Descriptive Fractography

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RACTOGRAPHY is the examination of 'aces created by fracture and the interpre- ɔn of the fracture markings seen on these 'aces. It can be qualitative (for example, direction of fracture propagation), or it be quantitative (for example, the stress at time of failure). This article will only deal ı qualitative (descriptive) fractography; ntitative fractography is treated in the arti- "Quantitative Fracture Surface Analysis" this Section of the Handbook. The for- ıion of fracture markings is explained and mples given. Representative fracture sur- ɛs of glasses, single crystals, and poly- stalline ceramics are shown. Fracture ɡins from a variety of causes are presented.

Γhe science of fractography of glasses and amics has developed to the point where re is a considerable body of literature on subject. It is beyond the scope of this arti- to provide an exhaustive bibliography, but 'eral references are given which cover var- ıs aspects of descriptive fractography in ail (Ref 1–8).

ses and Significance of ractography

Fractography can be used to do many things ating to the fracture process, including:

- Locating fracture origins
- Determining direction of crack propagation
- Learning the sequence of crack propagation
- Deducing the stress state at the time of fracture
- Observing interactions between crack fronts and inclusions, grains, and so forth

The power of the technique in providing tal information about fracture makes it use- l in understanding failure in production or service. Fractography should be an integral ırt of strength testing, which means it is ıportant in materials research and quality ɔntrol. In-service failures often raise the issue f product liability, and fractography can rovide factual information for comparison ith eyewitness accounts. In short, fractog- ɪphy, both descriptive and quantitative, is ssential in developing and producing glasses nd ceramics, and in using them in any sit- ation where stress-induced failure occurs.

Techniques of Fractography

The examination of fracture-exposed surfaces normally should be done using a sequence of observations starting at low magnification: unaided eye, hand lens, stereographic optical microscope, normal optical microscope, scanning electron microscope (SEM), transmission electron microscope (TEM). Not all of these steps will be necessary for every examination. Sometimes specialized techniques, such as replicating fracture surfaces or applying a reflecting coating, need to be employed.

Reconstructing a broken part by putting the pieces back together shows the overall crack pattern. This, in turn, usually reveals the location of the origin(s), and provides information on such things as the stress state at the time of failure and the sequence of crack development. When examining the origin, both fracture surfaces should be looked at, since the key visual clue, such as an inclusion, may be on only one of the surfaces. Also, post-fracture damage often happens right at the origin, causing part or all of the origin to be missing on one or both pieces. Looking at both will make this kind of post-fracture damage more obvious. Adjustment of the illumination when using an optical microscope is critical to seeing fracture markings. In the SEM, imaging techniques need to be matched to the specimen for best results, and stereographic pairs are extremely helpful in revealing the surface topography. Fractography should be well documented with notes, sketches, and photographs.

Fracture Markings

A fracture tends to propagate as a spreading front, much like a wave front, that is, as a line. Markings are formed when something happens to disturb the propagation of this front, for example, if the fracture stops, or if the local stress field changes direction. Typical markings on the fracture surfaces of glasses and ceramics are illustrated and explained in this Section.

Brittle materials, such as glasses and ceramics, fail in tension. Even in those situations where the applied stresses are not tensile, resolved tensile stresses act on discontinuities in the material (cracks, pores, and so forth). The absence of significant plastic deformation means that the only way for the material to relieve the stress concentration is through fracture. As a fracture moves through a glass or a ceramic, its propagation direction and velocity are affected by the stresses it encounters.

Central to understanding fracture markings and their interpretation in brittle materials is the so-called law of normal tension, which states that the fracture propagates normal to the direction of the local principal tension. In isotropic materials like glasses, the law of normal tension governs crack propagation. In single crystals and in polycrystalline materials at the microscopic level, strong cleavage tendencies will also play a role, particularly in the direction of propagation.

Mirror, Mist, and Velocity Hackle. Figure 1 shows a portion of the fracture surface of a glass rod broken in bending. The fracture origin is not seen in detail, but it is on the edge of the fracture surface, at the center of the smooth area. The fracture surface close to the origin is very smooth, and, when the illumination is just right, it will reflect light much like a mirror. Hence, this region is called the fracture mirror. A smooth surface like this indicates that the fracture was moving relatively slowly as a single spreading front. In fact, when glass is broken at low stress, for example, in many thermal failures, the entire fracture-exposed surfaces may be mirrorlike with no, or very few, markings.

In this example, typical of a strength test, the fracture was accelerating as it moved away from the origin. There is a considerable amount of stored elastic energy in the specimen at the time of failure, and much of this energy is used to create the fracture surface. However, when the velocity approaches the maximum for the material, the single crack front begins to break up on a microscopic scale. This is seen on the fracture surface as a roughening of the surface, giving it a misty appearance. This microscopic breaking up of the crack front allows an increased dissipation of the stored energy. This is often not sufficient, and the single crack branches (splits) into two cracks. The fracture at this point has reached its maximum velocity (about one-half

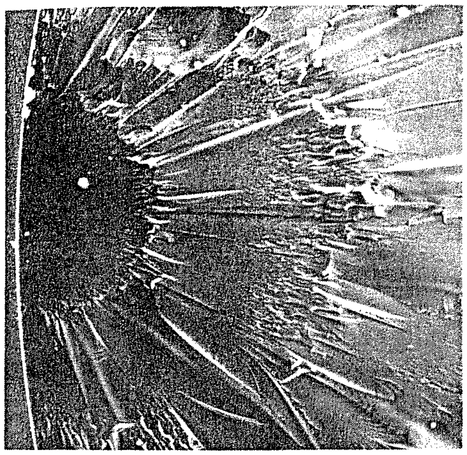


Fig 1 Fracture surface of a glass rod broken in bending. Fracture origin is at left; nearly semicircular region is the fracture mirror, bordered by mist and velocity hackle. Note the second region of mist and velocity hackle. SEM. 47×

to two-thirds the velocity of the transverse stress wave in the material). Branching is shown on the fracture surface by the presence of large, daggerlike marks called velocity hackle. In Fig 1, the mist and velocity hackle form the boundary of the fracture mirror. Velocity hackle is parallel to the direction of crack propagation.

Depending on the amount of stored elastic energy at the time of failure, the fracture may branch many times. This is the reason for the formation of the many fragments that occur in high-stress failures of glasses and ceramics. Multiple branching is shown in Fig 1, where the sequence of mist/velocity hackle occurs twice. The smooth region in between indicates the crack briefly slowed down before accelerating to the second branching.

The complexity of the fracture surface in the mist-hackle region is illustrated in Fig 2. From this photograph, it is seen that localized crack branching and secondary cracking on a microscopic scale causes the formation of many finger-shaped markings, creating small-scale surface roughness.

The shape of the fracture mirror is influenced strongly by the stress state at the time of failure, as illustrated by the example shown in Fig 3. This glass rod was strengthened by an ion-exchange treatment, which produces a thin layer of high compression at the surface. The fracture origin is a large surface flaw, part of which is seen as the crescent-shaped feature in the mirror. The fracture evidently started at both ends of this crescent, resulting in a double mirror with a narrow mist-hackle region between the two halves. The extended parts of the mirror at the surface are due to the acceleration of the crack being hindered by the surface compressive stresses. The size of the mirror is inversely proportional to the stress at failure. For more information on this relationship, see the article "Quantitative Fracture Surface Analysis" in this Section.

Wallner lines (named for the scientist who first explained their formation) are lines on the fracture surface which are caused by disturbances of the fracture front by sonic waves. As shown in Fig 4, Wallner lines resemble waves on the surface of a still pond when a stone is dropped in. The blow which broke the glass in Fig 4 also created strong sonic waves which intersected the advancing crack front, causing momentary deviations in the direction of the local principal tension. The crack front follows these deviations, tilting out of its original plane momentarily, creating the wavy lines seen on this surface. It is important to note that Wallner lines do *not* give the shape of the fracture front, unless the sonic wave encounters the entire front at the same time, for example, when the fracture was moving slowly. However, the fracture origin is always on the *concave* side of Wallner lines, and this fact can be used to determine the direction of propagation and the location of the origin.

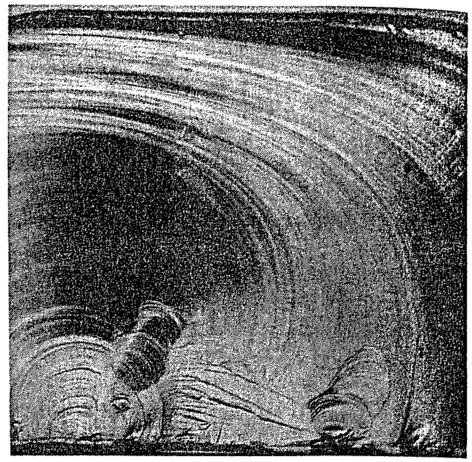


Fig 4 Fracture surface of a piece of glass broken by striking it with a hammer. Origin is at the lower left; the wave-like lines are Wallner lines. Optical microscope. 74×. Source: Ref 1

Twist Hackle. Another form of hackle occurs when the stress field ahead of a propagating crack twists, that is, undergoes rotation about an axis normal to the crack front (parallel to the propagation direction). Obeying the law of normal tension, the fracture tries to follow this change by a corresponding twist; however, it is energetically very unfavorable for the entire crack front to twist as a single plane. Instead, the single crack front breaks up into a series of parallel, but noncoplanar, fronts which do line up with the new axis of local principal tension. A good analogy is a venetian blind, in which the slats are parallel, but not coplanar. Initially, these individual fracture segments are disconnected; but this cannot remain so for very long, and the material between the segments breaks through, forming the hackle.

On the fracture surface, twist hackle appears as very narrow, sharp daggers, such as seen in Fig 5. Twist hackle, like velocity hackle, is aligned parallel to the propagation direction. The example shown in Fig 5 is a portion of the fracture surface of a plate of glass broken in bending. The top edge of the photograph is at the surface that was in compression during the bending. The overall direction of propagation was from left to right, as can be seen from the curvature of the Wallner lines, but near the top of the picture the fracture was moving toward the top, nearly at a right angle to the compression surface. This appearance of twist hackle near the compression surface of a plate broken in bending is a characteristic feature for this kind of failure.

An examination of the other photographs in this article will reveal that twist hackle is a common occurrence on fracture surfaces of brittle materials. For example, twist hackle can be seen on the surface of the large hackle that runs diagonally through the region shown

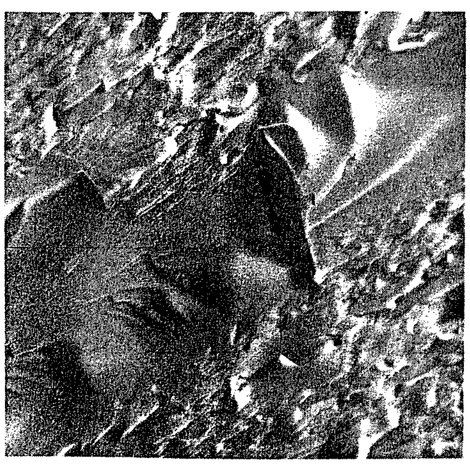


Fig 2 High-magnification view of mist hackle on a glass fracture surface. Fracture direction is from lower left to upper right. Twist hackle (compare with Fig 5) is present at several places on the large hackle that runs diagonally through the picture. SEM. 670×

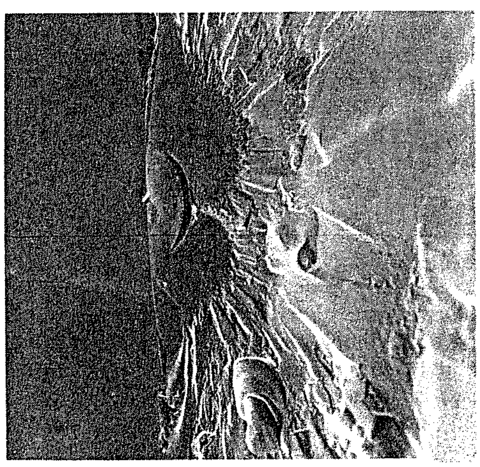
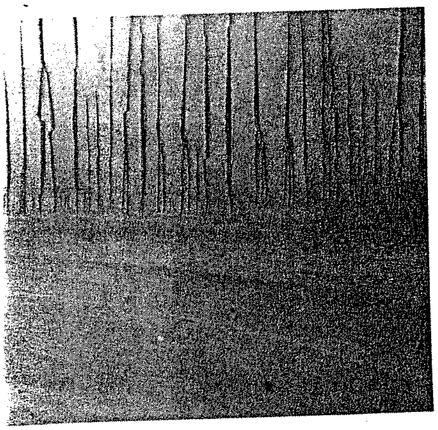


Fig 3 Double fracture mirror on the fracture surface of an ion-exchange-strengthened glass rod broken in bending. Specimen was tilted to show both the original surface (gray area at the left) and the fracture surface. Fracture started at the tips of the crescent-shaped flaw. SEM. 67×



g 5 Fracture surface of a glass plate broken in bending. Top of the picture is the compres-side. Overall direction of propagation was from left ight, but nearly bottom to top in the region shown . Twist hackle is seen at the top, and Wallner lines also present. Optical microscope. 50×. Source: 9

Fig 2. Twist hackle is *not* associated with particular velocity or range of velocities. fact, twist hackle can form at very low locities (for example, less than 1 m/s, or 3 ft/s).

Gull Wings and Wake Hackle. This set fracture markings is actually a combina-n of two other markings—Wallner lines and ist hackle. The appearance of gull wings d wake hackle is shown in Fig 6. Part of e fracture surface of a glass capillary is own; the dark circle is the hole of the cap-lary, and the fracture was moving from top bottom, as can be seen from the intersect-g Wallner lines. The mark at the bottom of e hole is twist hackle (called here wake ackle), and the two strong Wallner lines nning away from the wake hackle are the ull wings. These markings are associated with clusions in materials—pores, bubbles, solid articles—and are useful in determining the direction of propagation. As seen here, the gull wings and wake hackle are on the side of the inclusion that is farthest away from the fracture origin. The wake hackle (sometimes called a "tail"), therefore, points back toward the origin.

Gull wings and wake hackle form when the fracture front encounters an inclusion. Even in the case of a pore or bubble, the front must move around the inclusion; that is, it does not simply pass through as though nothing was there. Instead, the front moves around the inclusion, effectively splitting into two fronts. When these two fronts meet on the opposite side of the inclusion, they nearly always are no longer travelling in *exactly* the same plane. Therefore, they overlap slightly, and the material separating them breaks through. This is the same mechanism that was described above for the formation of twist hackle. The sudden breaking of the material between the two fronts generates a sonic pulse which interacts with the moving fracture, creating the gull wings.

Intragranular porosity is often seen in polycrystalline ceramics. When the fracture is also intragranular, gull wings and wake hackle are generated at many of these pores. This can be the primary way in which the direction of fracture propagation is determined, thus aiding in locating and identifying the origin of failure.

An arrest line (sometimes called a rib mark) is a sharp line produced on the fracture surface when the crack stopped and subsequently restarted. Such a line can also be produced when the crack abruptly changes its plane of travel (as opposed to the wavelike, momentary change in plane associated with Wallner lines). For example, the edge of the crescent-shaped flaw in Fig 3 is an arrest line, because it marks the extent of the flaw before the load was applied which led to failure. Subsequent growth (that is, the main fracture) took place in another plane, leaving a sharp demarcation between the initial flaw and the fracture-exposed surface.

Arrest lines *always* give the shape of the fracture front, since they mark the position of the front at the time of an arrest or abrupt change in plane of travel. Recall that Wallner lines give the shape of the front only in certain circumstances. The origin will be on the concave side of arrest lines; thus, they are useful in determining fracture direction and in locating origins. They also define the boundary between a fracture-initiating flaw and the fracture surface, allowing the flaw to be identified and examined.

Scarps. In many glasses and ceramics, crack propagation at low velocities is affected by the environment, in particular by water or water vapor. If a slowly moving crack is running wet (that is, the entire crack front is exposed to water or water vapor), no unusual markings are generated. However, if part of the moving crack front is exposed to water and part is not, lines called scarps are generated at the intersections between the wet and dry parts of the front. The scarps that have been identified to date are discussed in detail (Ref 1). Two of these will be presented here.

A deceleration scarp (Fig 7) is formed when a crack front which has been running dry slows down enough to allow liquid water on the free surface(s) to be drawn in by capillary action. This exerts viscous drag on the edge of the crack front in contact with the water. Therefore, this part of the front is retarded with respect to the central part, which is still dry. As deceleration of the crack continues, the water reaches more and more of the front until the entire front is moving in contact with water. During this process, a line is generated on the fracture surface which represents the location on the crack front between the wet and dry parts. In Fig 7, the free surface which was wet is at the top of the picture. The nearly vertical lines are Wallner lines generated by pulses from a sonic generator. In this case, the Wallner lines *do* give the shape of the crack front. The deceleration scarp is the line running approximately horizontally across the picture. From the shape of the Wallner lines, it is clear that the outside (wet) part of the crack was lagging behind the inside (dry) part.

Sierra Scarp. A most interesting scarp (shown in Fig 8) is formed when, in the absence of water on the free surfaces, a wet-running crack accelerates, cavitates (that is, jumps abruptly in velocity, thereby leaving the water behind), decelerates, and then is overtaken by the water coming behind it. The water does not catch up to all parts of the dry crack front at the same time; instead, fingers of water touch parts of the front. At each of these positions, the water assists crack propagation, causing these parts of the front to bow out ahead of the dry portions. These bowed-out parts expand as more water catches up, until the entire crack front is again run-

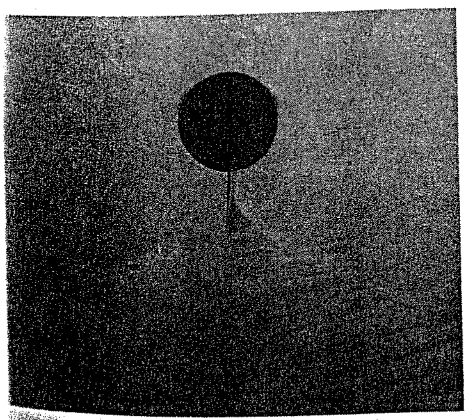


Fig 6 Fracture surface of a glass capillary broken in bending. Fracture propagated from top to bottom; gull wings and wake hackle formed when the front moved around the hole of the capillary (the black circle in the picture). Optical microscope. 50×. Source: Ref 9

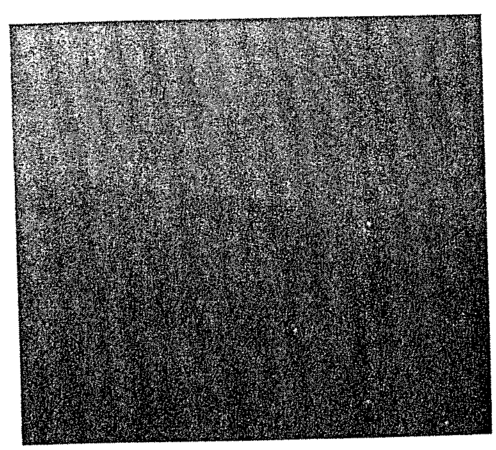


Fig 7 Deceleration scarp and timing marks on the fracture surface of a glass plate. Fracture propagated from left to right. Edge of the fracture surface corresponds to the top of the picture. Optical microscope. 45×. Source: Ref 10

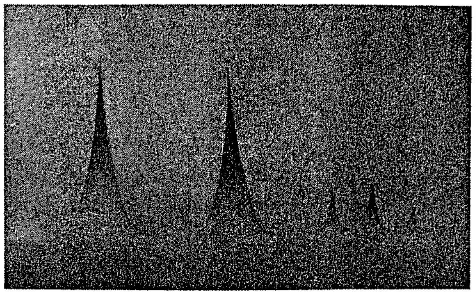


Fig 8 Sierra scarp on the fracture surface of a glass plate. Direction of fracture was from bottom to top. Optical microscope. 59×. Source: Ref 11

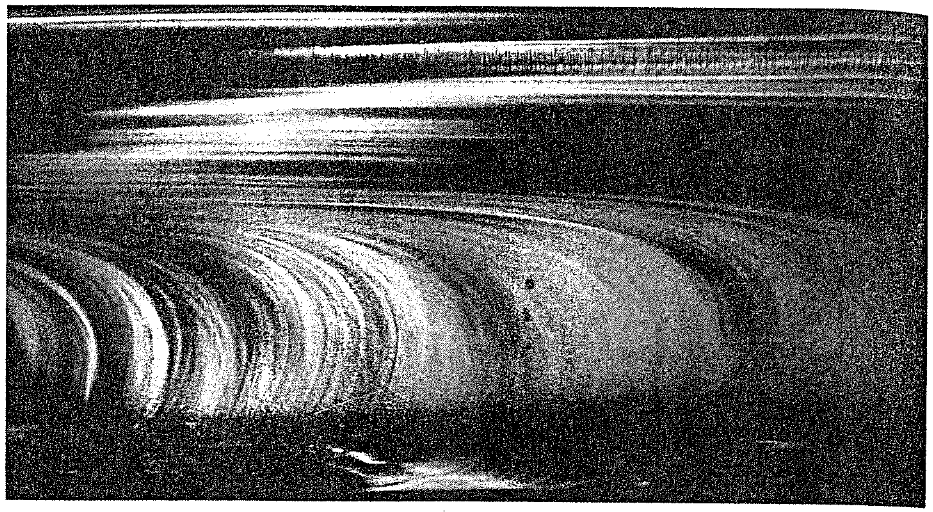


Fig 9 Wallner lines, mist hackle, and twist hackle on the fracture surface of a glass plate broken in bending. Fracture propagated from left to right; tensile surface at the bottom. Optical microscope. 35×. Source: Ref 1

ning wet. Again, the scarp, designated the Sierra scarp, is the locus of the boundary between the wet and dry parts of the front. Because this is happening at multiple locations, the scarps move toward each other, creating the line with multiple peaks seen in Fig 8. The name Sierra scarp was chosen because of this resemblance to a range of mountain peaks. In order for the Sierra scarp to form, a wet-running crack has to be subjected to a stress rise and decay. This may seem to be an unusual situation, but it occurs when there is fracture in a wet thermal downshock, as happens when a hot, wet drinking glass is touched by a cold metal utensil (knife, fork, and so forth).

Fracture Surfaces in Various Glass and Ceramic Materials

Glass. Fracture surfaces of glass have been shown in Fig 1 through 8. Glass is an ideal material for showing fracture markings, since it is homogeneous, isotropic, and has no microstructure to interfere with a spreading crack front. Crack propagation is governed solely by the stress state at the time of failure, whereby both applied and residual stresses (such as those induced by thermal or ion-exchange strengthening) play a role. Therefore, fracture markings can be seen easily and can be interpreted readily with respect to their implications regarding the stress state. Also, fracture surfaces will be smooth (mirrorlike) when generated by slowly moving cracks (for example, Fig 8), but will be rough and more complex when created by rapidly moving cracks (for example, Fig 1).

Two more examples of glass fracture surfaces will be presented here. The first, shown in Fig 9, is a fracture surface of a glass plate. An examination of the fracture markings reveals the stress state at the time of failure. The Wallner lines clearly indicate the crack was moving from left to right. The dark region at the bottom of the photograph is mist hackle; the short, straight lines near the top are twist hackle. Keep in mind that Wallner lines usually do not give the shape of the crack front when it is moving at high velocity. Putting this information together, it can be deduced that the crack was moving at or near terminal velocity along the bottom edge and that the crack front was leading along this edge. On the other hand, the velocity of fracture was much lower toward the top, and the direction of propagation was nearly normal to the top edge. Therefore, there must have been a stress gradient in the plate during failure, with high tensile stresses along the bottom edge. In other words, the appearance of the fracture surface (the fracture markings) leads to the conclusion that the specimen failed in bending, which was, in fact, the case.

The second example, shown in Fig 10, presents a very different picture. The sharp lines on the fracture surface are arrest lines produced by slightly changing the direction of the applied tension at regular time intervals. The crack was moving at much less than 1 m/s (3.3 ft/s), so these changes in the direction of applied tension produced slight, but sharp, changes in the plane of fracture. These deliberately induced arrest lines are called timing marks, since the velocity of propagation can be determined by measuring the distance between the arrest lines and dividing this by the time between the changes to the axis of applied stress. However, the purpose in showing this fracture surface here is to draw conclusions regarding the stress state at the time of failure from the information provided by the fracture markings. Since arrest lines show the shape of the fracture front, it is clear in this example that the crack was moving at a nearly uniform velocity along the length of the front shown. Only about one-half of the width of the fracture surface is seen in Fig 10. The slight lagging at the top is expected owing to the effect of the free surface. Therefore, the stress state at the time of failure must have been uniaxial tension. In fact, this was a double-cantilever specimen, and the stress at the crack tip is essentially uniform tension.

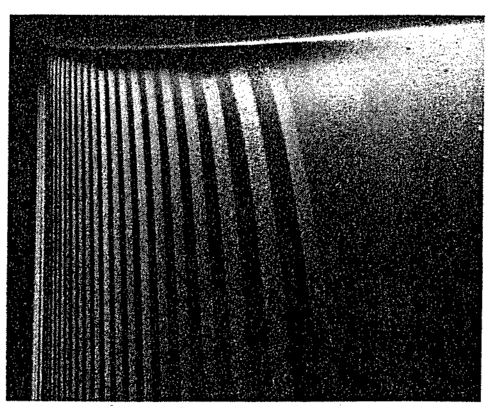


Fig 10 Arrest lines ("timing marks") on the surface of a glass plate broken in nearly uniform tension. Crack propagated from left to right. Only about one-half of the entire width of the fracture surface is shown in this photograph. Optical microscope. 75×. Courtesy of G. Caso, New York State College of Ceramics, Alfred University

Single Crystals. When single crystals are broken, crack propagation is influenced by cleavage tendencies as well as by the stress state. Therefore, the appearance of fracture surfaces can be very different when cracks are moving in different crystallographic planes. Each material has to be investigated for its particular fracture behavior.

Rice points out some general observations about fracture in single crystals (Ref 4, 5). When the fracture occurs on primary cleavage planes, mist and velocity hackle occur usually without the crack branching mentioned above for glasses, or the branching occurs much farther away from the origin than would be expected in glasses. On the other hand, fractures which start on secondary cleavage planes usually branch without first exhibiting mist and velocity hackle. For cracks

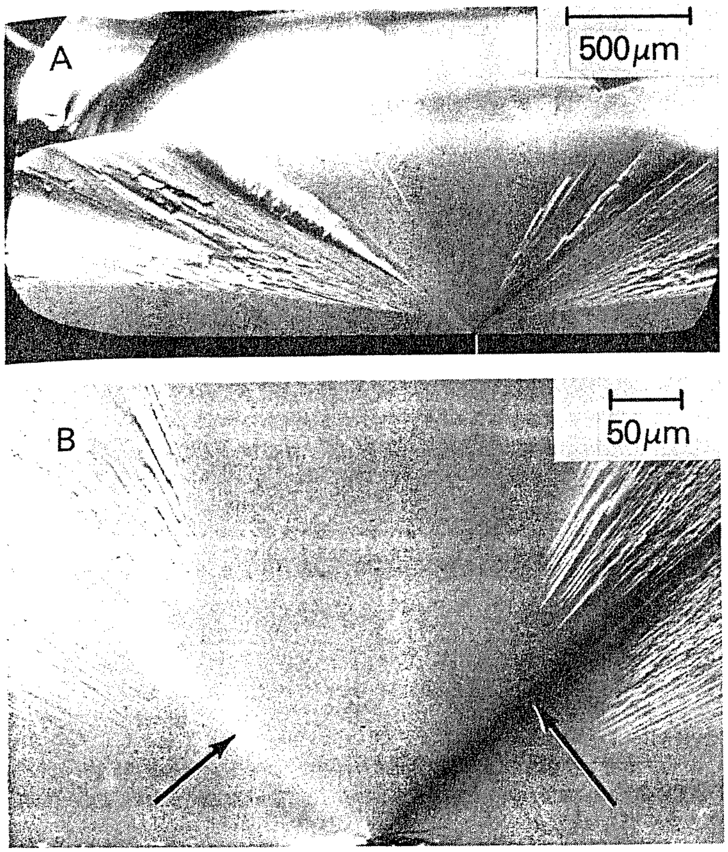


Fig 11 Views at lower and higher magnification of the fracture surface on a $MgAl_2O_4$ single crystal showing the mirror region with whisker-lance mist hackle (onset indicated by arrows); {100} tensile surface and ⟨100⟩ tensile axis. Source: Ref 5

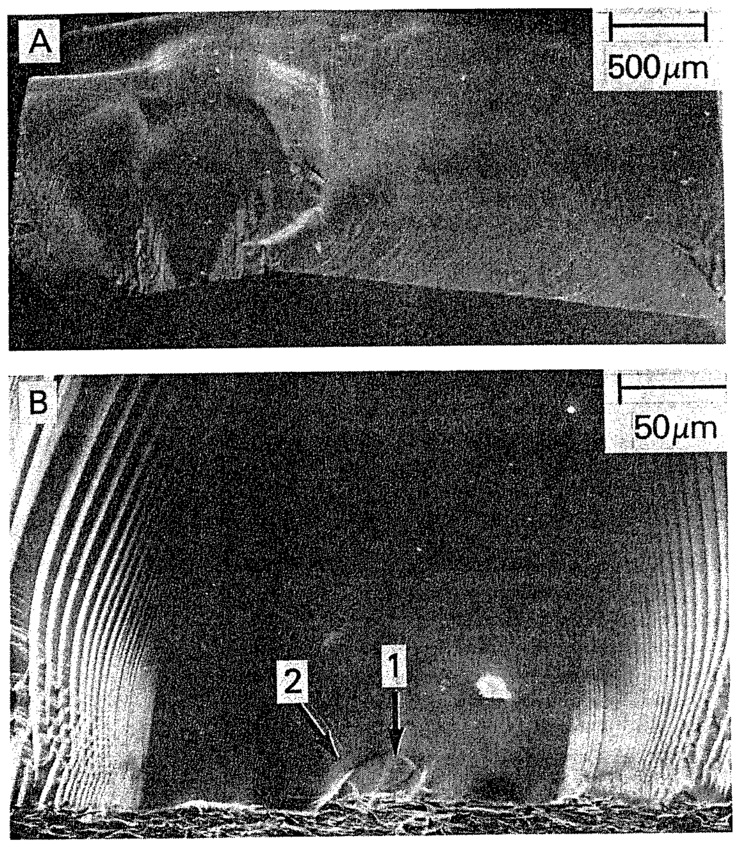


Fig 12 Arc-rib mist hackle on the fracture surface of a single crystal of $MgAl_2O_4$; {100} tensile surface and ⟨100⟩ tensile axis. Numbers indicate the approximate extent of the fracture origin. Source: Ref 5

propagating on primary cleavage planes, mist occurs as radial ridges radiating away from the origin. These grow in density and size, with no clear distinction between mist and velocity hackle. Rice calls these markings whisker-lance mist hackle. Figure 11 shows fracture surfaces of single-crystal $MgAl_2O_4$ which exhibit this kind of hackle. Note that these markings occur only in certain directions, and, according to Rice, apparently only form when crack branching is energetically unfavorable, that is, when the fracture is on a primary cleavage plane.

When the fracture starts on a secondary cleavage plane, on the other hand, another type of hackle is formed—cathedral or arc-rib mist hackle, as shown in Fig 12. These marks increase in amplitude with increasing distance from the origin, until branching occurs. Arc-rib mist hackle also occurs only over certain portions of the fracture surface, that is, there are crystallographic limitations to the formation of these marks in certain directions.

The fracture surface of another crystal of $MgAl_2O_4$, shown in Fig 13, illustrates the influence of crystallographic orientation on fracture propagation. In this case, the tensile surface is a plane in the {110} system, and the tensile axis is ⟨100⟩. The arc-rib system is very complex in the mirror region, and there are intersecting segments of whisker-lance mist hackle.

Figure 14 shows a broken single crystal of CaF_2 which has an internal origin (the crack curving to the left). This specimen was broken in bending, and this is one reason for the asymmetry of the mirror surrounding the origin. In particular, notice the absence of mist and hackle above the origin, that is, on the neutral-axis side. Also, the onset of the whisker-lance mist hackle is variable.

Space limitations prevent a more complete survey of fracture surfaces of single crystals. The reader is referred to the literature, particularly Ref 4 and 5 for more examples and more detailed information, including the effect of temperature.

Polycrystalline ceramics at the macroscopic level are isotropic; therefore, the stress state at the time of fracture governs the overall fracture patterns that develop in these materials. However, polycrystalline ceramics often present special challenges in fractography, because the microstructure strongly affects crack propagation at the microscopic level, causing perturbations all along the moving crack front. Fracture markings easily seen on glass fracture surfaces may be difficult or impossible to see on fracture surfaces of polycrystalline ceramics. In general, the problem is worse in coarse-grained ceramics. Markings in individual grains may be easier to see in larger grains, but the overall fracture surface is usually rougher, obscuring longer-range markings (that is, those that extend over many grains, such as Wallner lines, arrest lines, and velocity hackle).

On the other hand, fine-grained ceramics may have fracture surfaces that closely resemble those of glasses, as seen in the example shown in Fig 15. Mist, velocity hackle, and Wallner lines are clearly seen on this fracture surface of a piece of electrical porcelain. The shape of the Wallner lines and the fact that the mist and velocity hackle appear only along one edge indicate a stress gradient when failure occurred. It might be concluded that the piece failed in bending, as in Fig 9. However, this piece was a hollow cylinder which broke spontaneously while being cut with a diamond saw. Therefore, the stress gradient was present as a result of processing. In fact, the insulator was cooled too rapidly, resulting in compressive stress on the outside surface (at the top in Fig 15) and tensile stress on the inside surface (at the bottom in Fig 15).

The polycrystalline Al_2O_3 fracture surface in Fig 16 illustrates the point made above about

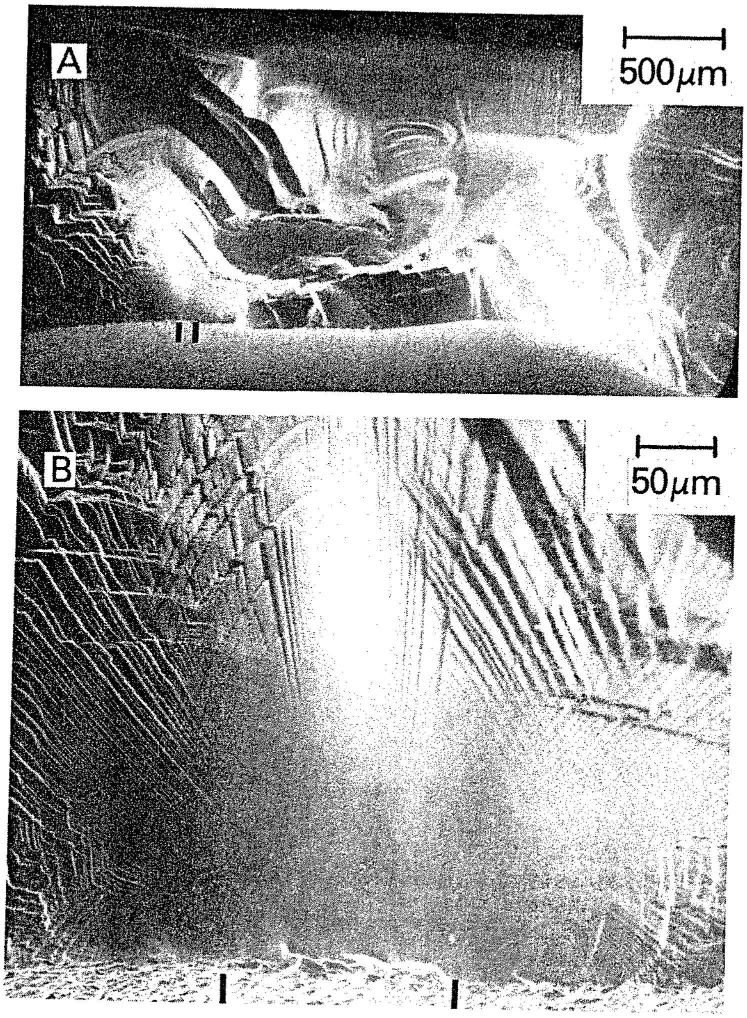


Fig 13 Complex arc-rib mirror and fracture surface of a single crystal of $MgAl_2O_4$. Note the intersecting segments of whisker-lance mist hackle; {110} tensile surface and ⟨100⟩ tensile axis. Source: Ref 5

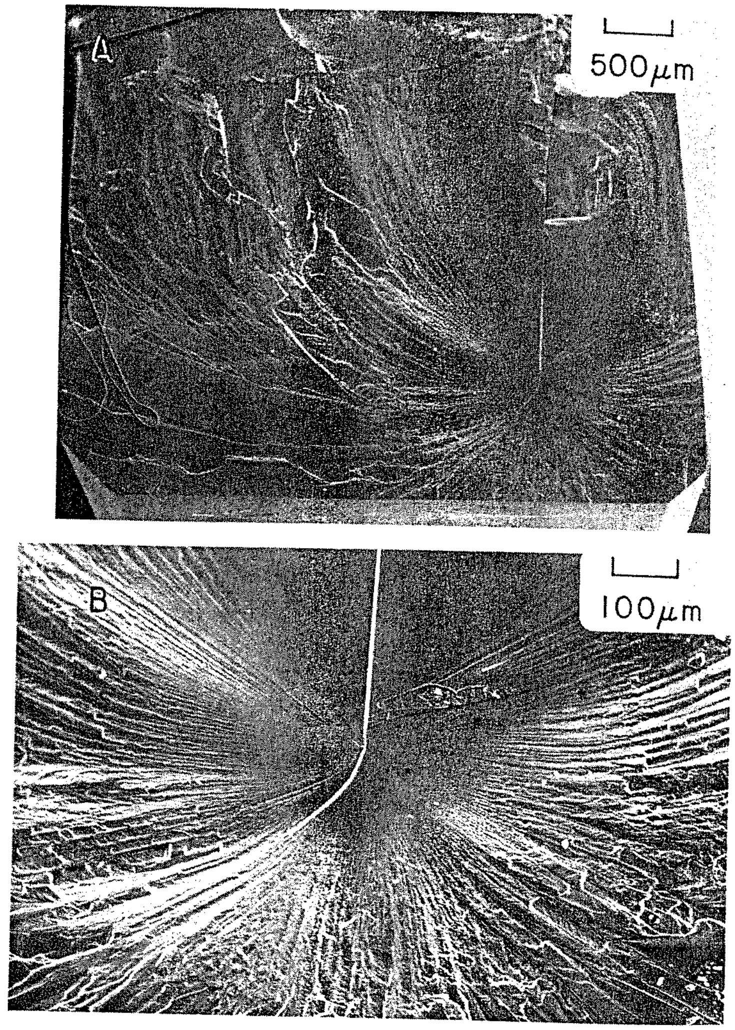


Fig 14 Internal origin in a bend specimen of single-crystal CaF_2. Origin is a crack, seen curving to the left; tensile surface was at the bottom. Source: Ref 5

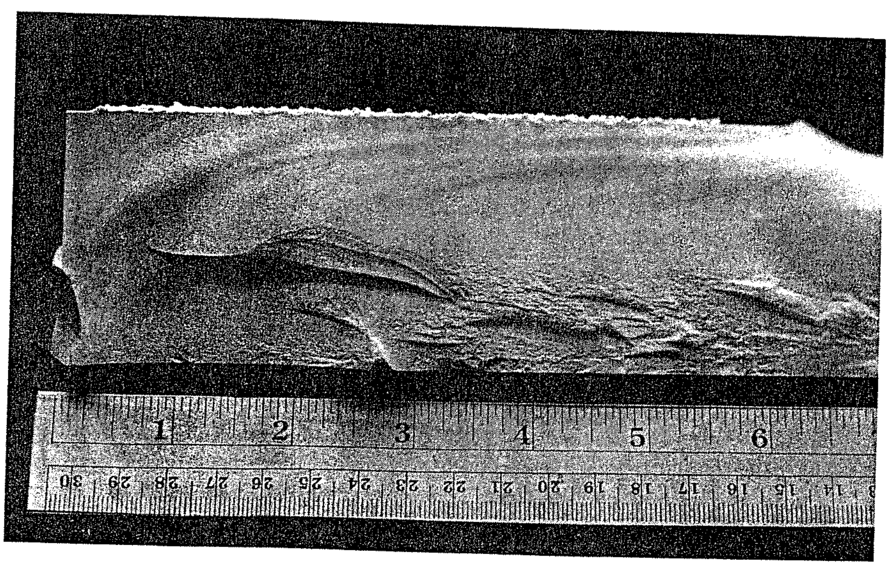
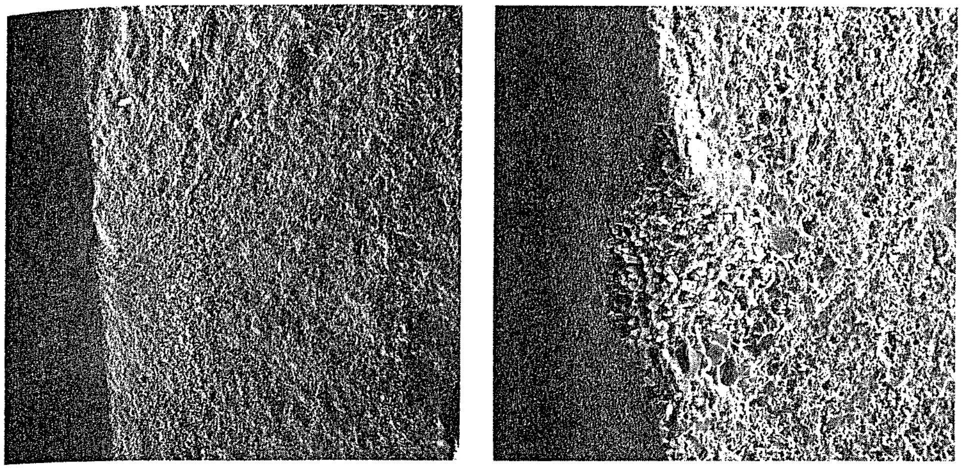


Fig 15 Fracture surface of a porcelain insulator which broke during cutting with a diamond saw. Fracture moved from right to left. Mist and velocity hackle and Wallner lines are readily seen in this fine-grained material. Optical microscope. Source: Ref 1

ceramics, even when the material has a small average grain size. In this photograph, and in several others to follow, the specimen was tilted in the SEM, allowing both the original surface and the fracture surface to be seen. The gray region at the left in Fig 16(a) and (b) is the original surface. In Fig 16(a) the origin is on the left, about halfway up from the bottom of the picture. The fracture surface close to the origin is relatively smooth compared to the region farther away. This is the fracture mirror, but it is difficult to define its extent with any accuracy. Outside of the mirror, there are ridges which run radially away from the origin, and these are presumably a form of velocity hackle. However, these ridges are also difficult to see.

A point can be made here regarding the level of magnification one should use in examining fracture surfaces of polycrystalline ceramics. Velocity-hackle ridges and the mirror region are often seen most readily using the unaided eye or a hand lens. This may be the quickest way to locate the fracture origin. Sometimes, however, it is virtually impossible to "read" the fracture surface well



(a) (b)

Fig 16 Fracture surface of fine-grained Al_2O_3 shown at low and high magnifications. Specimen was tilted in the SEM allowing original surface (gray area at left) and fracture surface to be seen simultaneously. SEM. (a) 100×. (b) 500×

the difficulty of seeing fracture markings in enough. In such cases, it may then be necessary to resort to very high magnifications using the SEM to try to see fracture markings in individual grains (gull wings and wake hackle, in particular, at internal pores) in order to trace the way back to the origin. Of course, this is painstaking and time-consuming work.

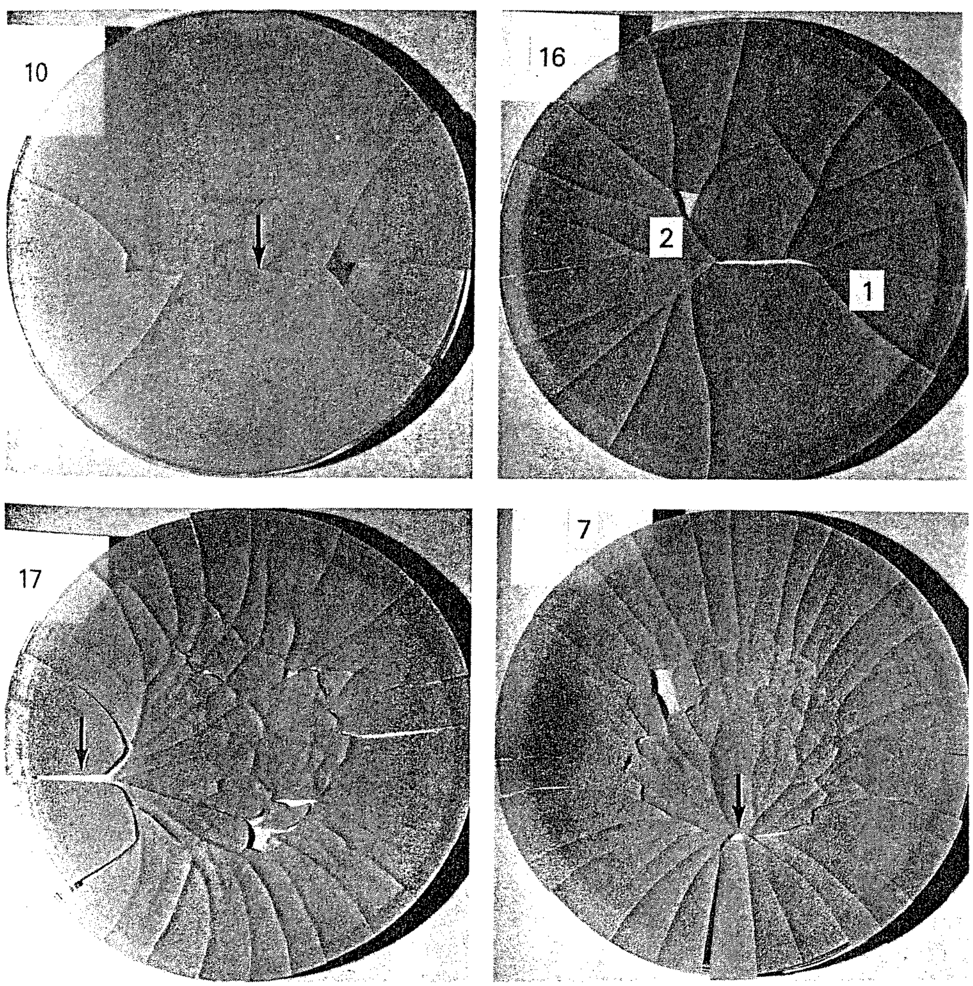


Fig 17 Crack patterns of four specimens of MgF_2 broken in biaxial flexure. The more extensive branching is associated with higher stress at failure. Arrows indicate locations of fracture origins. Disks are ≈50 mm (2 in.) in diameter. Source: Ref 5

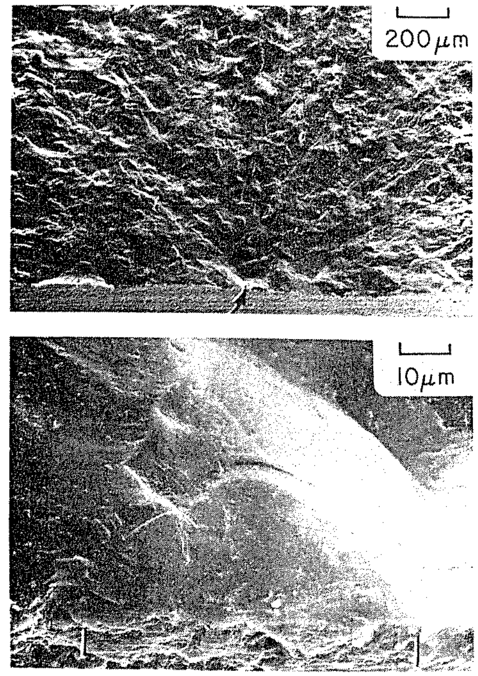


Fig 18 Two views at different magnifications of the fracture surface of large-grained B_4C. Source: Ref 5

Another way to locate the fracture origin, especially in strength tests, is to make use of the overall crack pattern. This can be facilitated in bend tests by applying tape to the compression side of the specimen before breaking it. The tape holds the pieces together without influencing the strength results. For example, Fig 17 shows four disks of MgF_2, broken in biaxial flexure, which failed at different stresses. The branching pattern is used to determine where the origin is located. Also, the branching is more extensive when the failure stress is greater.

Figure 18 shows the fracture surface of a specimen of large-grained B_4C. As in Fig 16, the mirror region is difficult to see, and velocity hackle shows up as ridges radiating away from the origin. Again, low magnification is more useful in observing these markings.

Fracture Origins

The key to understanding strength and failure of test specimens and manufactured parts is identifying the cause of fracture, that is, the fracture origin. Cracks, pores, bubbles, inclusions, grain boundaries—all of these discontinuities serve as stress concentrators in glasses and/or ceramics and can, therefore, be fracture origins. This section will present examples of fracture origins grouped together according to their mechanism of formation—indentation or impact, machining, processing. More examples can be found in the references listed earlier and in Ref 12 to 13.

Fig 19 Indentation and associated cracks on a glass surface made by a Vickers diamond with a load of 2000 g. Bright areas are reflections from the surfaces of sub-surface cracks. Optical microscope. 500×. Courtesy of G. Klassen, New York State College of Ceramics, Alfred University

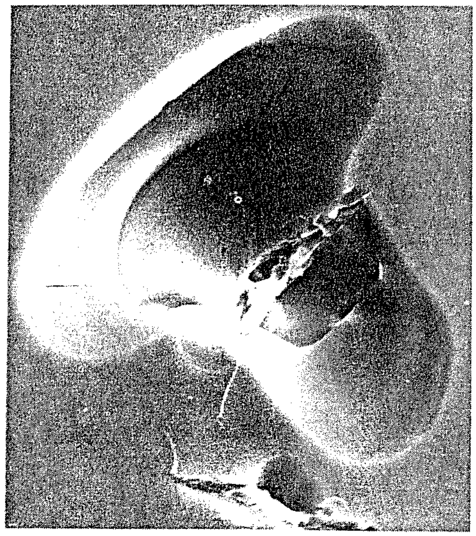


Fig 21 Impact site on a glass surface made by a 100-μm particle of SiC. SEM. 450×. Source: Ref 14

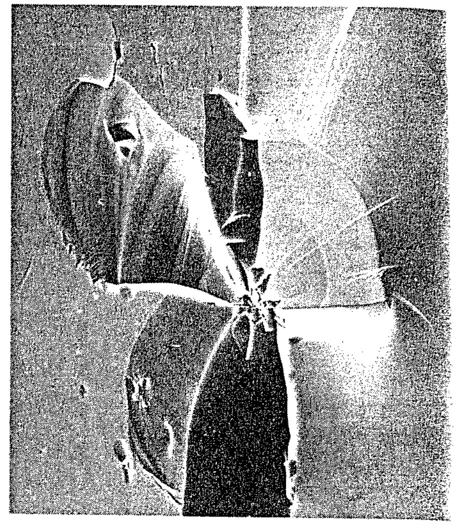


Fig 23 Impact fracture origin in glass caused impact damage from a 100 μm SiC p ticle. Specimen was tilted in the SEM. Original surfc is at left, fracture surface at right. SEM. 190×

Indentation and Impact Sites. Surfaces of brittle materials are particularly susceptible to contact damage caused by hard objects, either during indentation or impact (or machining, covered below). Figure 19 shows an indentation site caused by pressing a Vickers diamond onto the surface of a piece of glass. The cracks running from the corners of the indentation and the one coming off of one side are normal to the surface and extend some distance into the glass. These are the cracks that will become fracture origins when stress is applied to the piece. There are other cracks on the surfaces of the indentation, and the bright areas outside of the indentation are reflections from sub-surface lateral cracks that have not made it up to the surface. When they do, they cause material removal. The semicircular region shown in Fig 20 is a so-called half-penny crack that was generated from a similar indentation site by heating the glass and then thermally shocking it at the site with a copper block. The original indentation crack is seen on the edge of the fracture surface at the center of the half-penny crack.

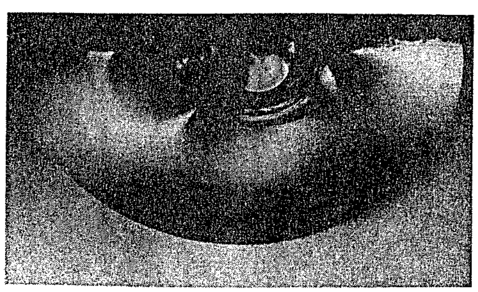


Fig 20 Half-penny fracture origin in glass. Crack at Vickers indentation site was extended using a thermal-shock technique to produce the large half-penny flaw. Optical microscope. 110×. Courtesy of V.D. Fréchette, New York State College of Ceramics, Alfred University

Similar damage is produced when sharp particles impact glass or ceramic surfaces, as illustrated by the example in Fig 21. The lateral cracks reached the surface, causing material to spall off. Complex cracking and loss of material occurred at the center of the impact. Sub-surface cracking is not visible in this SEM photograph. However, Fig 22 shows a similar impact site after the specimen was broken in a strength test. As described earlier, the specimen was tilted in the SEM, allowing the original surface (at the left) and the fracture surface (at the right) to be seen simultaneously. The relationship between the impact site and the fracture origin is clear. The size of the origin flaw, as measured along the surface, is about the same as the size of the spalled-off region. This is typical, but there are many cases where the spalled-off region is much larger than the origin flaw, and vice versa. Note the twist hackle along part of the origin flaw.

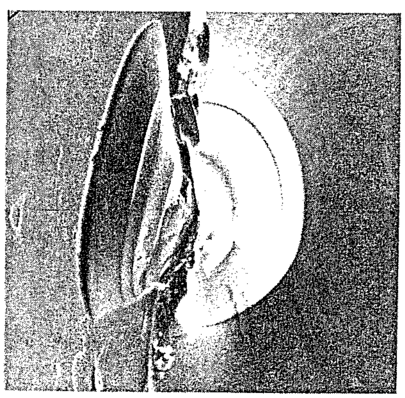


Fig 22 Impact fracture origin in glass caused by impact damage from a 100 μm SiC particle. Specimen was tilted in the SEM to reveal original surface (left) and fracture surface (right). SEM

Another impact origin is shown in Fig to make the point that impact origins oft have a more complicated morphology th indentation origins. Here, the origin looks li a truncated half-penny. In fact, the origin cra is intersected by a second crack (the narro bright feature at the impact site), and the or gin flaw itself continues behind the fractu surface seen in the photograph. Nonetheles this other crack influenced how the fractu started, that is, it affected the strength.

Blunt objects, such as spheres, also ca produce contact damage, as shown in Fig 2 The elliptical lines on the left side of the pho tograph are contact cracks on the original su face of the specimen. (They are actuall circular, but appear elliptical in this pictur because of the tilting of the specimen in th SEM.) These contact cracks run normal to th

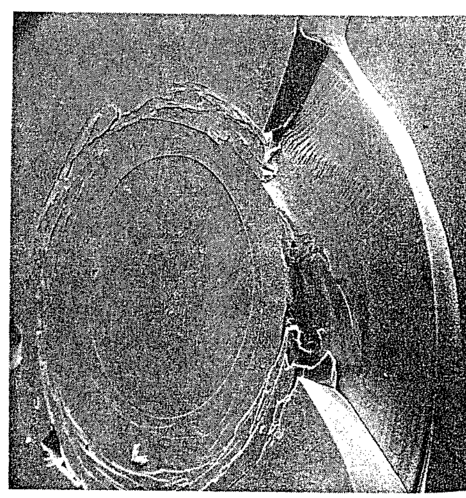


Fig 24 Hertzian impact site in glass. Specimen was tilted in the SEM to reveal original surface (left) and fracture surface (right). SEM. 145×

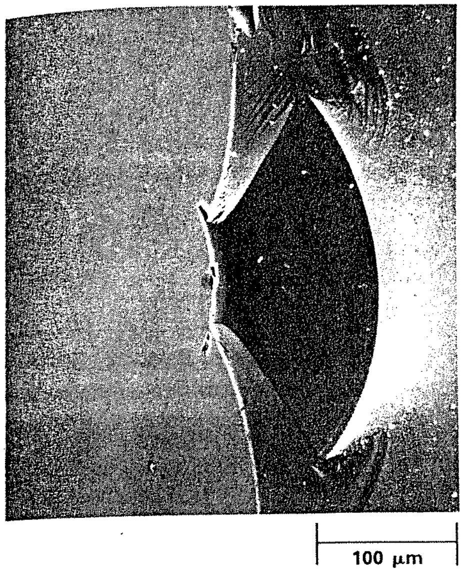


Fig 25 Hertzian fracture origin in glass. Original surface is at left, fracture surface at right. Main fracture started from base of Hertzian cone. SEM

surface for a short distance before flaring out into cone-shaped cracks (so-called Hertzian cones, named in honor of Hertz, the scientist who described the stress field associated with blunt-object contact). This is what happens when a "BB" hits a window, for example. Portions of two of these cones are seen in Fig 24. Notice the twist hackle and Wallner lines on the surface of the cone flaring out from the larger surface crack. Figure 25 presents a clearer picture of a Hertzian cone as a fracture origin. A single contact crack can be seen on the original surface, flaring out into the sub-surface cone. The twist hackle seen at two locations make it evident that the main fracture started from the base of the cone. This is not always the case, however, as shown in Fig 26. The cone in Fig 26 has been cut by the main fracture, which evidently (and surprisingly) started at the surface and not from the base of the cone. This is shown by the mist and velocity hackle at the lower left of the picture, which indicate the fracture was moving from upper right to lower left and had reached terminal velocity.

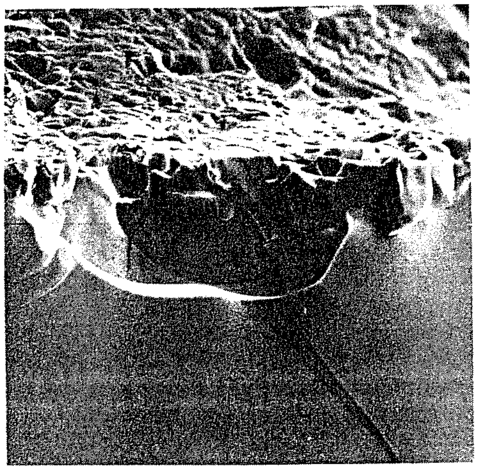


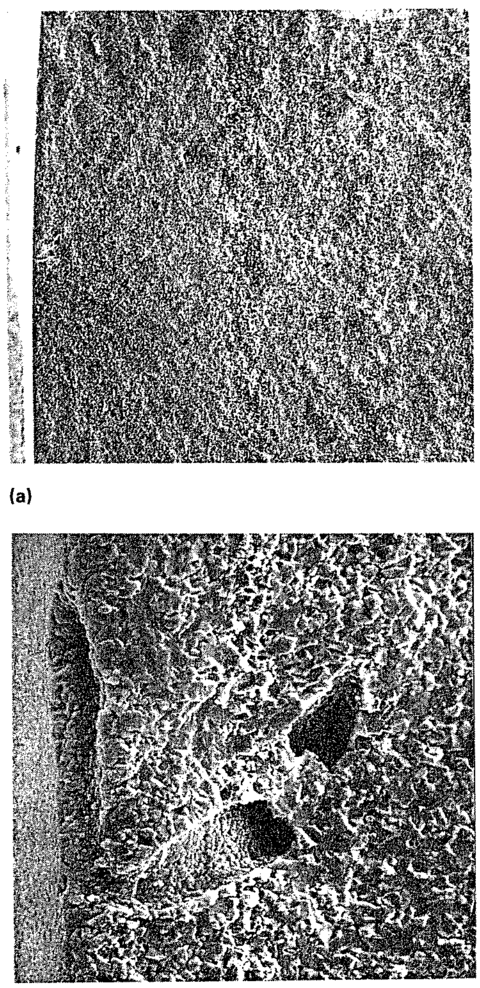
Fig 27 Machining flaw as fracture origin in glass. Rough surface is the bottom of a groove cut by a diamond saw. SEM. 200×

Machining Flaws. When glasses and ceramics are machined or when they are cut using a diamond saw, extensive sub-surface damage is produced. The crack systems are similar to those seen at indentation or impact sites, but are still more complex, since many particles are involved instead of just one. Two examples of machining flaws are presented here. More examples can be found in Ref 4, 5, 8, and 12 to 13.

The first is a machining flaw in glass produced when a diamond saw was used to cut a groove in the glass (Fig 27). It appears that a series of sub-surface cracks linked up to produce the large flaw that caused failure of this piece when external loading was applied. The second shows a machining flaw in hot-pressed Si_3N_4 that resulted from diamond grinding of the surface (Fig 28). Machining grooves on the original surface are evident in the upper part of the picture. Notice that this flaw is very long compared to its depth, and that it is aligned with the machining grooves. Both are features commonly observed when machining flaws are the origins of fracture.

Processing Defects. As used here, processing defects include all discontinuities in a material that can serve as fracture origins and which can be traced back to some step in manufacturing, except for those defects produced by contact damage. Examples include bubbles and crystalline inclusions in glasses, and pores, large-grained regions, and microcracks in polycrystalline ceramics.

Although pores are not as effective in concentrating stresses as cracks, they are a frequent cause of failure in polycrystalline ceramics. The example in Fig 29 shows a pore with an unusual shape that happened to be right on the tensile surface of this Al_2O_3 specimen when it was loaded in bending. Appar-



(a)

(b)

Fig 29 Lower and higher magnification views of fracture surface of fine-grained Al_2O_3 with a surface pore as fracture origin. SEM. (a) 69×. (b) 690×

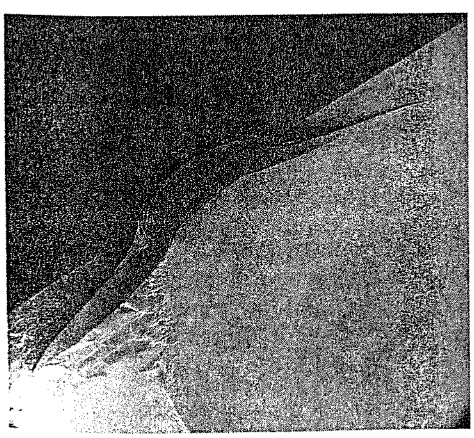


Fig 26 Hertzian fracture origin in glass. Line running diagonally through the picture is the edge between the original and the fracture surface. Main fracture started at the edge of the contact crack on the right-hand side of the cone. SEM. 40×

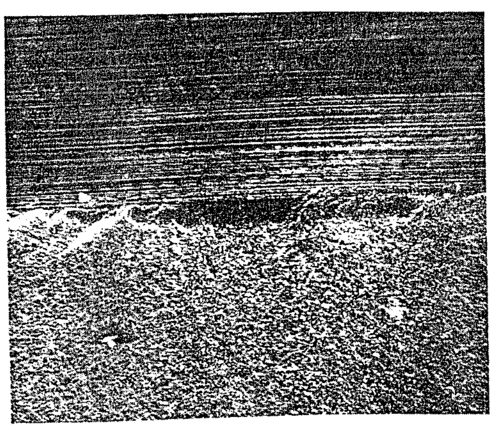


Fig 28 Fracture surface of Si_3N_4 with machining flaw as origin. Specimen was tilted in the SEM showing the machined surface at the top and the fracture surface at the bottom. Machining flaw is aligned with grooves on the original surface. SEM. 60×. Source: Ref 15

ently something organic was in the green material (possibly a hair or a segment of poorly mixed binder) which burned out during sintering, leaving this large pore. Although the material overall is fine grained with only very small pores, this large pore is a processing defect which significantly reduced the strength of this particular piece.

Figure 16, discussed earlier, is an example of a large-grained region as fracture origin. In the high-magnification view of Fig 16(b), the origin is seen to be a region where the grains are larger than the average, and where densification is very incomplete. Notice the transgranular fracture surrounding the large-grained area. It is common to see transgranular fracture close to the origin, where the fracture was travelling slowly.

Glazed ceramics are interesting because origins can be in the glaze, at the glaze/body interface, or in the body. Locating and identifying fracture origins is, therefore, especially critical in understanding causes of failure. Figure 30 shows an example of an origin in the glaze. In this case, there was a large grain of unreacted quartz located between two large bubbles. There will be cracking around such quartz particles owing to stresses that develop because of thermal-expansion differences between the quartz and the glaze. The large bubbles are also defects, but it was the quartz particle that caused fracture.

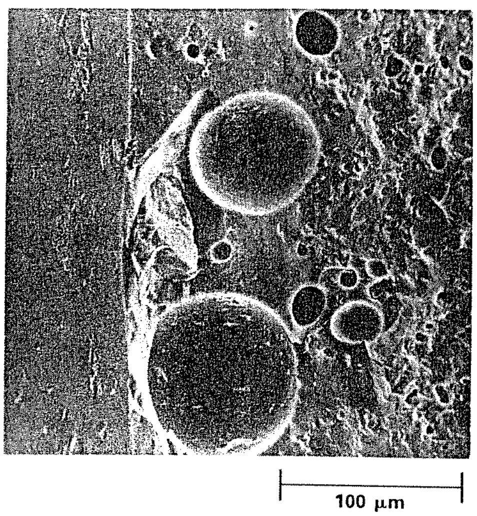


Fig 30 Fracture surface of glazed porcelain. Fracture origin is a quartz grain between the two large bubbles in the glaze. SEM

Fracture origins at the glaze/body interface are also very common. The glaze should be in compression and the body in tension. Reactions at the glaze/body interface may lead to local values of tension much higher than expected for the bulk of the body. Therefore, defects at the glaze/body interface are subjected to the combined effect of applied and residual stresses, making them frequent failure origins.

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