Kirk-Othmer Encyclopedia of Chemical Technology.

LAMINATED MATERIALS, PLASTIC

Laminates are materials made up of plies or laminae stacked up like a deck of cards and bonded together. Plywood is a common example of a laminate. It is made up of thin plies of wood veneer bonded together with various glues. Laminates are a form of composite material, ie, they are constructed from a continuous matrix and a reinforcing material (1) (see also Reinforced plastics).

High performance composites may be laminates wherein veils of carbon fiber are treated with an epoxy resin, stacked up to the desired final product thickness, and then laminated together under heat and pressure (see Composite materials; Carbon and graphite fibers). Simply mixing together carbon or glass fibers and polymeric resins to form a reinforced plastic leads to a composite material, but this is not a laminate if not constructed from discrete plies.

Laminates are a special form of composite material or reinforced plastic because the continuous reinforcing ply of fibrous material imparts significant strength in the x–y plane. The strength along the z axis results from interlaminar bonding of resins. Very few fibers are oriented in the z direction, so it tends to be the weak link in this type of composite.

The reinforcing ply of laminates may be a woven fabric scrim, a nonwoven web of polymer monofilaments, or a mat of fibers. One of the most common reinforcements in use is also one of the oldest, ordinary cellulose fiber paper.

During the papermaking process, some degree of fiber orientation results in the machine direction. Typical papers are twice as strong in the length direction as in the cross direction. Therefore, because laminates have evolved into building-sized modules such as 4×8 sheets, all plies in the paper-based laminates are oriented in the same direction, and the laminate properties are quite anisotropic. The length or machine direction is much stronger than the cross machine direction, and there is even less strength between plies where there is virtually zero reinforcement.

As the laminate industry grew, this anisotropic behavior was accepted and fabrication techniques adapted to it. For example, expansion and contraction space was left between wall panels, very strong adhesives were developed for bonding the product to substrates, special substrates were qualified, and where it was necessary to cut holes into the laminates the corners were radiused to prevent cracking from stress concentration.

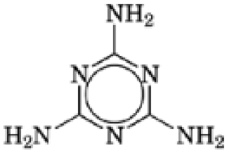
Early laminates tended to be small because available presses were small, and their original uses were to replace small parts such as the natural mica insulator boards used in radio chasses. As decorative laminates evolved from industrial laminates and the size grew to serve markets such as tabletops, countertops, and wall paneling, laminate dimensions tended to fall into the typical building module ratio of about two length to one cross, such as $2 \times 4\text{s}$, $4 \times 8\text{s}$, etc.

By comparison, high performance composite laminates are not only crossplied like plywood, but actually have laminae stacked at very specific angles to one another to achieve optimal uniform properties in the x–y plane (2).

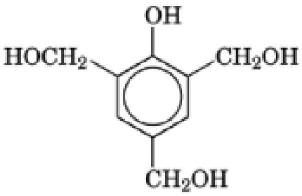
1. Resins

The commonly used resins in the manufacture of decorative and industrial laminates are thermosetting materials. Thermosets are polymers that form cross-linked networks during processing. These three-dimensional molecules are of essentially infinite size. Theoretically, the entire cured piece could be one giant molecule. The types of thermosets commonly used in laminates are phenolics, amino resins (melamines), polyesters, and epoxies.

The chemistry of melamines and phenolics is quite similar. In both cases formaldehyde [50-00-0] is added to the reactive sites on the parent ring to form methylol phenols (3) or methylol melamines (4) (see Phenol resins; Amino resins). There are six reactive sites on the triazine ring of melamine [108-78-1] **(1)** so it is possible to form hexamethylolmelamine. However, the most common degree of methylolation is 1.5–2.0. The ortho and para positions of phenol are active; thus phenol can be trimethylolated **(2)**. However, as with melamine, lower degrees of methylolation such as 1.2–2.5 are common.



(1)



(2)

It should be possible to form linear noncross-linked polymers of melamine–formaldehyde or phenol–formaldehyde by reaction of one mole of the parent with one mole of formaldehyde, but this is generally not the case. The melamine crystal itself is very insoluble in water and only becomes soluble as the formaldehyde molecules add on. If much less than 1.5 moles of formaldehyde per mole of melamine are used, the aqueous resin solution is very unstable.

In the case of phenolics, it is possible to make linear thermoplastic polymers called novolaks, but this is done by reaction of less than one mole of formaldehyde with one mole of phenol; the resulting resin has a large excess of free phenol. Usually in application hexamethylene tetramine (HEXA) is added to the novolak. When heated, the HEXA breaks down into ammonia and formaldehyde and enters the reaction to form a light degree of cross-links in the final product.

Both melamine and phenolic resins usually exist as aqueous solutions although alcohols may also be used as solvents. In their A stage after the reaction of phenol or melamine with formaldehyde, these resins are not really polymers. They are simply methylolated melamines or phenols with a small quantity of dimers or trimers resulting from condensation of a methylol group with another reactive site. Monomers are also present. After saturating paper or another reinforcing material with these resins and heating to remove the water or other solvent, the resins are in a dry, solid state referred to as the B stage. Very little polymerization occurs because the treating temperatures do not reach much more than 100°C and then for only a very short time. In order to condense into thermoset polymers, the C stage, much higher temperatures and longer times are required. The dried resins first melt and flow when heated in the press and eventually cure or thermoset as the temperature increases to the 130–150°C range for 20–40 minutes. Special fast curing resins can be cured at 170–180°C in about a minute or less.

The condensation reaction of methylolated melamine results in a methylene bridge linking two of the triazine rings. It is also possible for two methylol groups to condense together forming an ether linkage between two triazine rings. Considering that each triazine ring has an average of 1.5 methylol groups attached to it and a total of 4.5 remaining reactive sites that can condense with any methylol group to form a cross-link, it is obvious that a complex network structure results upon full cure. Modified melamines are available wherein one of the amino groups on the triazine ring has been substituted with a methyl group (acetoguanamine) or a phenyl group (benzoguanamine [91-76-9]). With less reactive sites, these polymers have lower final degrees of cross-linking. The situation with condensation of methylol phenols is exactly analogous.

Polyesters are also used in laminates, especially in low pressure laminate panels and flexible edge banding laminates or in special applications such as harsh chemical-resistant laminates. A typical polyester is made from one mole of isophthalic acid, one mole of maleic anhydride, and a slight stoichiometric excess of propylene glycol (5). The maleic anhydride provides the unsaturated sites for later cross-linking. Styrene or diallyl phthalate are the most common cross-linking agents. Unlike the melamines and phenolics that cross-link by condensation producing water as a by-product, the polyesters cross-link by free-radical addition at the double bonds (6). The free radicals may be produced from peroxides upon heating, from photoinitiators upon interaction with uv light, or they may be directly generated using high energy radiation such as that produced by an electron beam (see Polyesters, unsaturated).

The fourth common type of resin used particularly in industrial laminates is epoxy. Resins from the diglycidyl ether of bisphenol A are the most common type of epoxy resin. The ether is formed by reaction of bisphenol A with epichlorohydrin (7), and cross-linked to form a thermoset by opening of the oxirane ring. Epoxy resins (qv) can catalytically homopolymerize or form cross-linked heteropolymers by coreacting through the epoxide groups with a curing agent such as triethylene tetramine. Since these often complex curing agents become part of the polymer structure, they can strongly affect mechanical properties.

2. Reinforcements

The reinforcing ply in a laminate may make up half or more of its total weight. Therefore, properties of a laminate are strongly dependent on the ply. These plies are specified by basis weight in grams per square meter and may range from as low as 15 g/m^2 for a lightweight overlay sheet to as much as 300 g/m^2 or more for a strong filler sheet. The caliper of the ply varies with its basis weight and the amount it was calendered during its manufacture. Therefore, the reinforcing ply density and porosity vary widely. Low density papers are easier to saturate, but tend to weaken when wet. High density papers are stronger and better as print surfaces, but accept resin poorly.

The most commonly used reinforcement for high pressure decorative and industrial laminates is paper (qv). The strong substrate layers, or filler, are kraft paper. Kraft is a brown paper made from a sulfate pulp process (8). It consists of both short cellulose fibers from hardwoods and long fibers from conifers. The long fibers impart most of the wet strength required for resin saturation processes.

For use in decorative laminates, the surface paper must be highly refined pure cellulose (qv) technically called alpha cellulose. It is made by the sulfite process. The alpha cellulose content of a given paper is determined by the amount of material remaining undissolved in 18% sodium hydroxide. Pure cellulose paper is required because this decorative layer will be pigmented and sometimes printed with a pattern such as a wood grain.

It must be colorless initially, and it must be stable to heat throughout processing. The laminate must also be light-stable throughout its useful life.

Decorative papers are pigmented for color and opacity. Titanium dioxide is commonly used for whites and in light pastel shades. The TiO_2 may constitute 35% of the total raw paper weight. Thus, pigmented papers perform very differently from nonpigmented ones, affecting both processing and final physical properties. This is because a 50% resin, 50% cellulose composite may actually be 50% resin, 35% cellulose, and 15% inorganic filler. Organic dyes and pigments are also found in decorative papers used in laminates. Being organic, they do not contribute to the ash content nor have much impact on physical properties. Sometimes rayons are used in the surface layer. Rayons are derived from further chemical reaction of already purified celluloses.

Other reinforcements that may be used in the substrate layers of decorative laminates and throughout the structure of industrial laminates are woven fabrics of glass or canvas and nonwoven fabrics of various polymeric monofilaments such as polyester, nylon, or carbon fibers. Woven and nonwoven fabrics tend to be much stronger than paper and have much more uniform strength throughout the x–y plane. They greatly enhance properties of laminates such as impact and tear strength.

The reinforcing ply acts as the carrier for the plastic resin during intermediate processing steps known as saturation and B-staging. It is this ply that together with the resin makes a laminate a composite material, and the layering of these plies that makes the final product a laminate.

3. Manufacture

3.1. Treating

Treating is the term used in the laminate industry for the application of the plastic resin to the reinforcing ply or carrier web that eventually forms a ply in the composite laminated product. Typical means to apply the resin are reverse roll coaters, dip and scrape, or dip and squeeze operations. In reverse roll coating, the resin is applied to only one side of the carrier web with the coating rollers metering on the correct amount of resin solution. For the dip and scrape or dip and squeeze methods, the paper is submersed beneath the resin solution, and then excess resin is scraped off with a doctor knife or the treated web is run through a set of metering rolls or squeeze rolls to control the pick-up. Although reverse roll coating is a more precise method, dip and squeeze is easier and the equipment less costly. Pick-up of resin is also affected by the porosity of the paper and the viscosity and solids of the resin solution. A more porous paper absorbs resin more rapidly and usually soaks up a greater quantity. This is particularly important in reverse roll coating when only one side of the paper is exposed to the resin. A less viscous resin penetrates better, but if viscosity is reduced by decreasing solids, final pick-up of dry resin may actually be reduced. Viscosity may also be reduced by using a resin of lower molecular weight or by use of a better solvent for the resin.

After the resin is applied to the paper, the wet treated web enters a drying oven where most of the solvent is evaporated off. Modern treaters, such as that shown in Figure 1, have air flotation ovens so that the web is never touched by hot conveyor bars that may cause streaks noticeable in the final product.

As the treated web passes through the oven, the solvent evaporates and the web temperature increases somewhat. However, due to the speed of the operation, normally $30-300\,\mathrm{m/min}$, dwell time in a typical $30-40\ \mathrm{m}$ long oven is very short. Since there is also evaporative cooling until most of the solvent is removed, the treated paper exiting the oven is not much hotter than the boiling point of the solvent. The oven drying process with thermosetting resins is referred to as B-staging. There is considered to be advancement of the resin during this process, but actually, due to the short time and low temperatures, nothing more than drying occurs.

The volatile content of the treated paper is important because moisture acts as a temporary plasticizer to promote resin flow during early stages of pressing (9). Dynamic mechanical analysis of the treated paper is a

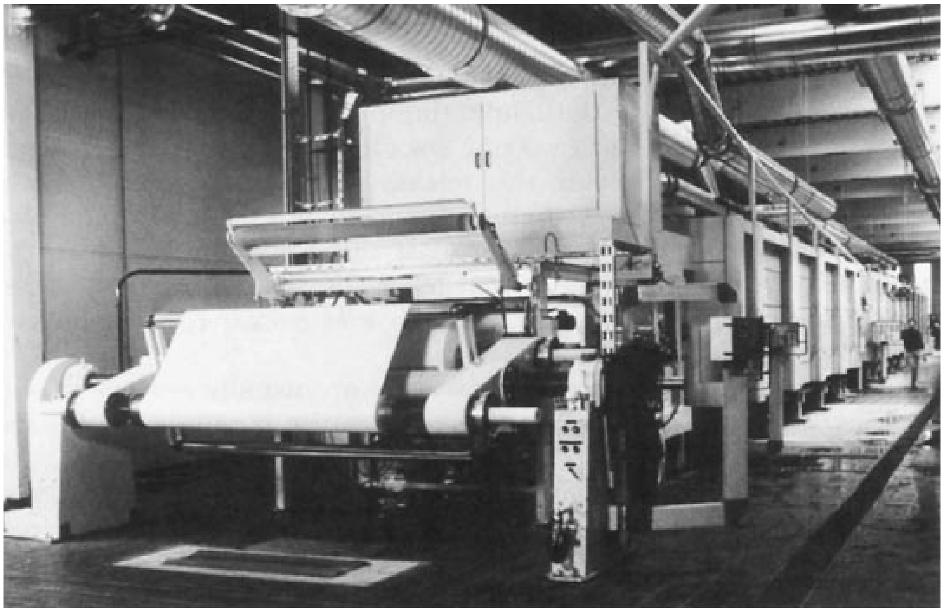


Fig. 1. Treating machine equipped with an air flotation oven.(Photo courtesy of VITS Babcock Maschinenbau, GmbH.)

very useful means to study the initial flow stages of a resin and the cure time required to complete cross-linking (10).

By use of a three unit beta-gauge system on a treater it is possible to achieve excellent control of treating parameters. The first gauge traverses the raw paper and makes a continuous record of its basis weight. The second gauge is positioned after the coater head and measures the add-on weight of wet resin. The third gauge at the oven exit measures the dry resin weight plus any residual volatile. With feedback loops to the coater head, very precise control can be maintained. At the exit of the oven, the treated paper may either be sheeted or rerolled. If it is rerolled, it must be later sheeted in a separate operation prior to collation.

In the case of some types of polyesters, the dried treated sheet is very tacky, and must be interleaved with a plastic release film to prevent blocking in the roll prior to use. Certain polyesters and acrylics can be converted to a gelled state by exposure to actinic radiation.

3.2. Collation

Collation is the process by which the individual laminate plies are assembled prior to curing in the press. The buildup of the laminate determines the final properties of the product. The topmost sheet in the buildup may be a texturing or embossing paper as well as being a release sheet to allow for separation of the laminate from the caul plate used to mold it.

The texturing sheet may also contain a plastic coating that transfers to the laminate surface during the laminating process to provide special surface properties. The caul plate itself may be smooth or textured and act directly as the release. Immediately beneath this release sheet, there may be a decorative layer or a ply that imparts special properties such as a metallic foil for electrical conductivity or a static dissipating layer. If the decorative layer is a printed pattern, it may be covered by a special layer that transparentizes during the laminating process. This transparent ply provides a wear-resisting layer above the printed pattern.

Beneath the special surface layers, there are usually several plies of materials designed to provide physical strength to the laminate. In the cases of decorative and industrial laminates based on paper-reinforcing plies, they are normally stacked in the same direction with the length dimension parallel to the machine direction of the paper. This gives laminates noticeable directional properties. In high performance laminates used in aerodynamic applications, the plies are often crossed or even arranged at very specific angles to provide more isotropic properties.

When multiple laminates are pressed in a single opening between heated press platens (daylight), it is necessary to separate them. They are usually pressed face to face, back to back. A sheet of wax paper or plastic film can be used between the backs of two laminates to separate them. Smooth caul plates are inserted between two laminate faces. The plates are the tools used in flat-bed press processing and have an important function in molding the planar laminate surfaces as well as acting as release and texturing media. Laminates can be press cured in plateless (veneer) packs, but such laminates tend to have surface waviness resulting from nonuniformities in the multilayers of reinforcement material, and are not generally satisfactory for decorative purposes.

3.3. Press Curing

The laminate as an article of manufacture is prepared in a flat-bed press. Modern high pressure presses may be as large as $2\ \mathrm{m} \times 5\ \mathrm{m}$, and low pressure presses are as long as 7.5 m. Normally, high pressure presses have multiple openings or daylights, sometimes 20 or more, as shown in Figure 2. Low pressure presses have only a single daylight. The high pressure presses are designed to be operated up to pressures of 14 MPa (2000 psi) and the low pressure presses up to about 2 MPa (290 psi). Continuous presses are also in use for the manufacture of low pressure products. Some continuous high pressure presses are being built, but they are not in wide usage.

During the press operation, which is actually a form of compression molding, the resin-treated laminate plies are heated under pressure and the resins cured. The initial heating phases cause the resin to melt and flow into voids in the reinforcing ply and bond the individual plies together. The applied heat simultaneously causes the resin to polymerize and eventually to cross-link or gel. Therefore, resin viscosity reaches a minimum during the press cycle. This is the point at which the curing process becomes dominant over the melt flow process. Dynamic mechanical and dielectric analyses (11) are excellent tools for study of this behavior.

With a sufficiently long press cycle, a state of complete cure is reached. At this point, the laminate is cooled in the press, under pressure, and removed for finishing operations. If the press is opened at a temperature above the boiling point of trapped volatiles, vaporization occurs causing interlaminar blistering which ruins the laminate.

The quantity of resin applied to the reinforcing ply to achieve a state of full densification varies inversely with the laminating pressure. Therefore, high pressure laminates pressed at about 7 MPa (1000 psi) need only about 25–30% phenolic resin in kraft paper, whereas low pressure $(1\ \mathrm{MPa} = 145\ \mathrm{psi})$ laminates need 50–60% resin in the reinforcing ply if all voids are to be filled in the final product.

Low pressure processes are generally of very short duration (30–90 s), and high pressure cycles are typically one hour or more. Therefore, it is economical for the low pressure presses to be single opening or continuous whereas the high pressure presses must be multiple opening. Because of the short low pressure cycles and heat-transfer considerations, usually only one or two laminates or one panel can be pressed in the single daylight. By contrast, a dozen or more laminates may be pressed in a single high pressure press daylight, and these laminates may consist of 5–10 plies each. As laminates become thicker, the number per daylight must decrease because the opening is physically limited to about 50 mm by the overall press size and ram travel distance. High pressure laminates may be up to 25 mm thick, in which case only a single one is pressed in one daylight. The productivity of a large high pressure press in meters per minute may be very high in spite of it being a batch process. For example, 4-m long laminates pressed 12 per daylight in a 20 daylight press on a one-hour cure cycle are produced at a rate of $16\ \mathrm{m/min}$. It is difficult for low pressure processes to match this

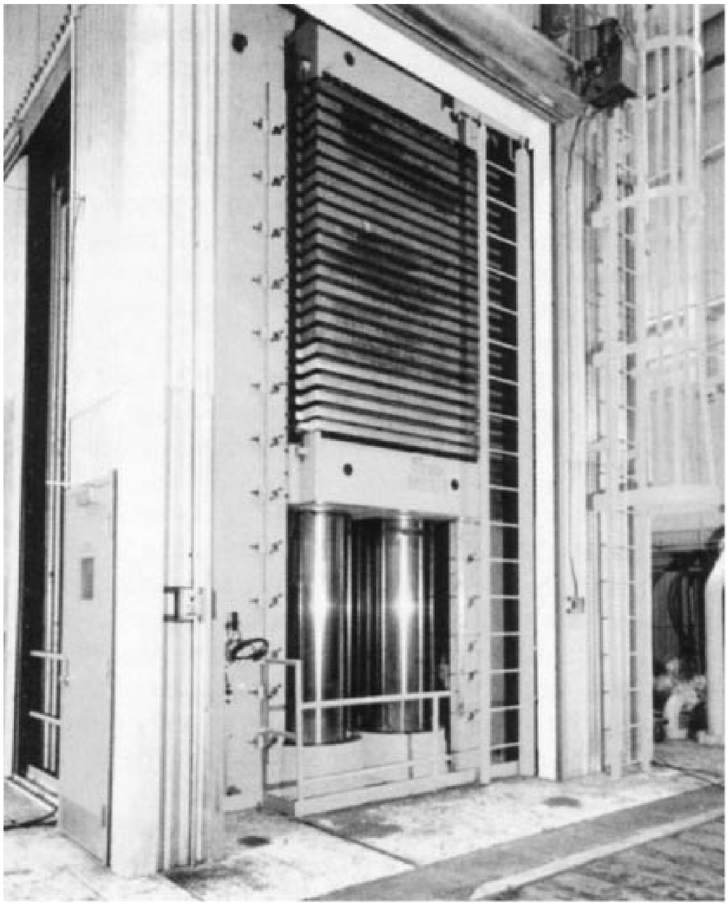


Fig. 2. Multiopening flat-bed laminating press.(Photo courtesy of G. Siempelkamp, GmbH & Co.)

rate of production and impossible for them to press multiple ply products because heat transfer never allows the interior plies to reach melt flow temperatures or the resins to cure during the short dwell times. Some short cycle high pressure presses are now entering the market. They offer increased manufacturing flexibility at about the same production rate as the older long cycle presses.

Low pressure presses are usually operated at about 180°C as compared to high pressure presses at about 135°C, but the extra low pressure press heat is not adequate to compensate for the short dwell time. Special fast curing resins must be used in conjunction with the low pressure presses.

Although flat-bed laminating is similar to compression molding, it is accomplished without edge constraints. In other words, the molds are open at the edges and theoretically the pressure in the x–y plane may fall to zero at the edge even though the z-direction pressure normal to the plane of the laminate is at 10 MPa (1450 psi). If it were not for the flow restraining characteristics of the paper ply normally found in high pressure laminates, it would not be possible to press in these open-edged molds. Edge effects do occur in laminates. Excess resin sometimes flows out at the edge and volatiles escape there. However, the extreme edges are normally trimmed away before the product is used.

Some high performance laminates consisting of carbon fiber webs and epoxy resins are cured in autoclaves. An autoclave is a pressure chamber in which the pressure is applied hydrostatically.

Table 1. Performance Properties and Values for Decorative Laminates

Type designation	Nominal thickness, mm	Thickness tolerance, mm	Wear resistance cycle[a]	Ball impact resistance, mm[a]	Dimensional change, %[b,c]		Boiling water resistance rating[a,d]	Radiant heat resistance, s[a]
					MD	CD		
general-purpose, GP 50	1.270	±0.127	400	1270	0.5	0.9	NE	125
general-purpose, GP 20	0.508	±0.127	400	381	0.8	1.3	NE	60
post-forming, PF 42	1.067	±0.127	400	762	1.1	1.4	SL	100
specific-purpose, SP 125	3.175	±0.203	400	1905	0.3	0.7	NE	200
high wear, HW 120	3.048	±0.203	3000	1905	0.3	0.7	NE	200
fire-rated, FR 50	1.270	±0.127	400	1143	0.5	0.9	NE	75

[a] Minimum.
[b] MD = machine direction; CD = cross direction.
[c] Maximum.
[d] Rating system: NE = no effect; SL = slight effect.

3.4. Finishing and Fabrication

Since laminates are normally pressure cured in flat-bed presses and plies overextend the plates, laminates have rough or uneven edges when removed from the press. These edges are sawed off and the back of the laminate is often sanded to improve the strength of subsequent bonding to various substrates.

Common grades of laminates tend to be thin materials ranging from 0.5–1.5 mm in thickness, therefore for most applications they must be supported. In the manufacture of furniture, cabinetry, and countertops the laminates are bonded to particle board or plywood. Since the laminates consist largely of cellulosic paper, their dimensional stability is similar to wood, particularly to particle board.

In small pieces or as inserts, laminates may be used unsupported because they are quite stiff and strong. The modulus of a high pressure decorative laminate is about 7 GPa (106^2 psi) at room temperature. Thick laminates range up to 25 mm and are very strong, having flexual strength of 130 MPa (19,000 psi). These products are used unsupported as toilet partitions, laboratory tops, and so forth.

An important fabrication operation for laminates is post-forming. This is an operation in which a laminate is heated and bent. It is really an anomaly because laminates are thermoset products as opposed to thermoplastics and as such are supposed to be cross-linked into an intractable network structure. However, in the early days of development of decorative laminates it was necessary to cut strips and bond a self-edge of the material to finish the appearance of a countertop. An obvious benefit would be to bend the laminate around an edge to finish it off. In order to accomplish this post-forming, special papers having a degree of stretch were used along with special resins. Also, press cure cycles specifically designed to limit the resin cure to a slightly incomplete state were used. By doing so, it became possible to produce special laminates that could be rapidly heated to about 150°C and quickly bent to a simple radius of curvature. If the heatup is too slow, the laminate dries out and cure may advance with the end result being a crack in the bend. Because the paper-reinforcing ply in the laminate is not very extensible, complex bends cannot be made.

4. Properties and Grades

The properties of standard grades of high pressure decorative laminates manufactured are shown in Table 1. Tables 2 and 3 show properties of industrial laminates (12, 13).

Table 2. Performance Properties of 3.2-mm Thick Industrial Laminates[a]

	Flex strength, MPa[b]					Impact strength, J/m[d]		
Grade	Lengthwise	Crosswise	Water absorption, %	Permittivity,[c] 1 MHz	Dissipation factor, 1 MHz	Lengthwise	Crosswise	Dielectric breakdown parallel to laminations, kV
X	172	152	3.3	6.0	0.05	29.4	26.7	
XP	96.6	82.8	2.2					40.0
XPC	82.8	70	3.0					
XX	103	96.6	1.3			21.4	18.7	40.0
XXP	96.6	82.8	1.1	5.2	0.05			60.0
XXX	93.1	81.4	0.95	5.7	0.045	21.4	18.7	50.0
XXXP and C	82.8	72.4	0.65	4.8	0.04			60.0
ES-1,2,3	93.1	93.1	1.8					
C	117	110	2.5			101	90.7	15.0
CE	114	96.6	1.6			85.4	74.7	35.0
L	114	100	1.6			72	58.7	15.0
LE	110	96.6	1.3	6.0	0.070	66.7	53.4	40.0
AA	124	110	2.5			192	160	
G-3	138	124	2.0			347	294	
G-5	307	262	2.0	8.0	0.080			23.0
G-7	138	124	0.35	4.2	0.022	347	294	32.0
G-9	379	241	0.70	7.4	0.018			60.0
G 10,11 FR 4,5	379	310	0.15	5.4	0.035	374	294	45.0
N1	70	65.5	0.40	3.9	0.039	160	107	60.0
FR1	96.6	82.8	2.2	6.0	0.06			40.0
FR2	82.8	72.4	0.55	4.8	0.04			60.0
FR3	138	110	0.50	4.8	0.04			60.0
CEM-1[e]	207	172	0.20	4.8	0.04			45.0
CEM-3[e]	228	186	0.20	5.4	0.035			45.0

[a] Values from NEMA LI-1-1089.

[b] To convert MPa to psi, multiply by 145.

[c] Permittivity = dielectric constant.

[d] To convert J/m to ft.lb/in., divide by 53.38.

[e] 2.4-mm product.

Aesthetic properties are of greatest concern in decorative laminates. These include gloss, appearance, cleanability, wear resistance, stain resistance, and other surface properties. Physical properties are of most importance for industrial laminates. These include strength, electrical and thermal properties, expansion coefficient, and punchability. The definitions of the laminate grades in these standards follow.

4.1. Decorative Laminates

General-purpose type is a high pressure decorative laminate (HPDL) designed for both horizontal and vertical applications where appearance, durability, resistance to stains, and resistance to heat up to 135°C (275°F) are required.

Post-forming type is an HPDL similar to the general-purpose type but is capable of being thermoformed under controlled temperature and pressure in accordance with the laminate manufacturer's recommendations.

Cabinet liner type is an HPDL intended only for use in cabinet interiors.

Table 3. Performance Properties[a] of 3.2-mm Thick Industrial Laminates

Grade	Electrical strength perpendicular to lams, V/μm[b]	Insulation resistance, MΩ	Tensile strength, MPa,[c]		Modulus of elasticity, GPa[d]		Rockwell hardness, M	Density, g/mL
			Lengthwise	Crosswise	Lengthwise	Crosswise		
X	20		138	110	13.1	9.7	110	1.36
XP	19		82.8	62.1	8.3	6.2	95	1.33
XPC	17		72.5	58.6	11.0	5.5	75	1.34
XX	20	60	110	89.7	10.3	8.3	105	1.34
XXP	20	500	75.9	58.6	6.2	4.8	100	1.32
XXX	19	1000	103	82.8	9.0	6.9	110	1.32
XXXP,C	19	20,000/50,000	85.5	65.5	6.9	5.5	105/95	1.30
ES-1,2,3	22		82.8	58.6			118	1.40

[a] Thermal expansion for all grades $= 2.0 \times 10^{-6}\ \mathrm{cm/cm/^{\circ}C}$; specific heat $= 1.46 - 1.67\ \mathrm{J/(g{\cdot}K)}\ (0.35 - 0.4\ \mathrm{cal/(g{\cdot}C^{\circ})})$; thermal conductivity $= 0.3\ \mathrm{W/(mK)}$ $(7.0 \times 10^{-4}$ cal).

[b] To convert $\mathrm{V}/\mu\mathrm{m}$ to V/mil, multiply by 25.

[c] To convert MPa to psi, multiply by 145.

[d] To convert GPa to psi, multiply by 145,000.

Backer type is an HPDL without a decorative face intended for use as a balancing sheet in panel construction.

Specific-purpose type is a general-purpose HPDL with increased thickness.

High wear type is also a general-purpose HPDL with increased surface wear resistance.

Fire-rated type laminate is an HPDL capable of providing fire-rated characteristics as determined by the test methods required by the authority having jurisdiction.

Miscellaneous Types. Various decorative effects have been developed which meet specific aesthetic requirements. These laminates may have special visual appeal, such as gloss finish, deeply embossed textures, and metallic surfaces. They are designed for specific installations and may not be suitable for all applications. For this reason, they are not included in these standards. Information concerning their proper application, properties, and care should be requested from the manufacturer.

4.2. Industrial Laminates

4.2.1. Paper-Base Grades

Grade X is primarily intended for mechanical applications where electrical properties are of secondary importance. It should be used with discretion when high humidity conditions are encountered and it is not equal to fabric-base grades in impact strength.

Grade XP is primarily intended for hot punching. With good punching practice and depending on the complexity of the part design, sheets up to and including 1.6 mm (0.062 in.) may be punched at room temperature.

Grade XPC is primarily intended for cold punching and shearing. It is more flexible and shows higher cold flow but is lower in flexural strength than Grade XP.

Grade XX is suitable for usual electrical applications. It is not recommended for punching but may be machined using present state-of-the-art machine tools.

Grade XXP is better than Grade XX in electrical and moisture-resisting properties and more suitable for hot punching. It is intermediate between Grades XP and XXXP in punching and cold flow characteristics.

Grade XXX demonstrates good electrical properties in high humidity applications and has minimum cold flow characteristics.

Grade XXXP is better in electrical properties than Grade XXX and more suitable for hot punching. It is intermediate between Grades XXP and XXXPC in punching characteristics. This grade is recommended for applications requiring high insulation resistance and low dielectric losses under severe humidity conditions.

Grade XXXPC is similar in electrical properties to Grade XXXP and suitable for punching at lower temperatures than Grade XXXP. This grade is recommended for applications requiring high insulation resistance and low dielectric losses under severe humidity conditions.

Grade ES-1 is suitable for engraving as nameplates, etc. It is made with black or various colored surfaces and a white opaque core (usually melamine binder).

Grade ES-2 is similar in application to Grade ES-1 but made with a white subcore and black core (usually a phenolic binder) to obtain toughness when made in thick sheets.

Grade ES-3 is similar in application to Grade ES-1 but made with a white or various colored surface and black core.

4.2.2. Fabric-Based Grades

Grade C is made from cotton fabric weighing over $140\ \text{g/m}^2$ $(4\ \text{oz/yd}^2)$. The maximum thread count in any ply is 28/cm (72/in.) in the fill direction, and the maximum total thread count in the warp and fill directions is 56/cm (140/in.). Heavier fabrics provide higher impact strength but rougher machined edges. Its use for electrical applications is not recommended.

Grade CE is made from cotton fabric with the same weight and thread count limits as Grade C. Suitable for applications requiring good moisture resistance, greater strength than Grade LE, and electrical properties nearly equivalent to Grade XX. This grade is not recommended for primary insulation for electrical applications involving commercial power frequencies at voltages in excess of 600 volts.

Grade L is made from fine-weave cotton fabric weighing $140\ \text{g/m}^2$ or less. The minimum thread count in any ply is 28/cm in the fill direction, and the minimum total thread count in the warp and fill directions is 56/cm. Primarily suitable for machining and mechanical applications where finer edge detail and appearance than Grade C is required, Grade L has high density and good moisture resistance. Its use for electrical applications is not recommended.

Grade LE is made from cotton fabric with the same weight and thread count limits as Grade L. It is suitable for electrical applications requiring good moisture resistance and greater strength than Grade XX.

4.2.3. Asbestos-Based Grade

Grade AA is more resistant to heat than Grade C but not recommended for primary insulation at any voltage. It exhibits small dimensional changes when exposed to moisture.

4.2.4. Glass-Based Grades

Grade G-3 is glass fabric with phenolic resin binder which shows high impact and flexural strength. It is used for thermal and mechanical applications and has good dimensional stability.

Grade G-5 is glass fabric with melamine resin binder and high mechanical strength. It is one of the hardest laminate grades, with good arc resistance; it meets UL94 V-0 when tested in accordance with UL94. This material has excellent electrical properties under dry conditions and good dimensional stability. Electrical applications should be limited to operating temperatures of 50°C (122°F) or less.

Grade G-7, glass fabric with silicone resin binder, shows extremely good dielectric loss properties under dry conditions and good electrical properties under humid conditions, although the percentage of range from dry to humid conditions is high. This material has excellent flame, heat, and arc resistance and meets UL94 V-0 when tested in accordance with UL94. It also has good impact and flexural strength.

Grade G-9, glass fabric with moisture-resistant melamine resin binder, is similar to Grade G-5 but with better electric strength properties under wet conditions. Electrical applications should be limited to operating temperatures of 50°C (122°F) or less.

Grade G-10, glass fabric with epoxy resin binder, has extremely high mechanical strength (flexural, impact, and bonding) at room temperature and good dielectric loss and electric strength properties under both dry and humid conditions.

Grade G-11, glass fabric with heat-resistant epoxy resin binder, has properties similar to those of Grade G-10 at room temperature and, in addition, has high retention of flexural strength at elevated temperatures.

4.2.5. Nylon Cloth Grade with Phenolic Resin Binder

Grade N-1 has excellent electrical properties under high humidity conditions and good impact strength, but is subject to flow or creep under load, especially at temperatures higher than normal.

4.2.6. Flame-Resistant Grades

Grade FR-1, paper-based laminates with a phenolic resin binder, are similar in all properties to Grade XP, but so formulated to have at least a UL94 V-1 classification when tested according to UL94.

Grade FR-2, paper-based laminates with a phenolic resin binder, are similar in all properties to Grade XXXPC, but so formulated to have at least a UL94 V-1 classification when tested according to UL94.

Grade FR-3, paper-based laminates with epoxy resin binder, have higher flexural strength than Grade XXXPC and are formulated to have a flame resistance of at least a UL94 V-1 classification when tested in accordance with UL94. The material has low dielectric loss properties with good stability of electrical properties under conditions of high humidity.

Grade FR-4, continuous-filament glass cloth with an epoxy resin binder, is similar in all properties to Grade G-10, but so formulated to have at least a UL94 V-1 classification when tested according to UL94.

Grade FR-5, continuous filament glass cloth with an epoxy resin binder, is similar in all properties to Grade G-11, but so formulated to have at least a UL94 V-1 classification when tested according to UL94.

4.2.7. Composite-Based Laminates

Grade CEM-1 are laminates with continuous-filament glass cloth surfaces and a cellulose core, all with a flame-resistant epoxy resin binder. With good punching practice, sheets up to and including 2.4 mm (0.094 in.) in thickness may be punched at temperatures not less than 23°C (73°F). These laminates meet UL94 V-0 when tested in accordance with UL94.

Grade CEM-3 is laminated with continuous-filament glass cloth surfaces and a nonwoven glass core, all with a flame-resistant epoxy resin binder. Property values approach those of FR-4. With good punching practice, sheets up to and including 1.6 mm (0.062 in.) in thickness may be punched at temperatures not less than 23°C (73°F). The grade meets UL94 V-0 when tested in accordance with UL94.

5. Health and Environmental Concerns

Key resins used in the manufacture of laminates are made with formaldehyde (qv). The A-stage resins are manufactured to have low levels of free formaldehyde, less than one percent, and plant atmospheres as well as individual operators are monitored to be certain they are exposed to levels of formaldehyde that are below OSHA guidelines of 0.75 ppm (14).

In the final product, the formaldehyde has completely reacted to form a very inert thermoset resin. Spontaneous emission of formaldehyde from high pressure laminates is measured at approximately the accepted background level of 0.035 ppm (15). Melamine surfaced laminates are tested and approved for food service equipment by the National Sanitation Foundation (16).

In fires, melamine–phenolic laminates ignite slowly at high temperatures and burn slowly producing smoke that has about the same toxicity as wood smoke (17).

Disposal of laminate scrap resulting from edge trim, sanding dust, and fabrication trim presents other problems. The scrap within the manufacturing plant can be ground up and used as part of the fuel source in boilers with the proper permits and controls. Stack effluents from treating operations can be burned off in boiler feedstock or captured in charcoal filter beds. Fabrication shop scrap goes to landfills where it has not generally been a problem because of its density and inertness.

Although it would be desirable to recycle laminate scrap, this has been difficult because of its thermoset nature. However, a 1993 patent (18) suggested a means whereby scrap consisting of cellulose, thermoset resins, and partially reacted resins can be ground to a powder which is used as a filler in a thermoplastic resin. The filled thermoplastic resin is then used for molding of various articles.

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