakdown	Kv	>45	>45
Specific gravity	g/cm^3	2.23	2.23
Water absorption	%	0.02	0.08
Coefficient of thermal expansion			
X	ppm/°C	25	25
Y		34	34
Z		252	171
Thermal conductivity	W/mk	0.261	0.645
Outgassing			
Total mass loss	%	0.01	0.01
Collected materials	%	0	0
Condensation materials	%	—	—
Water vapor recovered	%	0	0
Visible condensate	%	NO	NO
Flammability (UL)	UL 94	V-O	V-O

uniform Dk. The exceptionally low Df extends the usefulness of this material into the GHz range and above. Typical properties of laminates that meet the requirements of type GYN are given in Table 6.8.

6.4.5 High-Dk (6.0 to 10.5) Laminates with E-Glass

Laminates that meet the high-Dk (6.0 to 10.5 at 10 MHz) are basically reinforced woven fiberglass, ceramic-filled PTFE-based composites designed for electronic and microwave circuit applications. The higher Dk permits moderate circuit miniaturization, especially for lower-frequency microwave and power-amplifier applications, which use low impedance lines. These materials are a "soft substrate" and are not sensitive to vibrational stresses. This allows miniaturized circuitry without requiring the complicated processing or fragile handling associated with

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TABLE 6.9

Typical Properties of PTFE/Woven Fiberglass Ceramic-Filled Laminate, High Dk

Property	Units	Unidirectional Values	Cross-Plied Value
Dielectric constant	1 MHz	—	—
	10 GHz	6	10
Dissipation factor	1 MHz	—	—
	10 GHz	0.003	0.003
Thermal coefficient of Er		–325	–233
Volume resistivity	Megohm-cm	1.5×10^{12}	1.4×10^{9}
Surface resistance	Megohm	3.8×10^{9}	1.8×10^{9}
Arc resistance	sec	>180	>180
Tensile modulus	kpsi	700	830
Tensile strength	kpsi	500	680
Compressive strength	kpsi	225	450
Flexural modulus	kpsi	357	615
Dielectric breakdown	Kv	>45	>45
Specific gravity	g/cm^3	2.45	2.84
Water absorption	%		0.08
Coefficient of thermal expansion			
X	ppm/°C	12	14
Y		14	16
Z		62	36
Thermal conductivity	W/mk	0.431	0.645
Outgassing			
Total mass loss	%	0.02	0.02
Collected materials	%	0	0
Condensation materials	%	—	—
Water vapor recovered	%	0	0
Visible condensate	%	NO	NO
Flammability (UL)	UL 94	V-O	V-O

brittle pure ceramic materials. Materials that meet the requirements of high Dk are given in Table 6.9 and Table 6.10.

6.4.6 Temperature-Stable Dielectric Constant and Low-CTE Laminates with E-Glass

These non-PTFE laminates are a ceramic thermoset polymer composite that does not soften when heated. The electrical and mechanical properties combine many of the benefits of both ceramic and PTFE laminates without requiring the specialized production techniques common to these materials.

The low coefficient of dielectric constant, typically less than 30 ppm/°C, results in consistent electrical performance over a broad temperature range. These laminates have isotropic CTE, very closely matched to copper, allowing for the production of high-reliability plated through holes

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TABLE 6.10

Typical Properties of PTFE/Woven Fiberglass Ceramic-Filled Laminate Type CLTE

Property	Units	Values
Dielectric constant	1 MHz	—
	10 GHz	2.98
Dissipation factor	1 MHz	—
	10 GHz	0.0026
Thermal coefficient of Er		—
Volume resistivity	Megohm-cm	1×10^9
Surface resistance	Megohm	1.3×10^8
Arc resistance	sec	>180
Tensile modulus	kpsi	471
Tensile strength	kpsi	8.2,8.0
Compressive strength	kpsi	225
Flexural modulus	kpsi	375
Dielectric breakdown	Kv	>45
Specific gravity	g/cm³	2.38
Water absorption	%	0.04
Coefficient of thermal expansion		
X	ppm/°C	10
Y		12
Z		34
Thermal conductivity	W/mk	0.5
Outgassing		
Total mass loss	%	0.02
Collected materials	%	0
Condensation materials	%	—
Water vapor recovered	%	0
Visible condensate	%	NO
Flammability (UL)	UL 94	V-O

and low shrinkage. The thermal conductivity is approximately twice that of traditional PTFE/ceramic laminates, facilitating heat removal (see Table 6.10).

6.4.7 Commercial-Grade Laminates

Commercial-grade laminates are woven-fiberglass-reinforced PTFE composite engineered to produce a low-loss laminate with a nominal Dk of 3.0. This material is designed for use in high-volume commercial applications. The high weight ratio of fiberglass to PTFE yields a laminate with greater dimensional stability than is normally expected of PTFE-based substrates. It also allows these materials to be processed like FR-4 laminates with minor modifications. The moderately higher Dk also allows a marginal reduction in circuit size for a typical microwave circuit. The low

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TABLE 6.11

Typical Properties of PTFE/Woven Fiberglass Ceramic-Filled Laminate Type Low-Cost

Property	Units	Values	Values
Dielectric constant	1 MHz	—	—
	10 GHz	3.5	4.5
Dissipation factor	1 MHz	—	—
	10 GHz	0.0026	0.0026
Thermal coefficient of Er		–213	–238
Volume resistivity	Megohm-cm	3.4×10^{13}	3.3×10^{13}
Surface resistance	Megohm	4.6×10^{11}	4.8×10^{11}
Arc resistance	sec	>180	>180
Tensile modulus	kpsi	154	155
Tensile strength	kpsi	147	150
Compressive strength	kpsi	223	228
Flexural modulus	kpsi	342	345
Dielectric breakdown	Kv	>45	>45
Specific gravity	g/cm^3	—	—
Water absorption	%	0.08	0.08
Coefficient of thermal expansion			
X	ppm/°C	35	30
Y		35	30
Z		115	110
Thermal conductivity	W/mk	0.31	0.32
Outgassing			
Total mass loss	%	—	—
Collected materials	%	—	—
Condensation materials	%	—	—
Water vapor recovered	%	—	—
Visible condensate	%	—	—
Flammability (UL)	UL 94	V-O	V-O

loss makes this laminate ideal for digital signal processing applications (see Table 6.11). Because there is a relatively higher amount of fiberglass, thermal expansion is reduced in all directions. This improves plated-through-hole reliability.

6.5 Laminate Construction

6.5.1 Cross-Plied and Non-Cross-Plied Construction (meet type GT)

Microwave material is usually woven fiberglass/PTFE resin composites with copper cladding on one or both sides, for use as printed circuit substrates. In cross-plied laminates, alternating layers of coated fiberglass

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plies are oriented 90° to each other. This provides a true electrical and mechanical isotropy in the *xy*-plane. Designers have found this degree of isotropy critical in some phased-array antenna applications. These materials are used in high-frequency applications where low loss and controlled Dk are requirements, such as filters, couplers, low-noise amplifiers, power dividers, and combiners. Using precise control of the resin-to-glass ratio, you are able to offer a range of materials from the lowest Dk and Df to more highly reinforced laminates having better dimensional stability.

When these materials are used in stripline or microstrip applications, they can be processed using conventional PTFE board fabrication processes. For all other applications, these materials can be processed using typical FR-4 process parameters with few in-line modifications. These materials are rated GT or GY.

6.6 Bonding

Stripline or buried microstrip bonding can be accomplished using either a bonding film or FR-4 prepreg. Black oxide treatment can be used when bonding with FR-4 prepregs. Some specialty ceramic-filled PTFE and non-PTFE products have their own customized bonding films or prepregs that match the electrical properties of the laminates. It is best to bond directly after copper etching. Adhesion to the copper can be improved with sodium or plasma etch prior to bonding.

In designing with bonding materials, it is necessary for the designer to take into account the differences in dielectric constant and loss between the bonding film or FR-4 prepreg and the laminate being bonded. Use of bonding materials with Dk and loss as close to the design laminate as possible will improve signal integrity.

6.7 Dimensional Stability

Dimensional stability of the laminate depends on the dielectric thickness, resin-to-glass ratio, copper foil thickness, and the percent of retained copper specific to each product design. Designs having significant ground planes will have improved dimensional stability. The stability of the laminate can be improved by using solid copper borders, minimizing mechanical scrubbing, or baking for 1 h at 300 to 310°F (150 to 155°C) and cooling slowly, prior to establishing a pattern for registration.

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6.8 Drilling

Only highly polished carbide drills should be used. The use of repointed drills is not recommended. Panels can be in stacks based on total thickness. The use of rigid entry (0.010 to 0.020 in.) and exit (0.060 to 0.093 in.) material is recommended. The following feeds and speeds are recommended as a beginning point to develop specific process parameters:

Chip load: 0.002 to 0.003 in. (0.050 to 0.076 mm)/revolution

Surface speed: 400 to 450 surface ft (7316 M/min)/min

Retract rate: 500 to 600 in. (12,700 to 15,240 mm)/min

Tool life: 500 to 1000 hits (depending on stack height)

References

Coombs, C., *Printed Circuit Handbook,* McGraw-Hill Publisher.
Data Sheets, Arlon Electronic Substrate Div.
Data Sheets, Rogers Corp.
Data Sheets, Taconic Plastics.
Guiles, C., CTE Materials for PWB's, Arlon Electronic Substrates Div.
IPC-4103.
Jawitz, M., *Printed Circuit Board Materials Handbook,* McGraw-Hill Publisher.
Lampe, J., *High Frequency Laminates,* IPC.
Sober, D., Fundamentals of Base Materials, IPC Workshop.
Watkims, R.M., Processing Teflon Boards for Stripline Fabrication, Transaction of the California Circuits Association.

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7

Metal Core and Constraining Core Materials

7.0 Introduction

Designers of printed wiring boards would like to design boards using standard E-glass impregnated with a high-temperature epoxy, polyimide, or cyanate ester resin and with surface-mounted components on both sides of the board. Unfortunately, the differences in CTE between the board and these components can cause the solder joints, during thermal cycling, to work-harden, resulting in foil cracks, component failure, and possibly board design failure. Designers can solve the CTE problem between the board and components by using low-CTE materials such as quartz, Kevlar®, Thermount®, copper-invar-copper (CIC), copper-molybdenum-copper (CMC), or silicon carbide–aluminum (SiC/Al). All of these could solve the CTE problem. CIC and CMC offer more rigidity that could reduce vibration/flexural hardening of the solder joints. In addition, the CIC and CMC can also act as a thermal heat sink to extract most of the heat generated when the components are placed close together.

Constraining core layers that are used to control in-plane expansion are designed into the printed wiring board intended primarily for surface mounting of leadless ceramic chip carriers. The essential requirement for the constraining layer is that it has to have a low CTE in the *xy*-axis of the board and have a sufficiently high modulus of tension to prevent the rest of the board from expanding at its characteristic rate of 14 to 18 ppm/°C.

By varying the ratio of copper to invar or molybdenum, the designers can handpick the CTE of the restraining core materials. The choice of substrate materials depends on many parameters, and the number of restraining layers will also be decided by thermal and mechanical constraining performance requirements.

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7.1 Copper-Invar-Copper (CIC)

The main problem in producing CIC printed wiring boards is created by bonding very dissimilar materials together. CIC has a low CTE (~4.6 ppm/°C) and a high modulus of elasticity (~20,000,000 psi), which will dominate the printed wiring board. The B-stage and laminate materials have a higher CTE (~17 ppm/°C in the *xy*-axis and ~60 ppm/°C in the *z*-axis) and a lower modulus of elasticity. Constraining the B-stage to the CIC core will restrict the *xy*-axis expansion. This will cause the *z*-axis to expand to more than double to ~120 to 160 ppm/°C. The CIC has a high modulus of elasticity that moves very little in response to mechanical stress; therefore all of the stress now moves into the lower-modulus-of-elasticity materials (B-stage). If the board strength is less than the stress, debonding will occur.

CIC was developed by Texas Instruments as a roll-bonded metal composite consisting of an invar core with copper on both sides of the invar. The high-pressure, roll-bonding process creates an intermetallic bond between the copper and the invar. This is the same process used by the U.S. government to produce the current quarters. The invar has an inherently low coefficient of expansion and a high modulus. Copper is used as the cladding surface because it is the metal most commonly used in the printed wiring industry, has good heat transfer, and can be treated and handled using conventional chemistries. The CIC copper surfaces are double-treated and have an oxide modular "tooth" structure that will withstand the shear stresses experienced due to the CTE mismatch of the CIC and the resin system.

The thin copper-invar-copper layers can be used as a "distributed plane" and the heavier section can be used as cores in printed wiring boards. It is used to control the overall expansion of the board during thermal cycling. CIC layers constrain the expansion and can also serve as a power and ground plane.

CIC is used either as a heavy core or in the form of a distributed foil plane. Thinner distributed planes are probably more effective in controlling the CTE. Using a lesser percentage of invar has a greater effect on controlling the CTE, especially when located near the board surface. Heavy cores are more appropriate if their use is also intended as a heat sink. Thin invar is really not a good source to remove heat, as thicker mass is required to be effective. Invar is a nickel–iron alloy with a low CTE and a high modulus. It is also very heavy. The use of 10% or more of CIC in a board stack-up can make this material a doubtful choice for avionic applications where weight is a primary consideration. The chemical composition of copper-invar-copper is given in Table 7.1, and the

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TABLE 7.1

Chemical Composition of Restraining Materials

Material	Chemical Composition	Chemical Symbol	Percentage	Copper-Invar-Copper	Copper-Moly-Copper
Invar	Phosphorous	P	%	0.025 max	n/a
	Sulfur	S		0.025 max	n/a
	Carbon	C		0.120 max	n/a
	Manganese	Mn		0.500 max	n/a
	Silicon	Si		0.250 max	n/a
	Nickel	Ni		35.5–36.5	n/a
	Iron+	Fe		Balance	n/a
Copper	Copper + Silver	Cu + Ag	%	99.9 min	99.96 min
	Phosphorous	P		0.005 max	0.0003 max
	Lead	Pb		—	0.0010 max
	Sulfur	S		—	0.0004 max
	Zinc	Zn		—	0.0030 max
	Mercury	Hg		—	0.0001 max
Molybdenum	Aluminum	Al		n/a	0.02 max
	Calcium	Ca		n/a	0.02 max
	Silicon	Si		n/a	0.02 max
	Iron+	Fe		n/a	0.02 max
	Chromium	Cr		n/a	0.02 max
	Nickel	Ni		n/a	0.02 max
	Copper	Cu		n/a	0.02 max
	Manganese	Mn		n/a	0.02 max
	Tin	Sn		n/a	0.02 max
	Titanium	Ti		n/a	0.02 max
	Lead	Pb		n/a	0.02 max
	Carbon	C		n/a	0.02 max
	Molybdenum	Mo		n/a	99.96 min

physical properties are listed in Table 7.2. A microsection of the CIC structure is shown in Figure 7.1.

7.2 Copper-Molybdenum-Copper (CMC)

Copper-molybdenum-copper is a roll-bonded laminate consisting of a core layer of molybdenum with a layer of copper bonded to each side of the core. The CMC material exhibits an outstanding combination of characteristics.

The CTE is closely matched with that of ceramics and is stable from –67 to 1652°F (–55 to 900°C). This material possesses a high thermal conductivity,

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TABLE 7.2

Physical Properties of Copper-Invar-Copper

Property	Units	Copper-Invar-Copper		
Ratios	%	5–90–5	12.5–75–12.5	20–60–20
Volume ratio (%)	Copper	4.5–5.5	11.25–13.75	18–22
	Invar	89–91	72.5–77.5	56–64
Coefficient of thermal expansion (–55 to 125°C) (longitudinal only)	ppm/°C	1.5–3.5	2.4–5.6	3.6–6.8
Yield (0.2% offset)	Mpa	206–310	241–345	173–276
	kpsi	30–45	30–50	25–40
Tensile strength	Mpa	379–482	379–482	310–413
	kpsi	55–70	55–70	45–60
Elongation (50.8 mm [2 in.])	% min	28	20	25
Temper (invar)	PPH	139–150	139–150	139–150
Surface finish untreated	Microns	1.27 max	1.27 max	1.27 max
Surface finish treated	Microns	2.54–5.08	2.54–508	2.54–508
Density	g/cm^3	8.18	8.33	8.43
	lb/in^3	0.296	0.301	0.305
Thermal conductivity	W·cm cm^2·°C			
	X-y	0.52	1.1	1.67
	Z	0.15	0.19	0.2
	Btu·ft ft^{2}hr·°F			
	X-y	30	64	97
	Z	9	11	1
Modulus of elasticity	105 MPa	1.47	1.4	1.35
	106 psi	21.4	20.3	19.6
Conductivity	%IACS	10	25	40
Resistivity	Megohm-cm	17.25	6.9	4.31

high mechanical stability, lower planar electrical resistance, nonmagnetic characteristics, and good electrical and shielding properties. In most cases, these applications require a low CTE to match ceramic, silicon, or constraining adjacent materials as well as excellent thermal conductivity for heat dissipation. The chemical properties of CMC are given in Table 7.1 and the physical properties are given in Table 7.3. A microsection of the CMC structure is shown in Figure 7.2.

In a variety of high-performance electronic packaging applications, particularly military, the CTE match with adjoining materials is critical. CMC has a low CTE that can be adjusted by changing the ratio of copper vs. molybdenum in the cladding structure.

CMC was developed for use as a constraining core material for printed wiring boards. This material, when used in conjunction with glass-reinforced high-temperature resins, will decrease the planar thermal excursion

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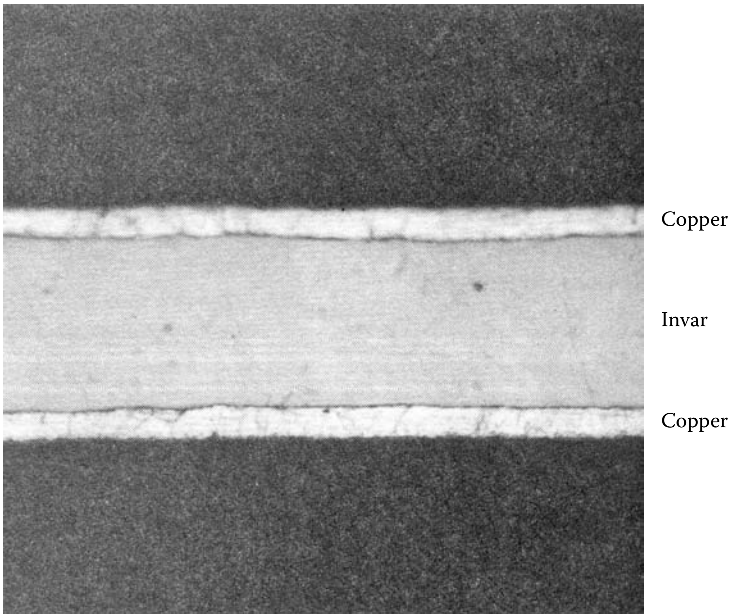

FIGURE 7.1
Cross-section of copper-invar-copper.

of the printed wiring board so that the CTE more closely matches that of the leadless ceramic chip.

With constraining core materials, the constraint in the *xy*-axis is transferred to the *z*-axis. Hole-wall cracking may occur if it is subjected to too many thermal cycles. The high-temperature thermal cycles should be 59 to 68°F (15 to 20°C) below the substrate material's Tg for long-term thermal cycling reliability. CMC is extremely popular for high-watt-density electronic packaging and is available in five different clad ratios:

Copper	Molybdenum	Copper
5	90	5
13	74	13
20	60	20
25	50	25
33⅓	33⅓	33⅓

CMC has a low *z*-axis CTE (42 to 43°F [5.7 to 6.0°C]), good thermal conductivity, and a high modulus. Unfortunately, it is very heavy, with a density of 0.363 lb/in.^{3} (10.08 g/cm^3), which is a severe penalty for avionics. The thermal conductivities of the five clad ratios listed above are shown in Table 7.4.

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TABLE 7.3

Physical Properties of Copper-Molybdenum-Copper (Cu/Mo/Cu)

Property	Units	Copper-Molybdenum-Copper		
Ratio		5–90–5	13–74–13	20–60–20
Volume ratio				
Copper	%	3.0–7.0	11.0–15.0	18.0–22.0
Molybdenum		86–94	70–78	56–64
Coefficient of thermal expansion (–55 to 125°C) (longitudinal only)	ppm/°C	5.0–5.2	5.5–6.5	5.7–6.7
Yield	Mpa	618–686	583–652	515–583
(0.2% offset)	Kpsi	90–100	85–95	75–85
Tensile strength	Mpa	724–792	620–689	551–620
	Kpsi	105–115	90–100	80–90
Elongation 2 in. (50.8 mm) length	% min	2	2	2
Surface finish	Microns	0.76	0.76	0.76
(untreated)		30	30	30
2 in. (50.8 mm) length		2.54–5.01	2.54–5.01	2.54–5.01
		100–200	100–200	100–200
Density	g/cm^3	10.02	9.82	9.66
	lb/in.^{3}	0.364	0.355	0.35
Modulus of elasticity	MPa	3.02×10^5	2.68×10^5	2.4×10^5
	psi	44×10^6	39×10^6	35×10^6
Thermal conductivity	Wcm	*X-y* 1.66	*X-y* 2.08	*X-y* 2.43
	cm^2 °C	*Z* 1.51	*Z* 1.7	*Z* 1.94
	Btu ft	*X-y* 96	*X-y* 120	*X-y* 140
	ft^{2}hr°C	*Z* 87	*Z* 98	*Z* 112
Conductivity	%IACS	40	51	60.4

7.3 Silicon Carbide–Reinforced Aluminum (SiC/Al)

Silicon carbide particulate–reinforced aluminum can be tailored to offer many of the same properties as CMC at substantially reduced weight (it has essentially the same density as aluminum). In addition, these composites have isotropic properties, have good thermal and electrical conductivities, and can be tailored to have CTE values from 6.5 to 18 ppm/°C.

In addition to a density of 0.107 lb/in.^{3}, a good thermal conductivity (180 W/m-k), and isotropic properties, the silicon carbide–aluminum has a much higher specific stiffness (Young's modulus/density, 34 Mpsi [3 g/cm^3]) than the CMC, which can result in higher resonant frequencies under vibration.

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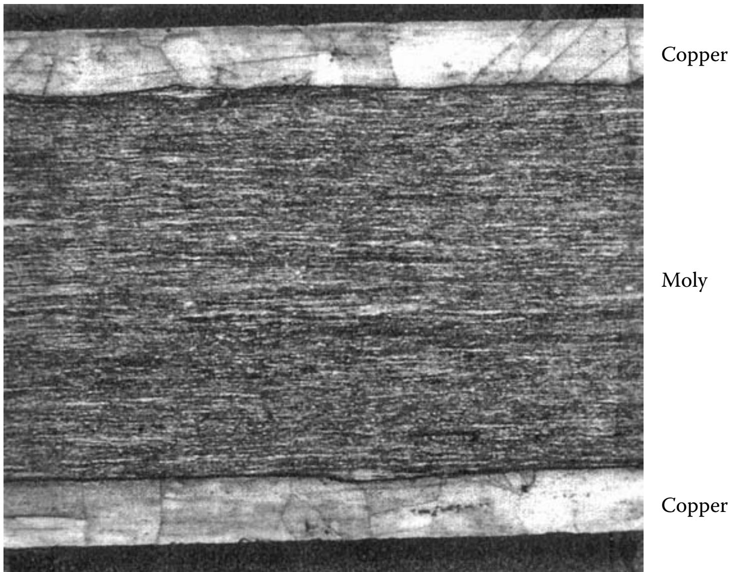

FIGURE 7.2
Cross-section of copper-moly-copper.

TABLE 7.4
Thermal Conductivity of Clad Copper-Molybdenum-Copper

Ratio	*Xy*-axis BTU·Ft/Hr·Ft² °F	*Xy*-axis W/mk	*Z*-axis BTU·Ft/Hr. Ft² °F	*Z*-axis W/mk	CTE (PPM/°F) (PPM/°C)	Modulus of Elasticity psi × 106	(Gpa)
Cu-Mo-Cu							
5–90–5	96	166	87	151	5.1	44	(303)
23–74–13	129	208	98	170	5.7	39	(269)
20–60–20	140	242	112	194	6.5	35	(241)
25–50–25	155	268	123	213	7.3	32	(220)
331/3–331/3–331/3	180	311	145	251	8.6	27	(186)

The material consists of 65% silicon carbide particles in a matrix of aluminum. The aluminum is chemically bonded to the SiC particles with such tenacity that if a sample is intentionally fractured, a cross-section will show the fracture through the SiC particle rather than a broken bond between the particles and the aluminum matrix material. The physical properties of SiC/Al are given in Table 7.5.

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TABLE 7.5

Physical Properties of Silicon Carbide (SiC/Al)

Property	Units	Value
Volume ratio	%	
Silicon carbide		65
Aluminum		35
Coefficient of thermal expansion (longitudinal only)	ppm/°C	6.2
Tensile strength	kpsi	33
	Mpa	225
Elongation	% min	
(50.8 mm [2 in.]) length		—
Surface finish untreated	Microns	
Surface finish treated	Microns	—
Density	g/cm^3	3
	$lb/in.^3$	0.107
Modulus of elasticity	105 MPa	
	106 psi	
Thermal conductivity	W·cm	180
	cm^2 °C	
	Btu·ft	98
	ft^2hr·°F	
Young's modulus-E	Mpsi	34
	Gpa	265
Poisson's ratio		0.2
4-point bend strength	MPa	300
Fracture toughness	$MPa\text{-}m^{12}$	10

7.4 Coefficient of Thermal Expansion Trade-Offs (CTE)

There are several trade-offs that are important to remember when working with CTE-controlled materials:

- When the *x-y* CTE is constrained, the *z*-direction expansion will go up because the resin expansion is incompressible. This means that the through plating will be subjected to more stress than with normal multilayer boards.
- To achieve low CTE values without constraining cores, low resin content is required. If resin content is dropped too low, dry laminate, weave exposure, etc. are possible. The use of coarse-grade glass such as 7628 to get a low resin content may result in drilling problems, measling, etc. Higher-resin-content prepreg using glass fabrics such as 106 and 1080 will drive the CTE up.

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- Constraining core layers such as CIC or CMC will result in severe shear forces generated at the interface between the metal layer and the outer board material. Care must be taken to ensure that the bonding materials used are strong enough to take the shear forces without delaminating while still being rigid enough to transfer the modulus, and hence the CTE constraint, of the constraining material into the multilayer board.
- If other properties such as Dk are important, it is necessary to recall that the high resin content will have the opposite effect on the CTE.

References

Gray, F., private correspondence, Texas Instruments, Nov. 1989.

IPC-4562, Metal Foil for Printed Wiring Applications.

Morris, S., Processing CIC PWBs, *PC Fab,* Mar. 1990.

Nickelson, R. and Jain, S., Processing copper-molybdenum-copper PCBs, *PC Fab,* Mar. 1991.

Texas Instruments Data Sheet, Copper-Invar-Copper.

Texas Instruments, *Electronic Materials Newsletter,* July 1989.

Wilson, G.C., The impact of metal cored multilayer boards, *PC Fab,* July 1989.

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Appendix

Abbreviations, Definitions, and Terms

Various terms, definitions, and abbreviations used in this book are explained here. In some cases, examples are also given to further explain the function of the term or definition.

A.1 Arc Resistance

Arc resistance measures the resistance to formation of conductive traces when exposed to high voltage, low current (less than 0.1 A), and clean conditions (no dirt or moisture). This is a measure in elapsed time until tracking; therefore the units are "seconds" applicable to both thick and thin laminates.

A.2 Coefficient of Thermal Expansion (CTE) and Thermal Coefficient of Expansion (TCE) Have the Same Meaning

The coefficient of expansion is a characteristic thermomechanical property of a material or a composite. It is the tendency of the material to expand when heated. If there is no restraining fabric in the laminate, the resin would expand the same amount in each direction and the *xy*- and *z*-axis expansion would be roughly one third of the volume expansion coefficient. Reinforcing fabrics used in laminates (glass, quartz, and Kevlar®) have a lower CTE than the resin, and the high modulus values (glass at about 12,000,000 psi, Kevlar at about 19,000,000 psi) sharply restrain the in-plane expansion of the system. The volume of resin expansion is incompressible, which means that when the resin is constrained from moving in the plane of the laminate by the high-strength fiber reinforcements, the resin will expand in the unconstrained *z*-direction.

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The *z*-direction CTE increases sharply (as much as 4x) above the glass transition temperature of the resin system. In a typical system, this means going from 50 to 200 ppm/°C at the Tg.

The CTE in the *x*- and *y*-directions generally decreases slightly above the Tg because the resin modulus decreases and the constraining tendency of the reinforcement becomes stronger since its modulus is relatively unaffected by temperature changes.

A.2.1 Common CTE Materials

Material	CTE (ppm/°C)
Copper foil	17–18
Fiberglass fabric	5–6
Epoxy resin	35–45 (anisotropic)
Polyimide	30–40 (anisotropic)
Aluminum sheet	22–23
Kevlar fabric	–4 (in-plane)
Quartz fabric	0.5
Copper-invar-copper	5.5
Aluminum-ceramic	6.0

A.3 Comparative Tracking Index (CTI)

Comparative tracking index measures the resistance of a laminate to electrical failure in a contaminated environment as a result of electrical tracking (formation of conductive paths) on circuit surfaces. The comparative tracking index provides a comparison of the performances in insulating materials under wet and contaminated conditions.

A.4 Continuous Operating Temperature

Continuous operating temperature is the temperature at which a particular material can operate without undue deterioration.

A.5 Coordinates *X-Y-Z*

The *x*-, *y*-, and *z*-axes (or coordinates) of the laminates are the "Cartesian coordinates" of a piece of laminate. By convention, the *x*-axis corresponds

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to the warp direction of the fabric used to manufacture the laminate, and the *y*-axis to the fill direction of the fabric. The *z*-axis, as is the convention in analytical geometry, is the direction perpendicular (or normal) to the plane of the laminate defined by the *x*-axis and the *y*-axis. We refer to the *xy*-axis of the laminate when we are referring to the orientation of the prepreg in the laminate for layup purposes and when we are measuring the in-plane CTE of the material. The *z*-axis is always the direction of drilled holes, and critical issues of plated-through-hole reliability often revolve around the thermal expansion properties of the laminate in the *z*-axis.

A.6 CTE (See A.2)

A.7 CTI (See A.3)

A.8 Dielectric Breakdown Voltage (DBV)

Dielectric breakdown voltage measures the resistance of electrical failure in the *xy*-axis of the laminate as might occur between plated through holes. Electrodes are placed 1 in. apart through holes drilled in the laminate. Because the distance between the holes is fixed, the measurement is in kilovolts (kV). Dielectric breakdown voltage is a measure of an insulator's ability to withstand the stress of high voltages placed across it.

A.9 Df (See A.12)

A.10 Dielectric Constant (Dk [Also Called Permittivity or Er])

The Dk is the property of the insulating material that determines the relative speed that the electrical signal will travel in the material. It is also

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a measure of the degree to which the electromagnetic wave is slowed down as it travels through the insulating material. The higher the Dk, the slower the signal travels on a wire. Signal speed is roughly inversely proportional to the square root of the Dk. A low Dk will result in a high signal propagation speed, and a high Dk will result in a much slower signal propagation speed.

The Dk of nearly all printed circuit board dielectric materials changes with frequency and usually goes down as frequency goes up. Given a choice, lower Dk is nearly always better.

A.10.1 Typical Dk of Materials as Measured at 1 MHz

Hard vacuum	1.0
Pure Teflon®	2.1
Type GY Teflon glass	2.2–2.3
Type GX Teflon glass	2.55
Cynate ester/glass	3.2–3.6
Polyimide quartz	3.5–3.8
Polyimide/glass	4.0–4.6
Epoxy glass (FR-4)	4.4–5.2
Nonwoven aramide epoxy	3.8–4.1
Woven aramide epoxy	3.8–4.1
Ceramic-filled epoxy	6.0–10.2
Water	70

A.11 Dielectric Strength

The dielectric strength (also called electric strength) measures the resistance to electrical failure in the *z*-axis by high voltage. The voltage at failure is divided by the laminate thickness in mils, yielding a measurement in V/mil.

A.12 Dimensional Stability

Dimensional stability measures the nonreversible movement in the *x*- and *y*-axis during etching and thermal excursion. Dimensional stability should not be confused with coefficient of thermal expansion of a laminate, which is a reversible expansion in all three axes during heating. In terms of dimensional stability, the movement occurs once during the first major thermal excursion and then remains somewhat stable thereafter. It is

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interesting to note that dimensional stability has nothing to do with glass transition temperature.

Dimensional stability describes the changes in the *x*- and *y*-dimensions in a piece of laminate after the copper is removed and has been subjected to various specified thermal processes.

A.13 Dissipation Factor (Df [Also Called Loss Tangent])

Dissipation factor is the measure of the percentage of the total transmitted power that will be lost as power dissipation from the laminate material. The higher the Df of the insulating material, the greater the heat generated by the circuit board. The heat in itself is not an issue in most applications, but in systems where the Dk is significant, the heat buildup can change the capacitance properties of the circuit. Teflon is the best material for Df, capable of values as low as 0.0008 (in low-Dk-type CY Teflon/glass composites). Standard epoxies and polyimides have values between 0.01 and 0.04. Not only does polyimide quartz have a lower Df than polyimide glass (in the 0.0002 range), but the pure silica of the quartz is much better electrically than E-glass. The Df is not normally considered except in high-speed digital or microwave applications.

A.14 Dk (See A.10)

A.15 Er (See A.10)

A.16 Flammability

The flammability of the copper-clad laminate is most often associated with a test conducted by Underwriters Laboratories (UL). The UL 94 test measures the ability to self-extinguish after the source of extreme heat is removed. The results of the UL 94 rating are associated with the safety of the laminate. Almost all of the laminates used as printed circuit laminates around the world carry a UL 94 V-O rating.

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A.17 Flexural Strength, Flexural Modulus

The flexural strength measures the load a laminate will carry without breaking. In terms of the copper-clad laminate, flexural strength determines the ability of the laminate to support the weight of electrical components. It is a measure of the stiffness of the laminate, i.e., the force required per unit of deflection in bending. Flexural strength predicts the amount the laminate will sag particularly during wave soldering. Flexural strength and flexural modulus are both measured in the length and cross dimensions. Values are reported in pounds per square inch (psi).

A.18 Glass Transition Temperature (Tg)

The Tg is the temperature at which a polymer changes from a hard, brittle, glassy solid to a soft, rubbery solid. It is not the melting point of the polymer or laminate.

The combination of a low Tg and high CTE can lead to barrel cracking in the plated through holes in the circuit board. In general, the higher the glass transition temperature, the better the resistance of the laminate is to moisture, chemicals, and measling.

The out-of-plane CTE (*z*-axis) changes dramatically above the Tg. It is typical for the *z*-axis CTE to increase by three to four times from 50–50 ppm/°C below the Tg to 180–250 ppm/°C above the Tg. Because *z*-axis expansion causes stresses on the copper-plated through holes, the extra expansion above the Tg is often responsible for plated-through-hole copper cracking during processing or rework.

A.18.1 Typical Tg Values for Common Resin Systems

Resin	°C
Conventional polyimide	240–260
Epoxy-modified polyimide	200–240
Cyanate ester	230–250
BT/bismaleimide blends	180–240
Pure multifunctional epoxy	160–190
Tetrafunctional blends	140–160
Fr-4 (standard epoxy)	115–125

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A.19 Impedance

Characteristic impedance is of considerable importance in high-speed/high-frequency environments. When impedances are not matched between elements of a system, reflected waves can result in surge currents and significant power losses (which result in slow voltage rise rates and critical timing problems). Impedance should not be confused with signal propagation velocity, which is mostly a function of Dk.

A.20 Insulation Resistance

Insulation resistance measures the combined resistance (volume and surface) to current flow in the laminate material. Normally, the insulation characteristics of a laminate are adequately described by surface and volume resistivity; therefore insulation resistance is not a requirement. When carried out for information purposes only, the test results are reported in megohms.

A.21 Loss Tangent

Loss tangent is a measure of flow to the electromagnetic field through a dielectric that is absorbed or lost in the dielectric. This property is the least understood of all the properties that go into characterizing the laminate.

A.22 Moisture Absorption

All resin systems absorb some moisture or water when exposed to high-humidity environments. This absorption affects the printed circuit board in two ways. Water has a Dk of approximately 7.3. If the laminate absorbs a significant amount of water, the resulting relative Dk will be higher than 4.1, which is used to calculate impedance and can cause impedance mismatch.

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A more important effect of moisture absorption is increased leakage current. Materials with high moisture absorption may exhibit leakage in excess of what the circuit housed on them can withstand. To use high-absorption materials in such applications, it is often necessary to seal them with a special coating after first baking them dry. This represents an added cost as well as a problem when rework must be performed, as the coating must be removed from the rework and then reapplied. The two materials that mostly have this problem are polyimide and cyanate ester.

A.23 Peel Strength

Peel strength is the measure of the physical attachment between the copper foil and the dielectric material. It is important that the copper foil layer remain securely attached to the laminate during physical, chemical, and thermal excursion during board fabrication. As the width of the copper traces becomes narrower, the peel strength must be consistently high across the laminate. It is not sufficient to have only a high average. Peel strength values are reported in pounds per square inch (psi).

A.24 Surface Resistivity

The surface resistivity measures the resistance of the material between traces on a plane. Surface resistivity results vary widely with the test conditions used prior and during the test. The values are reported in megohms-cm.

A.25 TCE (see A.2)

A.26 Tg (see A.18)

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A.27 Volume Resistivity

Volume resistivity measures the resistance of the material from trace to trace through the laminate as might be found between plated through holes.

A.28 X, Y, Z (see A.5)

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