Kirk-Othmer Encyclopedia of Chemical Technology.

LAMINATED MATERIALS, GLASS

A laminate is an orderly layering and bonding of relatively thin materials. A commonly laminated material is glass. Most commonly, two pieces of float or sheet glass are bonded with poly(vinyl butyral) [9003-62-7] (PVB) (see Vinyl polymers, poly(vinyl acetals)) to produce a highly transparent safety glass, eg, an automotive windshield. This combining of transparent abrasion-resistant glass and resilient plastic achieves the durability and safety demanded of such products. Other materials that may be incorporated in laminated glass are colorants, electrically conducting films or wires, and rigid plastics. The value of the laminate is the utilization of the desirable properties from each of the constituents. In the case of laminated glass, the excellent weathering properties of the glass protect the impact energy-absorbing plastic interlayer from deterioration, abrasion, and soiling.

Benedictus, a French chemist who accidentally broke a flask that contained dried-on cellulose nitrates, is credited with founding the laminated-glass industry (1). The first patent was issued in 1906 (2). The growth of the laminated glass market was slow until automobile numbers and automotive speeds increased to the point that glass-caused injury was of concern. By the late 1920s, laminated windshields were standard in automobiles. The most common construction was two pieces of plate glass bonded with cellulose nitrate. However, the plastic interlayer introduced problems of haze, discoloration, and loss of strength, and it was replaced by cellulose acetate in 1933. Cellulose acetate demonstrated improved stability to sunlight but lacked strength over a broad temperature range and produced haze. The advent of the poly(vinyl butyral) resins in 1933 permitted the development of the modern interlayers that are used to make the majority of laminated safety glass in use; the resins were adopted for all automotive laminates by 1939.

Laminated glass is not a true composite material. The glass needs the safety net effect of the interlayer if impacted, and the interlayer needs the durability and rigidity of the glass for useful service other than during impacts. Exceptions where laminated glass more truly fits the definition of a composite are when it is used for noise attenuation (see Insulation, acoustic) or bullet resistance. In these applications, the alternate layering of rigid and soft materials achieves results beyond those produced by either alone.

1. Properties

Laminated materials frequently have limits on properties below those found in one of the components. Laminated glass with a PVB interlayer has a maximum service temperature not exceeding 70°C, far below that of solid glass. The strength of laminated glass is dependent on the number, thickness, and strength of the individual glass plies and on the characteristics of the particular interlayers used. For the majority of laminates consisting of two plies of annealed glass and one PVB interlayer, the bending strength is about 0.6 of that for an equal thickness of solid glass.

Glass–PVB laminates become more rigid with a decrease in temperature, and below -7°C approach the performance of solid glass. At temperatures above 38°C these laminates are less rigid and provide improved penetration resistance. Some applications utilize heat-strengthened or tempered glass for additional strength.

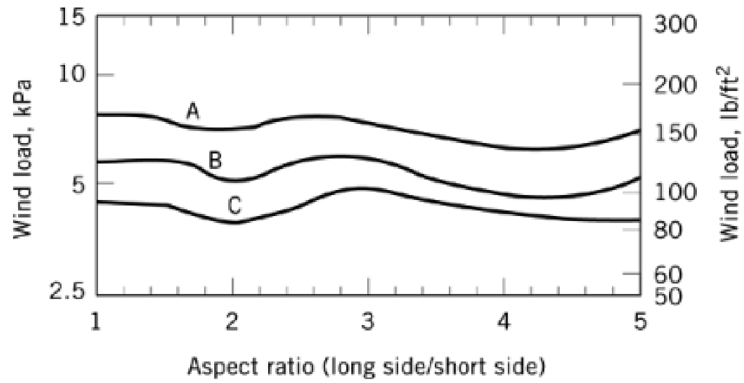

Fig. 1. Wind-load data for heat-strengthened and laminated 3.2-mm glass. Architect's specified probability of breakage is 8/1000 laminates for a 1-min uniform wind-load duration. Four sides supported in weathertight rabbet. Curves for different glazing areas: A, 0.93 m^2 (10 ft^2); B, 1.39 m^2 (15 ft^2); C, 1.86 m^2 (20 ft^2).(Courtesy of PPG Industries, Inc.)

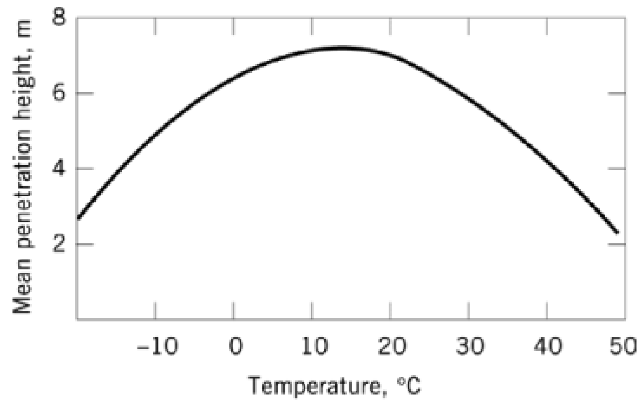

Fig. 2. Typical pen etration resistance vs temperature data from laboratory procedure ($_{305\times305-\mathrm{mm}}$ laminates, 0.76-mm PVB; 2.27-kg ball impact).(Courtesy of Monsanto Co.)

Figure 1 is an example of a wind-load chart for the combination of heat-strengthened and laminated glass (3). Wind-load information is used jointly by the architect, glazing contractor, and glass manufacturer to determine the permissible glazing area and glass thickness required to meet the design wind load.

Most laminated glass applications are concerned with impact strength, and minimum performance levels are required by specification. The impact strength of two plies of laminated, annealed glass and various PVB thicknesses are available (4). Aircraft laminates may utilize electrical resistance heating as deicing for vision enhancement.

Automotive and architectural laminates of PVB develop maximum impact strength near 20°C, as shown in Figure 2. This balance is obtained by the plasticizer-to-resin ratio and the molecular weight of the resins. It has been adjusted to this optimum temperature based on environmental conditions and automobile population at various ambient temperatures. The frequency and severity of vehicle occupant injuries vs temperature ranges at the accident location have been studied (5), and the results confirm the selection of the maximum performance temperature and decreasing penetration resistance at temperature extremes.

The optical properties of laminated glass are required to be equal to solid glass, because most applications are in vision areas. Light scattering by the interlayer essentially is nonexistent if PVB with the correct index

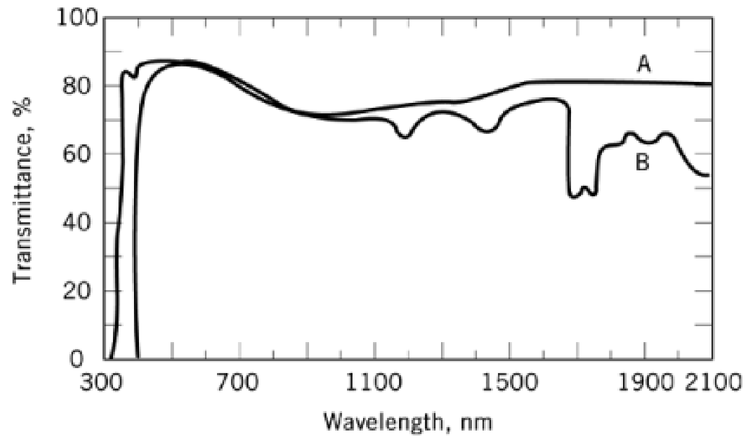

Fig. 3. Visible-light transmittance of automotive laminate: A, 475-mm monolithic glass; B, 5-mm laminated glass.(Courtesy of Ford Motor Co.)

of refraction is used. Clean-room practices can reduce the dust and lint that is attracted to the surfaces (see Sterilization techniques). Visible-light transmittance of a typical automotive laminate (2.1-mm glass, 0.76-mm PVB, 2.1-mm glass) is nearly equal to solid glass of the same thickness (Fig. 3), and noticeable color change usually is absent. Visible-light transmittance is about 88% for clear glass laminates and ranges from 70 to 80% for windshields made with tinted glass. Sunroof laminates have been made with as little as 4% transmittance to reduce solar load. All uv light is absorbed below 370 nm and several discrete absorption bands are in the infrared beyond 1100 nm. The uv absorption may be enhanced when additional protection of color dyes is required, eg, gradient shade bands in automotive windshields or merchandise in window displays. Generally, the solar uv transmittance is on the order of 30–35%, and the infrared is about 97% for 0.76-m thick PVB.

The index of refraction of PVB (1.48) is close enough to glass (1.520) to couple the two glass plies with a reflectance loss of only 0.02%:

$$R = \frac{(n_2 - n_1)^2}{(n_2 + n_1)^2} \qquad (1)$$

where R is the reflectance at the interface and n_1 and n_2 are the different refractive indexes. The absorption coefficient for visible light (400–700 nm) generally is -0.25 to -0.45 for PVB. This produces a transmission loss within the PVB of 0.7–1.3%, which is mostly in the blue and ultraviolet portion of the spectrum.

Subsequent to the lamination process, some defects may appear that were not visible previously in the glass. One of these phenomena is called a bull's eye when found in windshields. These are small depressions that are formed in the glass pair during bending by the presence of glass chips or other debris between the plies. Upon lamination, the pockets fill with PVB and become convex lenses. Conversely, shallow ridges on an internal glass surface may be absorbed in the PVB and the optics are improved. Various other optical distortions may be caused by nonparallel plies of glass or PVB.

2. Manufacture

Practically all conventional laminated glass utilizes plasticized poly(vinyl butyral) (PVB) as the interlayer. Curved, laminated windshields are by far the principal products; silicone and cast-in-place urethane resins are sometimes used in specialty applications. Laminators purchase PVB in rolls up to 500-m long, up to

270-cm wide, and from 0.38- to 1.52-mm thick. There are several placticizers used and at different ratios of plasticizer-to-resin content, depending on the product being manufactured. Flexol 3 GH, (bis(2-ethylbutanoic acid), triethylene glycol ester), manufactured by Union Carbide, is utilized at about 44 parts per 100 parts of resin. Other plasticizers (qv) used are di-n-hexyl adipate and dibutyl sebacate. There are at least five companies offering these products with manufacturing facilities in the United States, Japan, Belgium, Germany, and Mexico. Because the plastic is an adhesive material, it is shipped either with a dusting or parting agent on the surface or is refrigerated so it does not cohere. The refrigerated material is clean, moisture adjusted, and ready to laminate. The dusted material requires washing and moisture conditioning. Removal of the parting agent by warm water, followed by a chilled water rinse, adds about 0.2% water content to the plastic which must be compensated either by overdrying before washing, or drying after washing so as to achieve the desired 0.3–0.5% H_2O content. These steps are done more efficiently on the continuous roll before cutting. Moisture content of the PVB is extremely important because it has a direct effect on the adhesion characteristics of the glass/plastic surfaces.

The drying stage is carefully controlled to relax the sheeting of physical stresses as well as to adjust the moisture content. It consists of draping the sheeting over slat conveyors or driven rolls in a temperature- and humidity-controlled oven. The gradient band sunshade that appears in many windshields is either printed continuously on the interlayer roll at the PVB manufacturing plant or extruded into the sheet at the time of manufacture. To permit a more pleasing conformance to the curved glass, the banded interlayer may be preshaped which causes the extremities of the band to be more nearly parallel the horizon in the installed windshield. The shaping of the interlayer may be carried out on the continuous roll using a cone-shaped expander prior to cutting the blanks (6). The radius of curvature is preset, depending on the pattern of the particular windshield being manufactured. The interlayer then is cut to approximate laminate size and accumulated in low stacks (150 mm max) ready for assembly. Another method for shaping the interlayer involves warping in special ovens after the blanks are cut. The interlayer stacks must be stored in cooled, moisture-controlled rooms to control water absorption and blocking of the highly plasticized material.

The glass for laminating may be annealed, heat-strengthened, tempered, flat or curved, clear or colored. Thicknesses of $\geq 1.5 - 12$ mm are used. For flat laminates, the glass is cut to size, edged and treated, if specified, washed, and delivered to the clean room by conveyor. The washing process, in addition to cleaning, can affect the interlayer bond. Common water hardness residues at invisible levels can reduce adhesive strength of PVB to glass. The desired level is achieved by controlling the hardness of the final rinse water and by removing the water by air stripping as opposed to evaporative drying. The glass is cooled during drying to prevent premature sticking when the interlayer is placed on the glass, thereby permitting easier positioning of the components.

In order to manufacture curved laminates, the glass is preshaped before laminating. This is usually accomplished by simultaneously bending a pair of glass templates which are cut to the shape of the finished windshield and separated by an inert powder to prevent fusing of the plies. The bending process is typically carried out on a peripheral support, metal fixture, or mold; the pair slowly travels through a lehr so that the glass sags to shape by the force of gravity. Glass temperatures of 600°C are required to achieve the shape, and the shaping is followed by annealing to reduce stress. Banded windshields usually are constructed with one or more pieces of tinted, heat-absorbing glass to enhance occupant comfort and to reduce air-conditioning load.

The clean room typically is operated at 18°C and 26% rh, which produces an equilibrium condition for the desired interlayer moisture level. The interlayer is placed on one piece of glass, with the gradient band, if present, carefully positioned above the designated eye position. The adjacent piece is superimposed, excess interlayer is trimmed, and this “sandwich” is conveyed from the room through a series of heaters and rolls that press the assembly together while expelling air. Temperature is increased stepwise to 90°C and pressures of 170–480 kPa (25–70 psi) are applied. Solid rubber rolls usually are used with flat laminates, and curved glass requires segmented rolls on a swivel frame (Fig. 4) (7, 8). For more complex shapes, peripheral gaskets may be applied and the assembly may have the air evacuated (9), or the entire assembly may be placed in a bag and the air evacuated. The bag may or may not be removed prior to autoclaving, but when using an oil autoclave

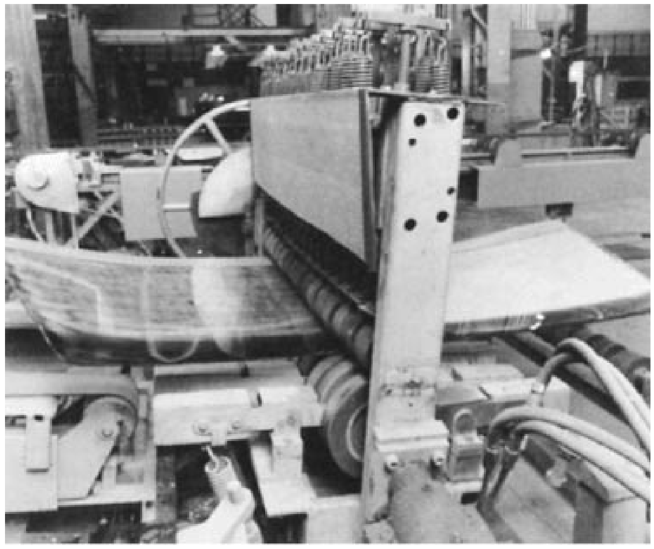

Fig. 4. The glass and vinyl "sandwich" is fed through a special de-air machine to remove trapped air and increase the adhesion of the vinyl to the glass.(Courtesy of Ford Motor Co.)

where the oil would damage one of the components, an oil-resistant Teflon or poly(vinyl alcohol) bag can be used (10). The tacked assembly is loaded onto racks for autoclaving, which may be either in an air or oil vessel capable of pressing the sandwiches at 1.38–1.72 MPa (200–250 psi) and 100–135°C for 30–45 min. Curved laminates and multiple laminates may require longer cycles to allow the polymer material to flow completely.

In the autoclave cycle, the pressure is increased more rapidly than the temperature and then is maintained toward the end of the cycle as the temperature is lowered, to prohibit bubble formation and reduce any chance of delamination. The exit temperature must be no greater than 50°C to avoid thermal breakage. During the cycle, residual air is absorbed by the interlayer, and the embossed surface of the interlayer flows and wets the glass surface, thereby producing the clear laminate. Occasional small residual bubbles of trapped air can be removed by an additional autoclaving cycle. The air autoclave process is becoming the preferred method because it eliminates the subsequent washing of oily residues that are produced in oil autoclaving. The elimination of the process oil and subsequent washwater waste products also are environmental improvements. In some cases, additional trimming of the interlayer or finishing of the glass edge is required. The protruding interlayer may be trimmed or removed by wire brushing, but care must be taken to assure that the glass edge is not damaged in the process. The labeling of safety glass is done by grit-blasting through a mask or by silk-screening of a ceramic frit enamel. A final step in some windshield manufacture is the bonding of a small metal plate to the windshield. This plate, which is used to support the rearview mirror, is laminated to the glass using a special formulation of poly(vinyl butyral).

Radio antennas have been incorporated in some windshield models by inclusion of a very fine copper wire placed across the top of the windshield and vertically at the center. The wire is tacked to the interlayer prior to assembly and is embedded into the interlayer during autoclaving. An electrical connector that is soldered to the antenna wire is bonded to the bottom edge of the windshield for ease of connection. This type of construction is, however, being increasingly replaced by silk-screening of the antenna patterns directly on the glass using a silver-frit mixture.

3. Production and Shipment

Chemical attack, particularly from moisture and alkaline conditions, is prevented by use of acidic packing materials and open, ventilated packages. Good crate design and proper handling throughout shipment avoids mechanical damage. Glass-to-glass contact is never permitted. Long-term storage must be in well-ventilated areas, never in sealed containers. In the case of trans-ocean shipping, however, sealed containers are often used with a desiccant added to prevent moisture attack of the glass (see Desiccants).

Flat laminates are separated only by newsprint or plastic beads (ie, Lucite) and are bound into a block to prevent movement between the laminates. Curved laminates are spaced to prevent abrasion and require supporting dunnage at several points to prevent breakage by excessive flexing during shipment. Banding and blocking are designed to add compressive forces only. Staining is not a problem in the uncovered areas, but the supporting members are specified to have an acidic content to prevent chemical attack.

Laminated glass products are considered noncombustible and are shipped without DOT hazardous warning labels. Flat laminate packs, because of their high density, do not fill the car or trailer and require sturdy bracing to prevent shifting. Glass products are shipped and stored in a vertical plane, and during transportation they are placed so that each plate has an edge in the direction of travel.

4. Economic Aspects

The growth of laminated glass closely followed the growth of motor vehicles from the late 1920s to the 1960s. Windshields and side glasses of all domestic vehicles were laminated during this period. In the early 1960s, the flat, laminated, side glass was almost entirely replaced by curved, tempered glass. The curved windshield laminated glass market continued to follow automotive trends, but the flat glass products redeveloped around architectural uses. Architectural products currently represent 5–10% of the laminated glass volume. Increased consumer safety awareness and security needs are expanding the flat laminate market. Safety codes (eg, 16CFR 1201 and ANSI Z97.1) specify laminated glass as one means of meeting their requirements (11, 12). In hurricane-prone areas laminated glass is being specified increasingly by local authorities.

Laminated windshields, as opposed to tempered glass windshields, are gaining in market share outside of North America. From 37% of the non-North American market of 1976, they were estimated to have reached 75% by 1982 (13). In addition to North America, Belgium, Italy, and the Scandinavian countries permit only laminated windshields, and other nations are increasing use by customer option. The trend toward laminated windshields is expected to continue and nonlaminated windshields will likely be obsolete by the year 2000 (14).

5. Specifications

Almost all of the laminated glass made is tested and certified to comply with certain safety performance standards. In the United States, there are two types of standards: automotive and architectural. For the former, *ANSI Z26.1-1973* is used and is incorporated in the Federal Motor Vehicle Safety Standard 205 (15). It specifies safety performance, durability, and optical quality. Specific tests are required depending on the location in the vehicle where the glazing is to be used. Item 1, the most difficult to meet, may be used in any location in the vehicle. It requires, in addition to other tests, support of a 2.3-kg ball dropped from 3.7 m onto a 305-mm square of laminate. Item 2 (safety glazing for any location except windshields) may be met by laminated glass using thinner PVB because it does not require the 2.3-kg ball test and the optical distortion tests. Laminated glass may also be used in locations specifying item 3 (no visible transmittance requirement) or item 11A (bullet-resistance glass; also requires appropriate tests, eg, ballistic tests). Automotive safety glass is required to be labeled as to the manufacturer, code, item, and model number that identifies the type of construction.

Conformance to the standard is achieved by submitting samples to an approved laboratory for evaluation and submitting the laboratory report to the American Automotive Manufacturers Association (AAMA). The approved certificate is sent to the manufacturers with copies to the state and provincial jurisdictions for which the AAMA serves as approvals agent (16).

Laminated glazing materials used in building locations specified by federal regulations are certified to comply to federal standards by the Safety Glazing Certification Council (SGCC) (17). Other locations requiring safety glazing specified by state or local code may use alternative standards (12). Glass complying to these standards is labeled permanently as to the standard (or standards) that it meets, including thickness, identification of the manufacturer, and plant. Also, it usually contains a date of manufacture. In situations where the large laminated sheets are cut into smaller pieces by the local distributor or installer, each piece is permanently labeled to indicate that it was cut from glass meeting the standard.

Certification to these standards is obtained by submitting a test report from an approved laboratory to the SGCC. Once certified, the product is assigned an SGCC certification number to identify it and the factory at which it was made. Subsequently, samples are selected randomly by the administrator at least twice a year to ensure continued adherence to the standard. Based on these re-evaluation reports, SGCC authorizes continued use of the certification label and the product listing published in its directory. The building standards are concerned mainly with body impact, and they require testing by impact on the glazing with a 45-kg bag. Detailed testing procedures and interpretations are available (11, 12).

Bullet-resistant glass products are tested according to UL 752 (18). The test specifies that three shots are fired from 4.6 m and impacting within 100 mm of each other in a triangle, and that there is no penetration of the projectile nor any glass embedded in the corrugated board. The level of approval is determined by the velocity and energy level of the bullet at the muzzle of the firearm. Additional tests required include impacts 38 mm apart and tests over temperature ranges of 13–35°C for indoor use and -31.7 to 49°C for outdoor use.

The above-mentioned codes contain requirements for accelerated durability tests. In addition, interlayer manufacturers and laminators expose test samples for several years under extreme weather conditions, eg, the Florida coast and Arizona desert. The laminated products weather extremely well, with no change in the plastic interlayer. Occasionally, clouding is noted around the edges when exposed to high humidity for long periods, but this is reversible. Colored areas of PVB laminates may fade while subjected to extensive uv/solar irradiation, which could cause an appearance issue. This has not, however, been shown to alter the laminate's other performance properties.

6. Analytical and Test Methods

Interlayer moisture is one of the important controls for PVB-to-glass adhesion of current formulations (although moisture-insensitive formulations are being developed). The moisture content equilibrates with the relative humidity to which the interlayer is exposed and thus is variable. Prior to lamination, interlayer moisture content is measured by one of three methods. The most rapid is by air absorption using a spectrophotometric technique to determine a ratio of the 1925-nm to the 1705-nm wavelength peak (Fig. 3). A slower but less expensive method is weighing the interlayer before and after vacuum desiccation. The third and classical method is by Karl Fisher reagent; this technique is usually confined to instrument calibration exercises. The infrared method, in addition to being the most rapid, permits measurement of the interlayer moisture content while the interlayer is in the laminate. Instrumentation is available for monitoring interlayer moisture in full-size parts.

Interlayer bond strength is determined by either pummeling the laminate at $-18^{\circ}\mathrm{C}$ to break away the glass and to determine the amount of adhering glass particles or by compressively shearing the laminate

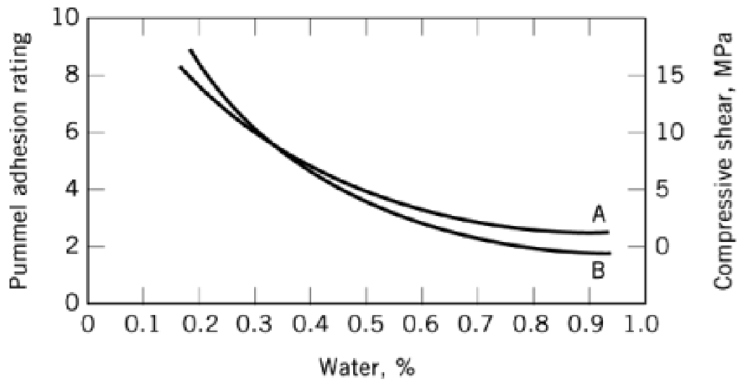

Fig. 5. Typical effect of moisture on PVB adhesion: A, pummel data $_{(-20°C)}$ from Monsanto Co.; B, compressive shear data from Du Pont Co. To convert MPa to psi, multiply by 145.

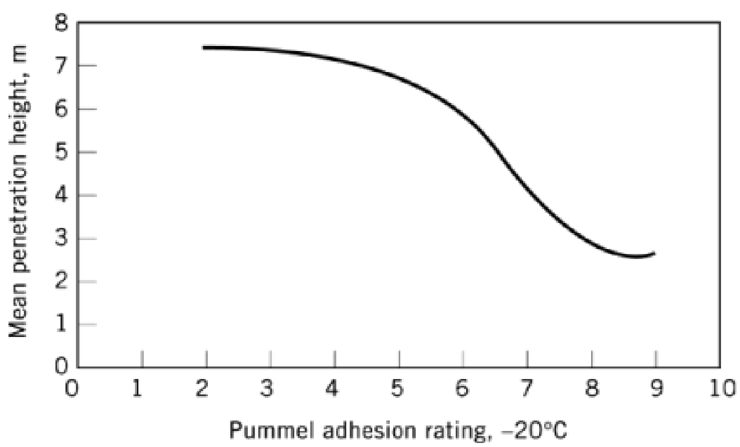

Fig. 6. Typical variation of mean penetration height with adhesion (2.27-kg ball, impact at $_{-2°C}$ on $_{305 \times 305-mm}$ laminates; 0.40%water, 0.76-mm PVB).(Courtesy of Monsanto Co.)

sample in a universal test machine. The optimum pummel range is three to five units on an arbitrary scale (from 1 to 10) established by the industry. The relationship of pummel value and compressive shear data to water content of the interlayer is given in Figure 5 and that of pummel value to mean penetration height is given in Figure 6. These data are influenced also by residual hardness of the water used to wash the glass.

Subsequent to processing, an inspection is made for incomplete bonding, inside dirt, and glass quality. In the case of windshields, rigid optical standards must be met, and these must be evaluated for the completed windshield. Extensive test requirements are described in the appropriate codes (11, 12, 15, 18–24), and they include light stability, resistance to optical distortion, humidity, boil test, abrasion resistance, and assorted impact tests.

7. Uses

7.1. Penetration-Resistant Windshields

Performance difference between windshields manufactured in Germany and the United States was reported in the early 1960s (25, 26). Three variables contribute to the greater safety of the German windshields against impact: thinner glass (especially the inboard member), thicker plastic interlayer, and higher moisture content of the interlayer. The latter acts as a plasticizer and in adhesion control (see Plasticizers). By reducing the adhesion of the interlayer to the glass, more interlayer area can be released and stretched during impact. Also, the thicker interlayer, in addition to having more inherent strength, causes more fracturing of the glass during impact than in the older model of windshield. This, in turn, increases the amount of released interlayer for impact energy absorption. Upon review by the SAE Glazing Committee, it was agreed that the improvement was desirable, if it could be accomplished without taking the risk of increased water content. The U.S. PVB manufacturers subsequently developed controlled adhesion interlayers without increasing moisture above the previous standard content, and the glass fabricators utilized this material to produce laminated windshields with more than twice the impact resistance of the pre-1966 windshields. This product was introduced in limited production in 1965 and was used in all United States car lines for the 1966 models (27).

The ASA (now ANSI) performance code for Safety Glazing Materials was revised in 1966 to incorporate these improvements in windshield construction. The addition of test no. 26 requiring support of a 2.3-kg ball dropped from 3.7 m defined this level of improvement. It was based on a correlation established between 10-kg, instrumented, head-form impacts on windshields, on $0.6 \times 0.9\mathrm{-m}$ flat laminates, and the standard $0.3 \times 0.3\mathrm{-m}$ laminate with the 2.3-kg ball (28). Crash cases involving the two windshield interlayer types were matched for car impact speeds and were compared (29). The improved design produced fewer, less extensive, and less severe facial lacerations than those produced in the pre-1966 models.

Additional improvements have been incorporated since 1966 with the availability of thinner float glass. Glass thickness and interlayer thickness have been studied to optimize the product for occupant retention, occupant injury, and damage to the windshield from external sources (30, 31). The thinner float glass windshields are more resistant to stone impacts than the early plate glass windshields. The majority of laminated windshields are made of two pieces of 2–2.5 mm annealed glass and 0.76 mm of controlled adhesion interlayer.

7.2. Special Laminated Windshields

Combinations of strengthened glass and interlayer offer advantages of lessened weight, higher impact resistance, lowered laceration potential, and resistance to bending stresses. These may be needed in high speed aircraft, helicopters, and motor vehicles. The additional strengthening can be achieved by chemical or thermal processes. The chemical process by ion exchange in molten potassium salts produces highly compressed skin and increases center tension. Thermal processes, capable of inducing high stress into float glass are also widely used, although not usually in automotive windshields.

Another variation of special construction (bilaminate) windshields consists of one ply of glass and one ply of an abrasion-resistant plastic. Although these laminate types have been available for several years, their limited mechanical durability has resulted in limited acceptance. Other features, such as deicing/defogging and solar rejection, can be incorporated into laminated glass. As technology advances it is anticipated that variable light transmission will also be possible by utilizing the properties of liquid crystal or electrochromic materials. These likely will need to be protected from the environment by encapsulation in laminated glass.

Other automotive uses of laminated glass include colored glass and decorated glass. The privacy glass used in the side and rear glazing of vans can be made by laminating one or more layers of highly tinted PVB and clear glass. Opera windows containing metallic ornaments and sufficient plastic interlayer to accommodate

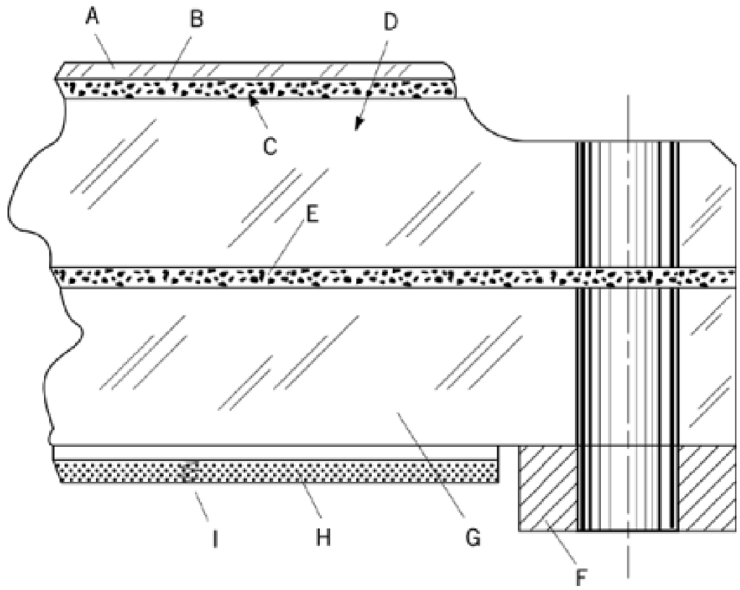

Fig. 7. Cross section of Sierracin windshield used on Boeing 747 (32): A, 2.2-mm chemically strengthened glass; B, Sierracote 3 conductive coating; C, 1.9-mm PVB; D, 23-mm stretched acrylic; E, 1.3-mm PVB; F, laminated cloth spacer ring; G, 23-mm stretched acrylic; H, 0.6-mm PVB; and I, 3.0-mm Sierracin 900.

their thickness have also been used. Laminated roof glazing can consist of a combination of coated glass and a colored PVB.

7.3. Aircraft Windshields

Aircraft windshields have extreme requirements in service temperature and pressurization and they must be resilient against high velocity bird impact. In addition, they must offer excellent visibility, both from optics and deicing capabilities, and an aerodynamic design. These highly specialized windshields are produced in low volume and are made by few companies, eg, Sierracin, PPG Industries, and Triplex Safety Glass Co. Construction varies with the need and service potential of the aircraft. Small planes of limited altitude and speed usually have acrylic monolithic windshields treated with a hardcoat material such as polysiloxane. Slower commercial aircraft use flat laminated glass made with aircraft-grade PVB (Monsanto Saflex PT). These aircraft require deicing capability which may be given by a conductive film that is pyrolytically or vacuum deposited on a glass surface, or conductive plastic film that is laminated in the sandwich. The third general class of aircraft windshield is for the modern, commercial, wide-body aircraft. These windshields become extremely complex, large in size, and expensive. A fourth type is for high speed, low flying military aircraft where birds, high skin temperature, and gunfire warrant extremely complex construction. The third and fourth types are multilayer constructions; typical examples are shown in Figures 7 and 8 (32, 33).

The Boeing 747 windshield (Fig. 7) is about 1.0×1.1 m and is curved to increase the pilot viewing area and to reduce air drag and air noise. Composed of seven plies, it weighs about 64 kg (32). The outer strengthened glass skin and the inner plastic shield may be replaced when damaged. The Triplex Safety Glass Co. also makes wide-body aircraft windshields, flat and curved, for Boeing and others. For the Boeing 747, two precurved, 12-mm plies of Ten-Twenty glass are laminated with PVB and covered with a 3-mm ply of Ten-Twenty glass bent

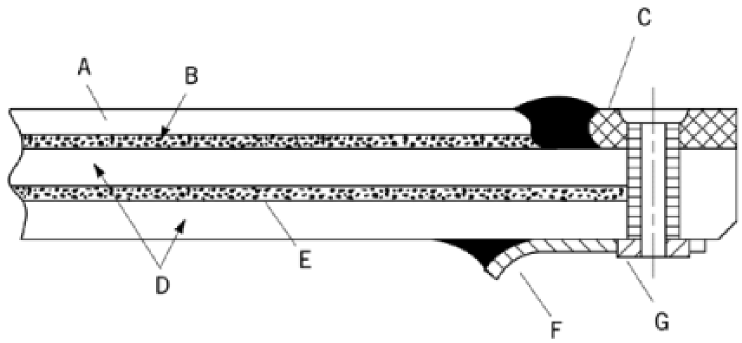

Fig. 8. Sierracin lightweight, birdproof F-111 windshield cross section (43). A, 3.0-mm as-cast acrylic face ply; B, S-100 silicone interlayer; C, fiber glass retainer; D, 6.4-mm polycarbonate structural ply; E, S-120 polyurethane interlayer; F, stainless steel bearing strip; and G, stainless steel bushing.

to conform to the curved windshield. An electrically conductive coating, Hyviz, is applied to the inner surface of the outer ply and then is laminated to the 12-mm Ten-Twenty ply (34).

The construction of the F-111 windshield shown in Figure 8 replaced a glass–silicone laminate previously used. The all-plastic windshield has improved impact resistance so that it is birdproof to 250 m/s (33). In this instance, the scratch resistance of glass was waived to obtain the impact performance at the allowed weight.

7.4. Architectural Products

Many specialized laminated glasses are made for architectural needs such as safety, sound attenuation, solar control, and security. These products may be further enhanced with colors and patterns for decorative effects. Safety glasses are specified in potentially higher risk breakage areas and overhead or sloped glazing (defined as more than 15° from vertical). Overhead glazing materials have varied in the past but more localities are accepting laminates. Sloped and overhead glazing frequently have heat-strengthened or tempered glass used in the construction of the laminate (35). Vertical passageway glazing usually is a 0.76-mm interlayer and sloped glazing is constructed with a 1.52-mm interlayer to accommodate the waviness of heat-treated glasses when they are used.

Noise attenuation is achieved effectively with laminated glass by the combination of the vibration damping effect of the plastic interlayer, an air gap, and usually an unbalanced glass thickness. Typical construction is 0.76–1.5-mm interlayer laminated with 3–10-mm glass. The type of glass or strength is not a factor in noise attenuation but a dead air space can be particularly effective in reducing selected frequencies. A Sound Transmission Class Index of 34–41 is achieved with single laminate glazing and can be improved if combined with double glazing that has large air spaces. Mounting of the glass in an airtight but flexible gasket reduces sound transmission (36). Airports, hotels, factory offices, and control rooms benefit from laminated acoustical glazing (37) (see Insulation, acoustic.

Laminated glass is used for solar control, particularly where a highly reflective surface is not desired and where the laminate contributes other benefits. In these applications, a uniformly pigmented interlayer is obtained from the manufacturer and the laminate can be prepared by the conventional process. Broad ranges of colors and transmission levels are available with shading coefficients as low as 0.41. Pigmented interlayer is considered to be more color stable than dyed interlayer. Browns, blues, greens, pink, white, and clear plastics containing uv absorbers are readily available. Body-colored glasses may be used also, usually with clear interlayer. In these cases, the laminate is dependent only upon the solar properties of the glass.

Laminated glass may also be made using any of the low emittance (low-e) glass products on the market, but the low-e coating must not be in contact with the interlayer for the low emittance property to be achieved.

All laminated glass increases the level of security to some extent. However, depending on the application, security glass is constructed of multiple layers of glass, PVB, polycarbonate, polyurethane, or other polymer materials. Laminated glass permits the same visual observation as normal glass but prevents or delays unauthorized entry (or exit) until the attempt can be detected. It complies with test UL 972 (38).

Bullet-resistant glass is contructed of many layers of glass and aircraft-type PVB depending on the level of resistance desired. Typical products are 38–50 mm thick and weigh $90 - 130\ \text{kg/m}^2$.

A third type of security glass is installed in modern penal institutions. This product is utilized for prisoner detention and obviates iron bars and their demeaning aspect. Typical construction utilizes three or more layers with at least one ply of thick PVB. Other constructions utilize polycarbonates, polyurethanes, and modified acrylics. Strengthened glass and electrically conductive circuits for alarms may be included. Large, heavy sections of similar construction have been used for underwater windows for boats, submarines, and aquariums. Four plies of fully tempered, 10-mm glass plus three plies of $\sim 1.9-\text{mm}$ PVB totaling 44.5 mm in thickness has a modulus of rupture of 172 MPa (25,000 psi) (39).

Glazing of laminated architectural glass requires additional care in the selection of sealants and drainage design. Sealants (qv) must be free of solvents (particularly aromatics) and mineral or vegetable oils (3) and must not provide pockets that would trap water at the glass–PVB edge. Similarly, the glazing detail must be designed with proper drainage (35). Generally, the practice is similar to that of glazing organically sealed insulating units (40, 41).

In the 1990s increased attention has been placed on the design and evaluation of transparent, architectural glazing panels that offer protection from sustained wind and snow loads, as well as gusts of hurricane strength winds (42, 43). Research at academic institutions has been aimed toward improving window performance during extreme weather conditions. Many of the recommended penetration-resistant construction types consist of glass–plastic laminates (44, 45).

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