Glass That Won't Shatter

Flat panes of window glass have been made since the first century A.D. The tendency of glass to break into long, sharp shards that can potentially cause injury, however, has spurred the development of glasses designed either to resist shattering or to break into small, harmless fragments without dangerously sharp edges.

The first solution for "safer" glass was invented in France in 1903 by artist and chemist Edouard Benedictus. Benedictus received a patent in 1909 for his *laminated* glass, a sandwich of flat glass and tough, transparent plastic material. The outside glass layer shattered when struck with enough force, but the inner plastic layer, which stretched and absorbed the energy of impact, also held the broken pieces of glass together, keeping them from flying in various directions.

Benedictus first laminated glass consisted of two sheets of glass with a thin sheet of cellulose nitrate between them. Cellulose nitrate, also originally used as a backing for photographic film, is highly flammable. It also discolors rapidly in some climates, beginning at the edges and eventually covering a wide area, making the layered glass unacceptable.

Laminated glass made with cellulose nitrate proved adequate, however, as windshield material for the newly burgeoning automobile industry. In the 1920s, more light-stable plastics, such as cellulose acetate, replaced cellulose nitrate as the transparent plastic binder. In 1936, cellulose acetate was replaced by polyvinyl butyral (PVB) sheeting. PVB does not discolor on exposure to light, and it retains its elastic properties even at -16°C. PVB also sticks to glass of its own accord and so needs no special adhesives.

Laminating flat glass is a straightforward process, but after the 1930s automobile windshields were all curved. In a curved windshield the two layers of glass must be perfectly matched. Paired sheets are placed on shaped frames and then heated in an electric furnace. The high temperature softens the sheets of glass, which then sag into the contours of the frame. The formed glass sheets are then washed and dried.

In the next step, a dry sheet of plastic film is positioned between the two pieces of glass; this operation takes place in an air-conditioned room where the temperature is below 16°C and the relative humidity is no higher than 30%. The glass/plastic sandwich is heated electrically, accompanied by pressure from rubber rollers to encourage preliminary adhesion. The glass/plastic sandwich is then placed in an autoclave, where the pressure is increased to 0.35 MPa and the temperature is raised to above 100°C to complete the adhesion process. The interlayer for normal automobile windshields is about 0.076 cm thick.

By using thicker layers or multiple layers, laminated glass can be made tough enough to stop even heavy-caliber bullets. "Bullet-resisting" glass absorbs the energy of the bullet while several plastic layers hold the fragments in place. Even at close range, a pistol shot will not break through 1.9 cm thick laminated glass (1.3 cm glass with 0.6 cm plastic). Even stronger "bulletproof" glass is made of several layers built up to about 3.8 cm thick. This type of glass is used in aircraft, military tanks, and banks.

Unlike laminated glass, *tempered* safety glass is a single, continuous piece of specially heat-treated glass. It had been known at least since the 17th century that a mass of molten glass hardened by dropping it into cold water can survive repeated blows with a hammer. These "Prince Rupert's drops," named after the man who popularized them, collapse into a heap of blunt granules when they are finally shattered.

Modern safety glass sheets are suspended in a furnace at about 650°C, just below the material's softening temperature, followed by sudden but uniform chilling by jets of air or cold gas. This process produces a skin of compressive stress of over 200 MPa in the glass. Tempered safety glass weighs and has the same physical appearance as regular glass, but it has five or six times the tensile strength. Safety glass is difficult to break, even when struck with a hammer; when it does shatter, the entire sheet of glass collapses into small, blunt fragments. The edges of these fragments are concave from the sudden, long-delayed shrinkage of the interior. (For this reason, all drilling and cutting must be done on the glass before it is tempered.)

Mass production of tempered safety glass was first developed in 1926 by the Libbey-Owens Company in Charleston, West Virginia. (In 1908, Libbey-Owens was also the first company to create a machine that could draw sheets of window glass.)

Tempered safety glass is almost universally used for automobile rear windows and door lights. Tempered safety glass is also widely used for windshields in Great Britain, although it has been deemed unacceptable in the United States and other countries—mainly because the glass is more rigid than the skulls of automobile occupants. Laminated glass, however, can yield without causing disastrous results. Also, the "frosted" appearance of cracked tempered glass makes an impacted windshield impossible to see through.

In yet another glass development, between 1912 and 1915 at the Corning glass works in the United States, Eugene C. Sullivan and William C. Taylor created a heat-shock resistant glass. This borosilicate glass, containing about 80% silica, 13% boric oxide, 4% alkali, and 2% alumina, is about three times as heat-shock resistant as other glasses. Known by the familiar trade name, Pyrex, this material is used in laboratory ware, baking ware, and glass pipe lines.

New glass, ceramic, and plastic materials are being combined to make tougher transparent materials for many of our industrial, laboratory, and household uses. Processing techniques are being adapted to make glass and similar materials tougher and safer. Perhaps we will someday have a material such as the "transparent aluminum" created for the aquarium used to transport the whales in the Star Trek IV movie...

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