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The Interpretation of Impact Fractures in Glassy Polymers

The behavior of glass under stress in connection with impact fractures has been the subject of considerable forensic interest. The interpretation of direction of force in impact fractures has found conspicuous application in criminal investigations. The matter has been reviewed by Matwejeff [*1*], Tryhorn [*2*], and more recently by McJunkins and Thornton [*3*].

The principal features of fracture behavior which are noted after impact are (1) conchoidal markings along the radial and concentric fractures; (2) mirror, mist, and hackle; and (3) the cratering effect observed on the side opposite the origin of force. These markings are found to be indicative of the stress forces which occur during fracture propagation. It is observed that glass breaks under tension, not compression, and may leave a series of curved lines (conchoidal marks) along the fracture. In radial fractures these conchoidal lines are asymptotic to the side of force origin, and are perpendicular to the surface opposite the force origin. In high energy impacts, small straight lines along, and perpendicular to, the conchoidal marks are also noted; these are termed hackle. Mirror and mist result from the manifestation of the same physical phenomenon resulting in the formation of hackle, but are seldom the subject of forensic consideration (Fig. 1).

An examination of the appearance of the fracture markings may enable the criminalist to determine the nature of the impact force which caused the fracture. These characteristics of glass fracture have been well studied and documented [*4-6*].

There is, however, a related area that has not been explored by the forensic scientist. Over the past several decades there has been a phenomenal increase in the utilization of glassy polymers as glass substitutes. Among these polymers are polystyrenes and polyvinyl chlorides, styrene acrylonitriles, cellulose esters, acrylics, and polycarbonates. The best known and most widely used groups of glass substitutes are the acrylics and the polycarbonates. The superior translucence (relative to glass), the low density, the relative inertness, and the general toughness and weatherability of these polymers suggest that they will be increasingly used in architectural situations in lieu of glass.

Polycarbonates have not come into use as widely as the acrylics, for two major reasons. First, the commercial availability of polycarbonates dates from about 1959, while acrylics have been available for over 40 years. Second, the price of polycarbonates is double or triple that of acrylics, without an equal corresponding advantage in most uses or properties.

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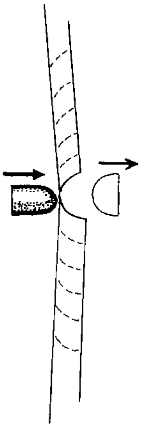

FIG. 1—*Classical means of depicting glass fracture by a projectile. The cone of glass removed corresponds to a fracture along conchoidal striae on the radial edges.*

Acrylics in thicknesses from ⅛ to ¼ in. have 7 to 18 times the impact resistance of double-strength glass, yet half the weight. Unlike glass they can be machined and tooled. The colorless variety has polychromatic light transmittance of 92% and a high resistance to ultraviolet radiation. The tinting possibilities are virtually unlimited.

Acrylics first found commercial use as aircraft glazing material. Their role in aviation today has expanded to include canopies, windows, instrument panels, and various light covers. In other applications acrylics are used for dome skylights, internally illuminated outdoor signs, enclosures for swimming pools, shopping centers, restaurants, and botanical gardens. They are often used in place of glass windows in industrial plants, school buildings, and other structures in which breakage by vandalism or accident is a costly problem. The automobile and boat industries are finding increasing uses for acrylics as light covers, windshields, dial covers, and ornamentation.

Some states, recognizing the safety hazard with glass, have enacted statutes requiring that all new installations of residential entry doors and storm windows be glazed with polymers instead of glass. Acrylics provide a practical substitute.

The engineering literature reflects a paucity of information relative to fracture phenomena in glassy polymers that is applicable to the forensic concern. Although several definitive works exist which deal with fracture propagation in polymers [*7-8*], they offer little assistance in an adequate reconstruction of the fracture forces when the nature of the original force is unknown.

The present study is an effort to supply the criminalist with some of the information necessary to perform an accurate reconstruction of the impact forces which could cause fracture propagation in acrylic polymers. As with glass, this reconstruction may be performed by an examination of the features found along the edges of fractures. The fractures in this study were created by the impact of high velocity projectiles.

The polymer utilized in this study was a polymethyl methacrylate. This polymer was chosen because it is typical of most acrylics found in many architectural and industrial applications. This acrylic was used in ¼-in. thickness for all tests. Two area sizes (10 by 10 in. and 12 by 12 in.) were used, held in a wooden frame.

Three series of tests were conducted. The first series employed a .22 caliber rifle using .22 Long Rifle ammunition, and firings were conducted at various distances. The second series was performed with pistols of various calibers, all fired from 25 ft. The calibers and chamberings included .22 Short, .22 Long Rifle, .22 Magnum, .32 Auto, 9-mm Luger, .380 Auto, .38 Special, .38 Super Vel, .357 Magnum, .44 Magnum, and .45 Auto. The third and final series of tests employed a single weapon and a single caliber (.38 Special). In this series, however, the cartridges were reloaded in fractional portions (by weight) of the original powder load. The velocities of the projectiles from the reloaded cartridges were then measured electronically at the time of the test firings.

Results and Discussion

There are several major areas in which significant results were obtained which are at variance with fracture phenomena observed in glass, including (1) the appearance of the cratering on the side opposite the force origin and (2) the dominance and appearance of the hackle marks on the radial fractures. These characteristics are dealt with separately below, each in terms of the physical characteristics observed and an explanation of these characteristics.

Appearance of Cratering

In the case of bullets fired through glass, a common phenomenon is the occurrence of beveling around the edge of the hole, on the side opposite the origin of the bullet. This beveling is generally conical and symmetrical for shots fired at an angle of 90 deg to the glass. In the case of the acrylic used in the present study, beveling was also found to be common; the appearance of this beveling, however, is decidedly different from that observed with glass. With the acrylic, the bevelled edges were observed to arch up and away from the center of the hole as the plate was transversed from front to back (that is, from side of force origin to opposite side) (see Fig. 2).

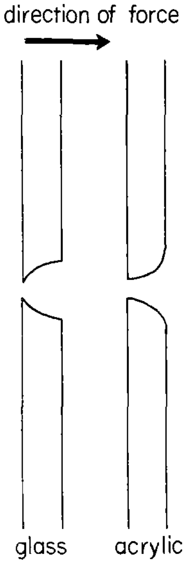

FIG. 2—*Appearance of cratering observed in high velocity, projectile-induced fractures of glass and acrylic polymer, respectively.*

The explanation of this characteristic is linked closely with the plastic deformation of the acrylic polymer and its ability to "flow," unlike glass [9]. (In this discussion the term "plastic" is used in the engineering sense to indicate a nonpermanent deformation, and not in the common sense of denoting a polymer of undefined nature.) When a projectile strikes a pane of glass and causes tension on the side opposite the force, a fracture is initiated. Then, as the projectile passes through the pane it forces a cone of glass ahead of it. The edges of this cone are consistent with the lines of stress initially created by the impact of the bullet. Acrylics appear to initially perform in a similar manner. Due to flow, however, the polymer deforms much more than glass before the tension becomes sufficient to initiate a crack. As a result of this increased bending, the stress forces present when the projectile forces a cone of material ahead of it are significantly different than in glass. In addition to the tension area ahead of the bullet and on the opposite side of the plate, the bending has created areas of high tensile stress on the same side as, and surrounding, the projectile. As the projectile passes through the

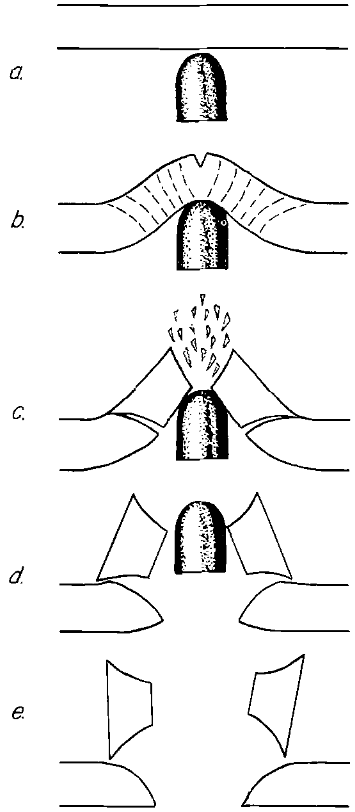

FIG. 3—*Principle of polymer fracture and cratering:* (a) *projectile approaches polymer sheet;* (b) *projectile strikes polymer and causes tension on the side opposite the force, while at the same time causing plastic deformation on the side of the application of force;* (c) *deformation due to the phenomenon of "flow" creates areas of high tensile stress on the same side as, and surrounding, the projectile;* (d) *the polymer material in the vicinity of the projectile is ejected; and* (e) *the plastic or nonpermanent deformation of the polymer sheet results in a return to the original plane.*

acrylic plate it pulls on the surrounding material sufficiently to initiate cracks at these areas of stress. Thus, the resulting coning effect is created (Fig. 3).

Dominance and Appearance of Hackle Marks

High energy impact fractures in glass result in a distinctive type of marking—hackle marks. It is generally believed that these short, fine marks result from the accumulation of stress in one domain, and when the speed of crack propagation is insufficient to relieve the energy of the tensile stress. Since entropy is increasing in the universe, there is a tendency toward a minimization of surface free energy. Hackle marks thus serve to create a maximum surface area along the fracture and thus dissipate more energy for a given moment.

Hackle marks were found to occur with the acrylic in this study, but with profound differences from the hackle observed in glass fractures. The hackle marks which occurred at the distal portions of the larger radial fractures were found to be very similar to those observed in glass. However, the hackle marks which occurred in close proximity to the origin of force in the larger radial fractures, and through the entire length of many of the shorter radial fractures, were found to be deeper, longer, and much more curved than those typical of glass fracture. In many of the shorter fractures these dominant hackle marks occurred to the virtual exclusion of conchoidal marks. This gives the appearance of inverted rib marks along the fracture and could be mistaken for such if examined independently of other fractures, or independently of other characteristics (see Fig. 4).

The explanation for this phenomenon is also related to the increased flexibility of glassy polymers relative to glass. Since deformation (and thus the tensile stress) decreases as the distance from the point of impact increases, this accentuated hackle is not observed beyond a certain radius from the point of application of the force. The distance appears to be dependent upon the shape, caliber, and energy of the projectile.

It should be noted here, for the purpose of the previous and following discussions, that no concentric fractures were observed during any of the tests; the fractures discussed are exclusively radial fractures. This lack of concentric fractures is obviously explained by the superior flexibility of the polymer.

Incidental to the examination of the fracture phenomena on fracture surfaces, indications of tendencies in relation to bullet energy and velocity were also observed. The major tendency noticed was an inverse relationship between the bullet velocity and length of radial fractures. The extremes of this relationship were demonstrated by the .22 Magnum and the .22 Short cartridges. The radial fractures caused by the .22 Magnum displayed an average length of only about 30 mm, while the fractures caused by the .22 Short projectiles were over 135 mm in average length. The muzzle velocities of the .22 Short and .22 Magnum are 1045 and 2000 ft/s, respectively (Fig. 5).

Another tendency which was observed was the inverse relationship between the muzzle energy of the bullet and the degree of curvature in the cratering. Lower energy projectiles tend to produce greater curvatures on the sides of the cone, while projectiles of higher energy display a straighter boundary along the crater edge (Fig. 6).

The tendencies discussed above may be explained by the difference in flexibility between the polymer and glass, as discussed previously. It appears that the higher velocity, higher energy projectiles act for a shorter moment, initiating fractures before an extensive amount of deformation takes place. Thus, less energy is transferred to the polymer in the form of tension and less fracturing takes place. The slower, lower energy

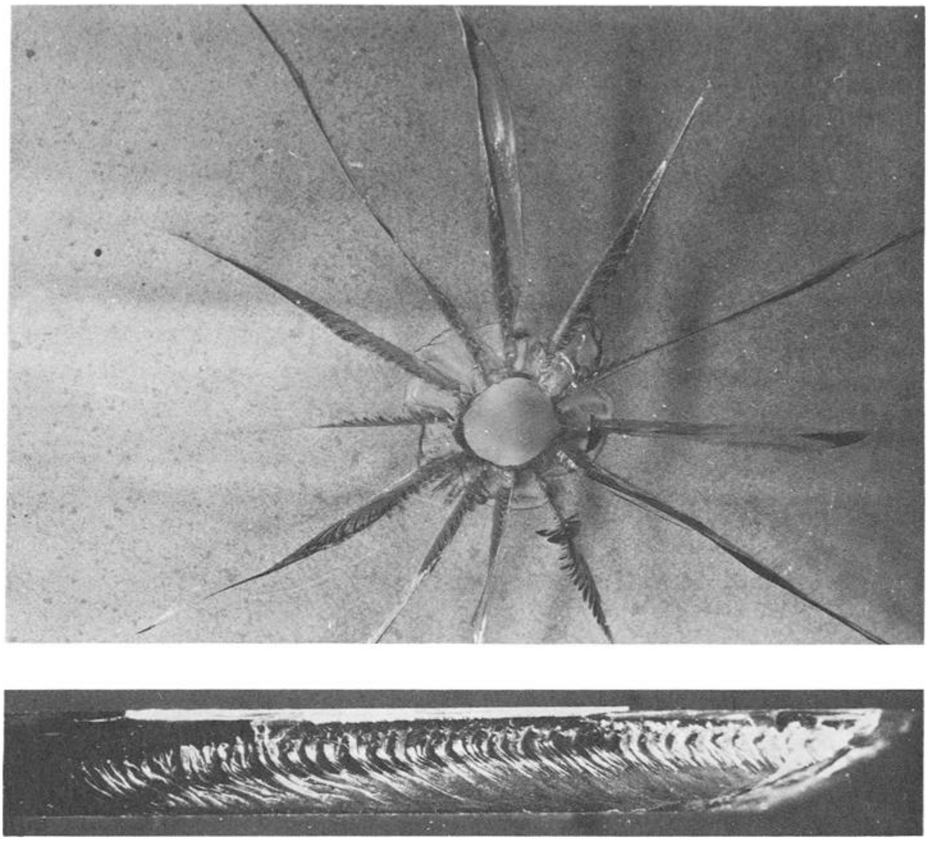

FIG. 4—*Fracture of acrylic polymer by a high velocity projectile:* (top) *the markings possessing the appearance of conchoidal marks in the radial fractures are actually hackle and* (bottom) *close-up view of hackle along a radial fracture of an acrylic sheet. If these markings were assumed to represent conchoidal markings as in glass, an erroneous determination of force would result. The direction of travel of the projectile is actually from top to bottom.*

projectiles act for a longer period of time. This results in more deformation and greater energy transfer in the form of tension. Thus, a more extensive fracturing takes place to relieve this greater energy.

Summary

While this study was not exhaustive of the area of impact fractures in glassy polymers, it does demonstrate that there are some significant differences between fractures in polymers and those encountered with glass. Those differences can be summarized as follows:

(1) the occurrence of pronounced, highly curved hackle marks, which could in many instances be mistaken for conchoidal marks;

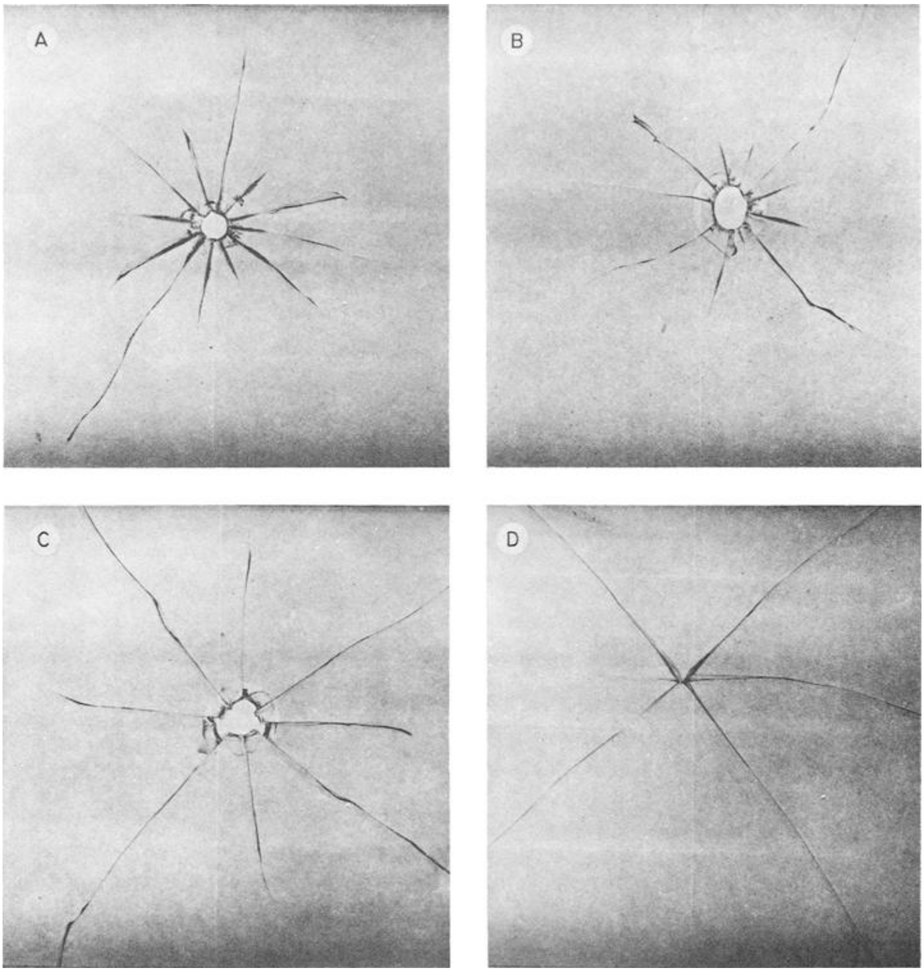

FIG. 5—*Relationship between projectile velocity and length of radial fractures:* (a) *.38 Special, full powder charge;* (b) *.38 Special, $^4/_5$ normal powder charge;* (c) *.38 Special, $^3/_5$ normal powder charge; and* (d) *.38 Special, $^2/_5$ normal powder charge.*

(2) the appearance of the beveled edges bordering the cratering on the side opposite origin of force; and

(3) a more apparent tendency toward an inverse relationship of muzzle velocity and energy to radial fracture length and degree of curving along crater boundaries.

The physical laws applicable to the fracture of glass are identical to those extant in the fracture of glassy polymers; no new forces are at play. All of the differences are capable of being explained in terms of the differences in flexibility and flow between glass and polymers, and the resulting differences in tension development and fracture propagation.

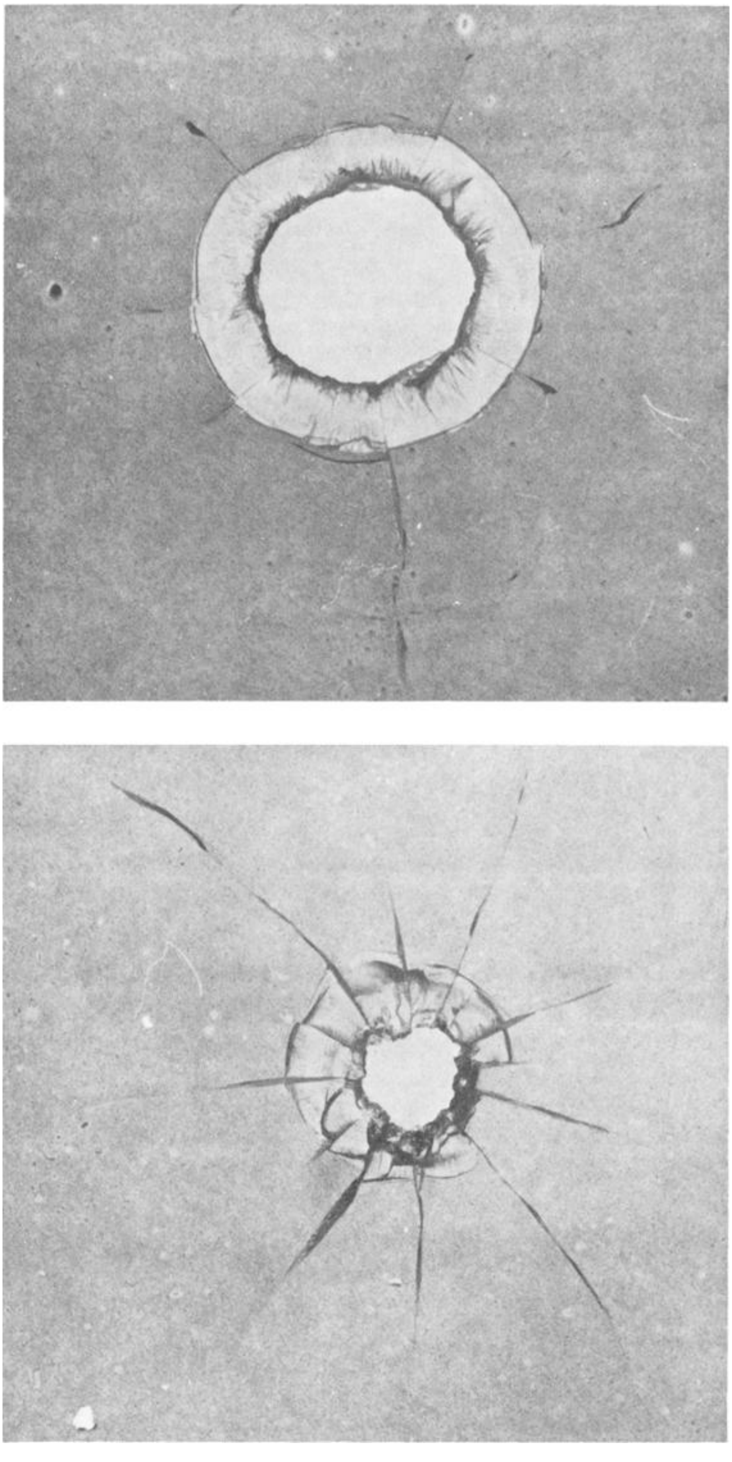

FIG. 6—*Relationship between projectile velocity and relative size of crater:* (left) *.44 Magnum and* (right) *.45 Colt Auto.*

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