Designation: C 1678 – 07

Standard Practice for Fractographic Analysis of Fracture Mirror Sizes in Ceramics and Glasses[1]

This standard is issued under the fixed designation C 1678; the number immediately following the designation indicates the year of original adoption or, in the case of revision, the year of last revision. A number in parentheses indicates the year of last reapproval. A superscript epsilon (ε) indicates an editorial change since the last revision or reapproval.

1. Scope

1.1 This practice pertains to the analysis and interpretation of fracture mirror sizes in brittle materials. Fracture mirrors (Fig. 1) are telltale fractographic markings that surround a fracture origin in brittle materials. The fracture mirror size may be used with known fracture mirror constants to estimate the stress in a fractured component. Alternatively, the fracture mirror size may be used in conjunction with known stresses in test specimens to calculate fracture mirror constants. The practice is applicable to glasses and polycrystalline ceramic laboratory test specimens as well as fractured components. The analysis and interpretation procedures for glasses and ceramics are similar, but they are not identical. Different optical microscopy examination techniques are listed and described, including observation angles, illumination methods, appropriate magnification, and measurement protocols. Guidance is given for calculating a fracture mirror constant and for interpreting the fracture mirror size and shape for both circular and noncircular mirrors including stress gradients, geometrical effects, and/or residual stresses. The practice provides figures and micrographs illustrating the different types of features commonly observed in and measurement techniques used for the fracture mirrors of glasses and polycrystalline ceramics.

1.2 *This standard does not purport to address all of the safety concerns, if any, associated with its use. It is the responsibility of the user of this standard to establish appropriate safety and health practices and determine the applicability of regulatory limitations prior to use.*

2. Referenced Documents

2.1 *ASTM Standards:*[2]

C 1145 Terminology of Advanced Ceramics

C 1256 Practice for Interpreting Glass Fracture Surface Features

C 1322 Practice for Fractography and Characterization of Fracture Origins in Advanced Ceramics

3. Terminology

3.1 *Definitions*: (See Fig. 1)

3.1.1 *fracture mirror*, *n*—as used in fractography of brittle materials, a relatively smooth region in the immediate vicinity of and surrounding the fracture origin **C 1145, C 1322**

3.1.2 *fracture origin*, *n*—the source from which brittle fracture commences. **C 1145, C 1322**

3.1.3 *hackle*, *n*—as used in fractography of brittle materials, a line or lines on the crack surface running in the local direction of cracking, separating parallel but noncoplanar portions of the crack surface. **C 1145, C 1322**

3.1.4 *mist*, *n*—as used in fractography of brittle materials, markings on the surface of an accelerating crack close to its effective terminal velocity, observable first as a misty appearance and with increasing velocity reveals a fibrous texture, elongated in the direction of crack propagation. **C 1145, C 1322**

3.2 *Definitions of Terms Specific to This Standard:* (See Fig. 1)

3.2.1 *mirror-mist boundary in glasses*, *n*—the periphery where one can discern the onset of mist around a glass fracture mirror. This boundary corresponds to A_i, the inner mirror constant.

3.2.2 *mist-hackle boundary in glasses*, *n*—the periphery where one can discern the onset of systematic hackle around a glass fracture mirror. This boundary corresponds to A_o, the outer mirror constant.

3.2.3 *mirror-hackle boundary in polycrystalline ceramics,*, *n*—the periphery where one can discern the onset of systematic new hackle and there is an obvious roughness change relative to that inside a ceramic fracture mirror region. This boundary corresponds to A_o, the outer mirror constant. Ignore premature hackle and/or isolated steps from microstructural irregularities in the mirror or irregularities at the origin.

[1] This practice is under the jurisdiction of ASTM Committee C28 on Advanced Ceramics and is the direct responsibility of Subcommittee C28.03 on Physical Properties and Non-Destructive Evaluation.

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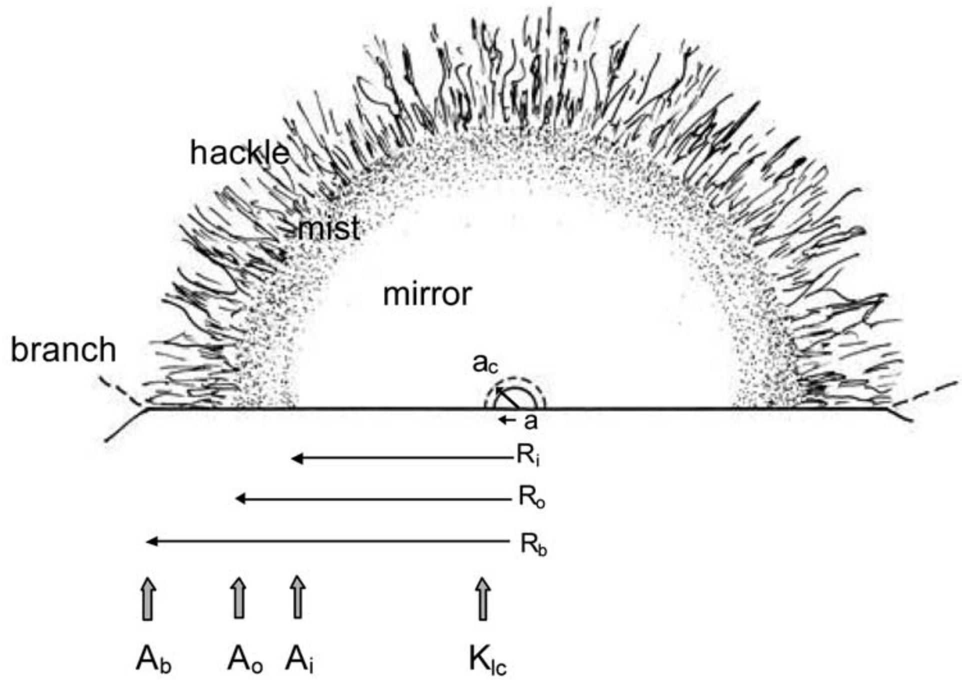
[2] For referenced ASTM standards, visit the ASTM website, www.astm.org, or contact ASTM Customer Service at service@astm.org. For *Annual Book of ASTM Standards* volume information, refer to the standard's Document Summary page on the ASTM website.



NOTE—The initial flaw may grow stably to size a_c prior to unstable fracture when the stress intensity reaches K_{Ic}. The mirror-mist radius is R_i, the mist-hackle radius is R_o, and the branching distance is R_b. These transitions correspond to the mirror constants, A_i, A_o, and A_b, respectively.

FIG. 1 Schematic of a Fracture Mirror Centered on a Surface Flaw of Initial Size (a).

3.2.4 *fracture mirror constant*, *n*—($Fl^{-3/2}$) an empirical material constant that relates the fracture stress to the mirror radius in glasses and ceramics.

4. Summary of Practice

4.1 This practice provides guidance on the measurement and interpretation of fracture mirror sizes in laboratory test specimens as well as in fractured components. Microscopy examination techniques are listed. The procedures for glasses and ceramics are similar, but they are not identical. Guidance is given for interpreting the fracture mirror size and shape. Guidance is given on how to interpret noncircular mirrors due to stress gradients, geometrical effects, or residual stresses.

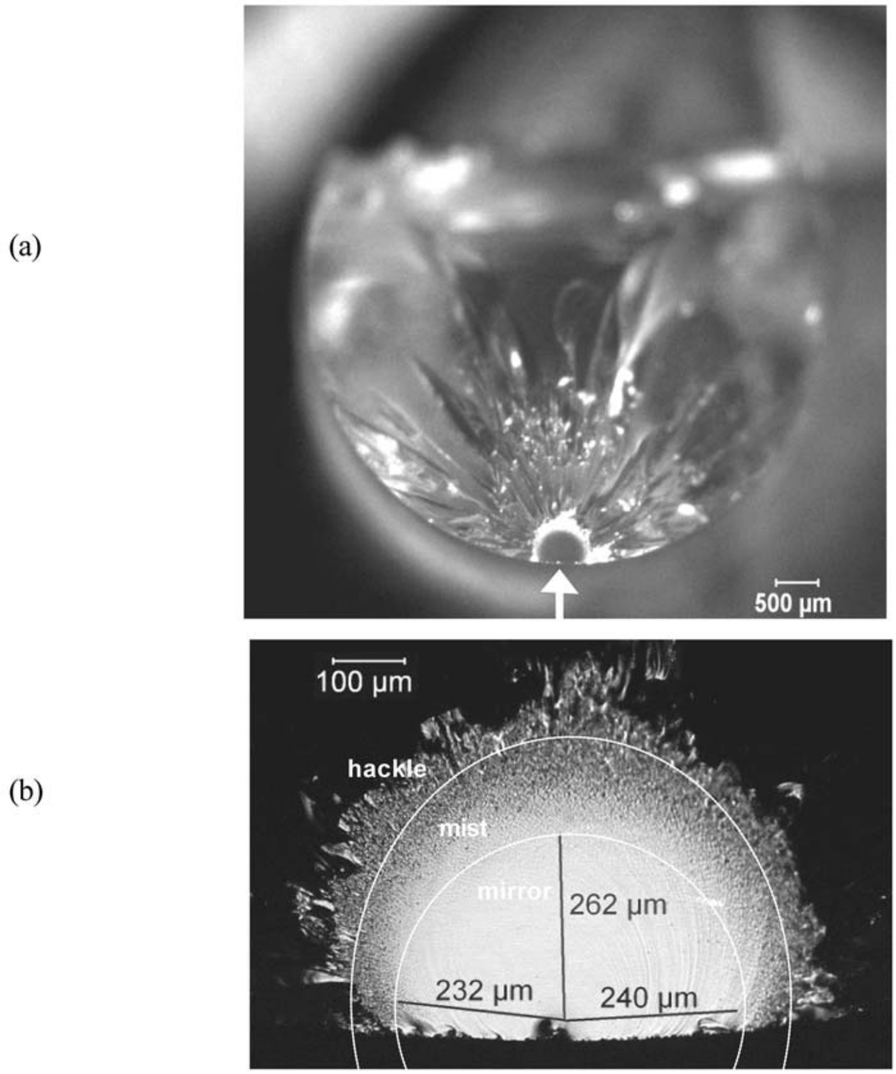
4.2 The stress at the origin in a component may be estimated from the mirror size.

4.3 Fracture mirror constants may be estimated from matched sets of fracture stresses and mirror sizes.

5. Significance and Use

5.1 Fracture mirror size analysis is a powerful tool for analyzing glass and ceramic fractures. Fracture mirrors are telltale fractographic markings in brittle materials that surround a fracture origin as discussed in Practices C 1256 and C 1322. Fig. 1 shows a schematic with key features identified. Fig. 2 shows an example in glass. The fracture mirror region is very smooth and highly reflective in glasses, hence the name "fracture mirror." In fact, high magnification microscopy reveals that, even within the mirror region in glasses, there are very fine features and escalating roughness as the crack advances away from the origin. These are submicrometer in size and hence are not discernable with an optical microscope. Early investigators interpreted fracture mirrors as having discrete boundaries including a "mirror-mist" boundary and also a "mist-hackle" boundary in glasses. These were also termed "inner mirror" or "outer mirror" boundaries, respectively. It is now known that there are no discrete boundaries corresponding to specific changes in the fractographic features. Surface roughness increases gradually from well within the fracture mirror to beyond the apparent boundaries. The boundaries were a matter of interpretation, the resolving power of the microscope, and the mode of viewing. In very weak specimens, the mirror may be larger than the specimen or component and the boundaries will not be present.

5.2 Figs. 3-5 show examples in ceramics. In polycrystalline ceramics, the qualifier "relatively" as in "relatively smooth" must be used, since there is an inherent roughness from the microstructure even in the area immediately surrounding the origin. In coarse-grained or porous ceramics, it may be impossible to identify a mirror boundary. In polycrystalline ceramics, it is highly unlikely that a mirror-mist boundary can be detected due to the inherent roughness created by the crack-microstructure interactions, even within the mirror. The word "systematic" in the definition for "mirror-hackle boundary in polycrystalline ceramics" requires some elaboration. Mirror boundary hackle lines are velocity hackle lines created after the radiating crack reaches terminal velocity. However, premature, isolated hackle can in some instances be generated well within a ceramic fracture mirror. It should be disregarded when judging the mirror boundary. Wake hackle from an isolated obstacle inside the mirror (such as a large grain or agglomerate) can trigger early "premature" hackle lines. Steps in scratches or grinding flaws can trigger hackle lines that



NOTE—(a) shows the whole fracture surface and the fracture mirror (arrow) which is centered on a surface flaw. (b) is a close-up of the fracture mirror which is elongated slightly into the interior due to the flexural stress gradient.

FIG. 2 Optical Micrographs of a Fracture Mirror in a Fused Silica Glass Rod Broken in Flexure at 122 MPa Maximum Stress on the Bottom.

emanate from the origin itself. Sometimes the microstructure of polycrystalline ceramics creates severe judgment problems in ceramic matrix composites (particulate, whisker, or platelet) or self-reinforced ceramics whereby elongated and interlocking grains impart greater fracture resistance. Mirrors may be plainly evident at low magnifications, but accurate assessment of their size can be difficult. The mirror region itself may be somewhat bumpy; therefore, some judgment as to what is a mirror boundary is necessary.

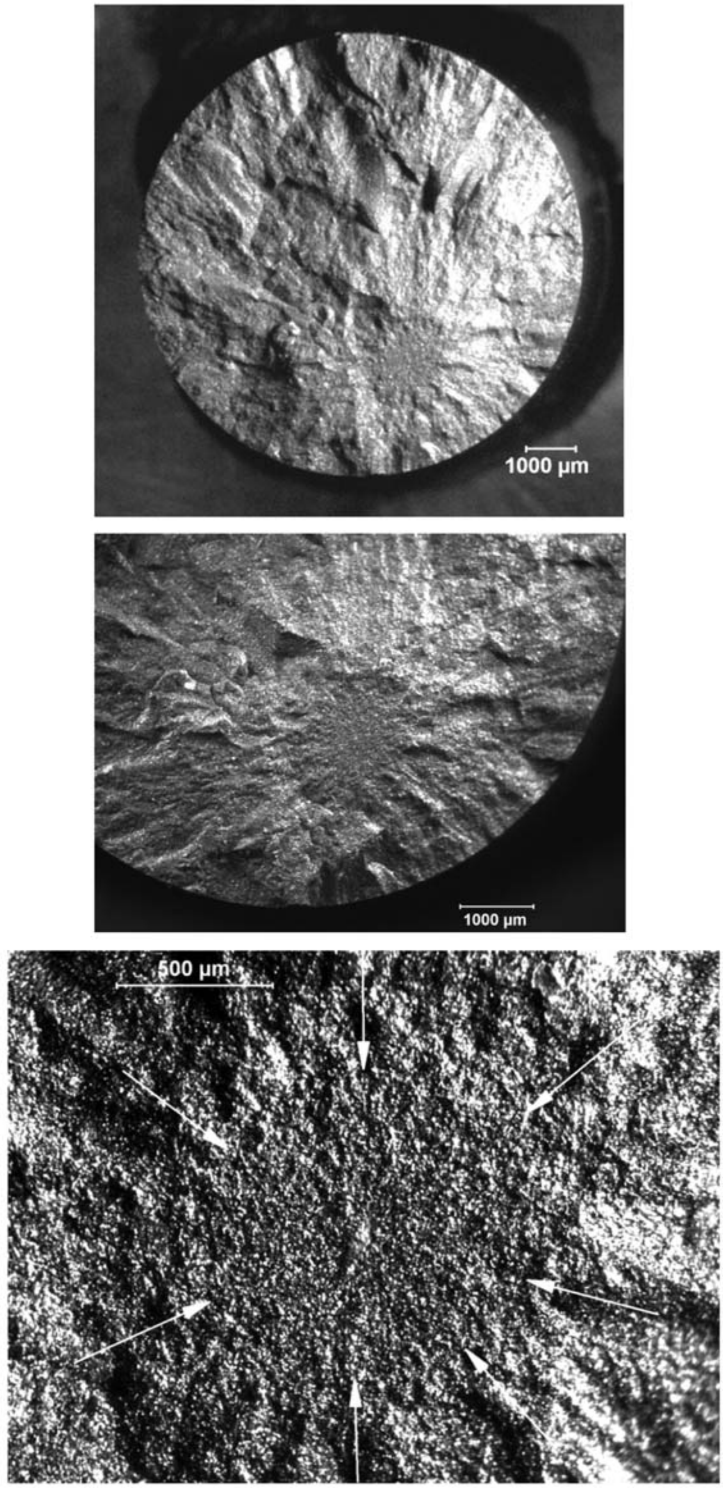
5.3 Fracture mirrors are circular in some loading conditions such as tension specimens with internal origins, or they are nearly semicircular for surface origins in tensile specimens, or if the mirrors are small in bend specimens. Their shapes can vary and be elongated or even incomplete in some directions if the fracture mirrors are in stress gradients. Fracture mirrors may be quarter circles if they form from corner origins in a specimen or component. Fracture mirrors only form in moderate to high local stress conditions. Weak specimens may not exhibit full or even partial mirror boundaries, since the crack may not achieve sufficient velocity within the confines of the specimen.

5.4 Fracture mirrors not only bring one's attention to an origin, but also give information about the magnitude of the stress at the origin that caused fracture and their distribution. The fracture mirror size and the stress at fracture are empirically correlated by Eq 1:

$$\sigma\sqrt{R} = A \tag{1}$$

where:
σ = stress at the origin (MPa or ksi),
R = fracture mirror radius (m or in),
A = fracture mirror constant (MPa$\sqrt{\text{m}}$ or ksi$\sqrt{\text{in}}$).

Equation 1 is hereafter referred to as the "empirical stress – fracture mirror size relationship," or "stress-mirror size relationship" for short. A review of the history of Eq 1, and fracture mirror analysis in general, may be found in Refs 1 and 2.



(a)

(b)

(c)

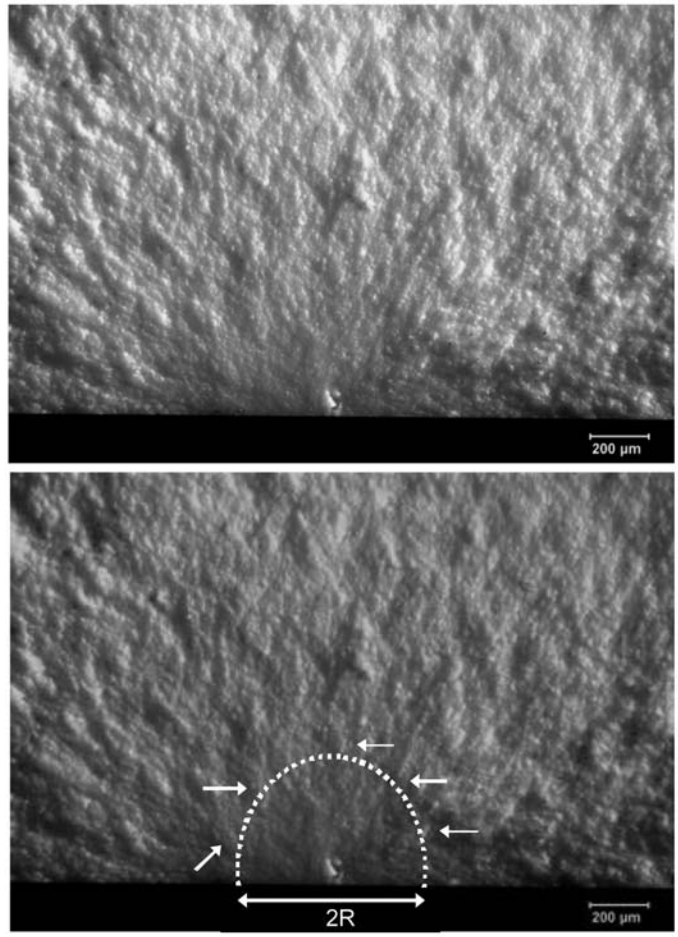
NOTE—Notice how clear the mirror is in the low power images in (a) and (b). The mirror boundary (arrows in c) is where systematic new hackle forms and there is an obvious roughness difference compared to the roughness inside the mirror region.

FIG. 3 Silicon Carbide Tension Strength Specimen (371 MPa) with a Mirror Centered on a Compositional Inhomogeneity Flaw.

5.5 A, the "fracture mirror constant" (sometimes also known as the "mirror constant") has units of stress intensity (MPa√m or ksi√in) and is considered by many to be a material property. As shown in Figs. 1 and 2, it is possible to discern separate mist and hackle regions and the apparent boundaries between them in glasses. Each has a corresponding mirror constant, A. The most common notation is to refer to the mirror-mist boundary as the inner mirror boundary, and its mirror constant is designated A_i. The mist-hackle boundary is referred to as the outer mirror boundary, and its mirror constant

(a)

(b)



NOTE— The mirror boundary is difficult to delineate in this material. (a) shows the uncoated fracture surface of a 2.8 mm thick flexural strength specimen that fractured at 486 MPa. Vicinal illumination brings out the markings. (b) shows a mirror-hackle boundary where systematic new hackle is detected (small white arrows) as compared to the roughness inside the mirror. The marked circle is elongated somewhat into the depth due to the stress gradient. The radius in the direction along the bottom surface (a region of constant stress) was 345 mm.

FIG. 4 A Fracture Mirror in a Fine-Grained 3 Mol % Yttria-Stabilized Tetragonal Zirconia Polycrystal (3Y-TZP).

is designated A_o. The mirror-mist boundary is usually not perceivable in polycrystalline ceramics. Usually, only the mirror-hackle boundary is measured and only an A_o for the mirror-hackle boundary is calculated. A more fundamental relationship than Eq 1 may be based on the stress intensity factors (K_I) at the mirror-mist or mist-hackle boundaries, but Eq 1 is more practical and simpler to use.

5.6 The size predictions based on Eq 1 and the A values, or alternatively stress intensity factors, match very closely for the limiting cases of small mirrors in tension specimens. This is also true for small semicircular mirrors centered on surface flaws in strong flexure specimens. So, at least for some special mirror cases, A should be directly related to a more fundamental parameter based on stress intensity factors.

5.7 The size of the fracture mirrors in laboratory test specimen fractures may be used in conjunction with known fracture mirror constants to verify the stress at fracture was as expected. The fracture mirror sizes and known stresses from laboratory test specimens may also be used to compute fracture mirror constants, A.

5.8 The size of the fracture mirrors in components may be used in conjunction with known fracture mirror constants to estimate the stress in the component at the origin. Practice C 1322 has a comprehensive list of fracture mirror constants for a variety of ceramics and glasses.

6. Procedure

6.1 Use an optical microscope whenever possible.

6.1.1 For glasses, use a compound optical microscope in bright field mode with reflected light illumination. A scanning electron microscope may be used if optical microscopy is not feasible.

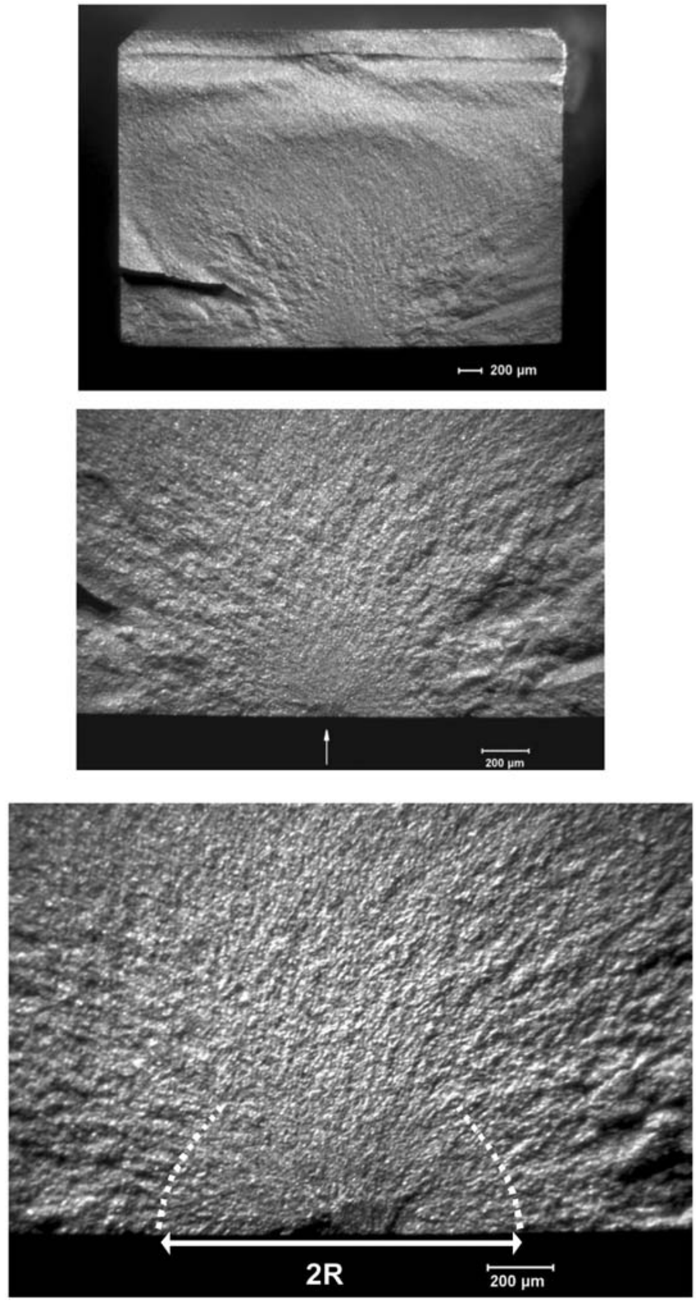
6.1.2 For ceramics, use a stereo optical microscope with low angle grazing (vicinal) illumination. A scanning electron microscope may be used if optical microscopy is not feasible

6.1.3 Differential interference contrast (DIC, also known as Nomarski) mode viewing with a research compound microscope is not recommended for either glasses or ceramics. It is not suitable for rough ceramic fracture surfaces. It also creates complications with glass fracture surfaces. There is no question that DIC mode viewing can discern very subtle mist features in glasses, but the threshold of mist detectability is highly dependent upon how the polarizing sliders are positioned. Hence, DIC measured radii are quite variable. DIC measured

(a)

(b)

(c)



NOTE—The mirror is incomplete into the bend stress gradient, but the mirror sides can be used to construct boundary arcs in (c) [(b) and (c) are close-ups of (a)]. Radii are measured in the direction of constant stress along the bottom.

FIG. 5 Silicon Nitride Bend Bar with a Knoop Surface Crack in a Silicon Nitride (449 MPa).

radii can be substantially smaller than those obtained with conventional viewing modes. It also must be borne in mind that not all users have access to interference contrast microscopes.

6.1.4 Dark-field illumination may be used for glasses, but some resolution may be lost with glasses and radii may be slightly larger as a result. Dark field is very effective with highly-reflective mirror surfaces of ceramic single crystals.

6.1.5 Scanning electron microscope images of mirrors are not recommended for glasses, since the mirror-mist boundary is usually indiscernible. SEM images often appear flat and do not have adequate contrast to see the fine mist detail at the ordinary magnifications used to frame the whole mirror. SEM images may be used with very small mirrors that would be difficult to see with optical microscopy, e.g., high-strength optical fibers. Scanning electron microscope images may be used for ceramics if necessary, but contrast and shadowing should be enhanced.

6.2 The fracture surface should be approximately perpendicular to the microscope optical path or camera.

6.2.1 This requirement poses a small problem if the mirrors in ceramics are examined with a stereo binocular microscope. This microscope has two different tilted optical paths. If viewing with both eyes in a stereo microscope, the specimen should be flat and facing directly upwards. The observer's brain will interpret the image as though the observer is facing it directly. Alternatively, if a camera is mounted on one light path of the stereo microscope, and it is used to capture or display the mirror, then the specimen should be tilted so that the camera axis is normal to the fracture surface. For example, slightly tilt the specimen to the right if the camera is attached to the right optical path.

6.3 Optimize the illumination to accentuate topographical detail.

6.3.1 For glasses, accentuate the mist and hackle features. Glasses may either be illuminated from directly down onto a fracture surface or by grazing angle, vicinal illumination. Vicinal illumination is less convenient with compound light microscopes, but the observer should experiment with whatever illumination options are available to accentuate subtle surface roughness and topography features.

6.3.2 For ceramics, accentuate the hackle lines. Ceramics should not be uniformly and directly illuminated such as by a ring light, since the light will reduce contrast especially in translucent or transparent materials. Ceramics shall be illuminated with grazing angle, vicinal illumination. Thin gold or carbon coatings may be applied to translucent or transparent ceramics as needed.

6.4 Use an appropriate magnification.

6.4.1 For glasses, use a magnification such that the fracture mirror area occupies about 75 % to 90 % of the width of the field of view. Fracture mirrors are reasonably easy to see in glasses, and magnifications should be used such that the fracture mirrors nearly fill the field of view.

6.4.2 For ceramics, use a magnification such that the fracture mirror area occupies about 33 % to 67 % of the width of the field of view. Mirror interpretation is more problematic with polycrystalline ceramics. Even though a mirror may be obvious at low or moderate magnification, at high magnification it may be impossible to judge a boundary. It is more practical to view the mirror region and the natural microstructural roughness therein relative to the hackle outside the mirror. "Stepping back" and using the 33 % to 67 % rule should help an observer better detect the topography differences. Supplemental lower-magnification images may aid interpretation. The magnification of the supplemental images should differ from that of the main measurement image by no more than a factor five, otherwise it is difficult to correlate features between the images.

6.5 Measure the mirror size while viewing the fracture surface with an optical microscope whenever possible.

6.5.1 For both glasses and ceramics, use either calibrated reticules in the eyepieces or traversing stages with micrometer-positioning heads. Alternatively, measurements may be made on digital images on a high-resolution computer monitor, while the fracture surface can be simultaneously viewed through the microscope eyepieces in order to aid judgment.

NOTE 1—Mirror size measurements made on computer monitor screens are subject to inaccuracies, because they are two-dimensional renditions of a three-dimensional fracture surface. Nevertheless, high-resolution cameras and monitors are beginning to match the capabilities and accuracy of an observer peering through the optical microscope.

6.5.2 Measurements from photos or digitally recorded images may be used as a last resort if the steps in 6.5.1 cannot be followed. This may be necessary for very small specimens or very strong specimens with tiny mirrors where a scanning electron microscope must be used to photograph the mirror. Measurements from other devices may be used provided that the criterion used for identifying the mirror boundary is carefully documented. Complementary high and low magnification images may be used to help aid in interpretation. Mirror size measurements from photographs are usually less accurate or precise. They frequently overestimate mirror sizes unless conditions are carefully optimized to accentuate contrast and topographic detail. Two-dimensional photographic renditions of a three-dimensional fracture surface usually lose much of the topographic detail discernable by the eye with a compound optical or stereo microscope. Video cameras shall not be used to capture mirror images, since they lack adequate resolution.

6.5.3 In ceramics, the fracture mirror regions may have an intrinsic roughness due to the microstructure. The mirror boundary is judged to be the point where systematic radiating new hackle commences and there is an obvious roughness change relative to the inside-mirror region. The new hackle that generates the mirror boundary is formed by the radiating crack running at or near terminal velocity. Ignore premature isolated hackle that may be generated well within a mirror. Wake hackle from an obstacle inside the mirror (such as a large grain or agglomerate) can trigger early premature hackle lines. Steps in scratches or grinding flaws can trigger premature hackle that emanate from the origin itself.

6.6 Measure radii in directions of approximately constant stress whenever possible. A mirror diameter may be measured and halved to estimate the radius if the origin site is indistinct or complex.

6.6.1 Measurements should be taken from the center of the mirror region, but some judgment may be necessary. A common procedure is to make a judgment whether a mirror is indeed approximately semicircular or circular. If it is, then multiple radii measurements may be made in different directions and averaged to obtain the mirror size estimate. The center of the mirror may not necessarily be the center of the flaw at the origin. Careful inspection of tiny localized fracture surface markings (Wallner lines and micro hackle lines) may reveal that fracture started at one spot on a flaw periphery. For example, fracture from grinding or impact surface cracks in glass often starts from the deepest point of the flaw and not at the specimen outer surface. Fig. 2 shows an example in glass. Large pores often trigger unstable fracture from one side. If an exact mirror center cannot be determined, measure a mirror diameter and halve the measurement. This is commonly done for semicircular mirrors centered on irregular surface-located flaws, whereby the mirror center may be difficult to judge. Circular embedded mirrors are easiest to interpret, such as in Fig. 3. Small semicircular mirrors on the surface of a part, such as in a bend bar or a flexurally loaded plate, are also not too difficult to interpret.

6.6.2 The stress mirror relationship is applicable for glass optical fibers tested in tension with mirror radii almost as large as the fiber diameter[3]. The mirror radius should simply be measured from the origin to the mirror-mist or mist-hackle boundary on the opposite side of the fiber, R_d as shown in Fig. 6.

6.6.3 Mirror shapes are commonly affected by stress gradients in a plate or a beam. Mirror radii are elongated in the direction of decreasing stress. In such cases, measure the mirror radius along the tensile surface where the stress is constant. Do not measure the mirror radii into the stress gradient. See Annex A1 for more information on how to interpret elongated mirrors and mirrors in stress gradients.

6.6.4 Fracture mirrors in glasses that are centered around a surface located origin may have a slight inward pinch towards the origin or a "cusp" due to free surface effects. Fig. 2 and several figures in Annex A2 illustrate such cusps. Truncate the cusps when interpreting the arc of the fracture mirror boundaries as discussed in Annex A2.

6.6.5 Residual stresses may alter fracture mirror sizes and shapes. Annex A3 provides guidance for such cases.

6.6.6 Nearly all the surface-centered mirrors shown in the literature, even in the classical papers, are not exactly semicircular, despite all the schematics that imply that they are. Thus, fractographers should not be alarmed if their mirrors are not perfect.

6.7 Exercise caution when fracture mirrors are large relative to the specimen cross-section size or very small relative to the grain size in ceramics.

6.7.1 At some point, geometric effects can cause departures from the stress-mirror size relationship. The point where the departure occurs depends upon the loading geometry and the stress state. Pronounced deviations occur once the fracture mirror size approaches or is greater than the component thickness in plate or beam bending fractures. Experimentally measured radii are usually greater than predicted by Eq 1. In contrast, deviations may be minimal in components tested in uniform tension.

6.7.2 In ceramics, systematic deviations from the mirror size relationship not only occur at large mirror sizes, but also at very small size. In the latter case, deviations may be due to internal stress effects, e.g., from thermal expansion anisotropy of grains.

6.8 If the objective is to compute the net stress at an origin site in a fractured component, use the mirror size and the fracture mirror constant and Eq 1. Practice C 1322 has a compilation of fracture mirror constants for glasses and ceramics.

6.9 If the goal is to evaluate one or more fracture mirror constants, then follow the steps 6.10-6.12.

6.10 Use the stress at the origin site. Correct the stress for location in specimens with stress gradients.

6.10.1 If the specimen was broken in controlled conditions where the stress distribution was known (e.g., beams, rods, or plates in flexure) correct the stress for the origin location. No correction is needed for a part stressed in uniform tension. The general principal that should be followed is that the mirror formation is guided by the stresses in the vicinity of the origin. Use of the stress at the origin site in conjunction with the procedures in 6.6 (whereby the fracture mirror size is measured in a direction of constant stress) gives matched pairs of stress and radii.

6.11 Evaluate the fracture mirror constants by regressing stress at the origin site on inverse square root of mirror radius.

6.11.1 Once a set of matching mirror radii and fracture stresses has been compiled, plot the data as linear stress versus inverse square root of mirror size, as shown in Fig. 7.

6.11.2 A variant of Eq 1 may be written as:

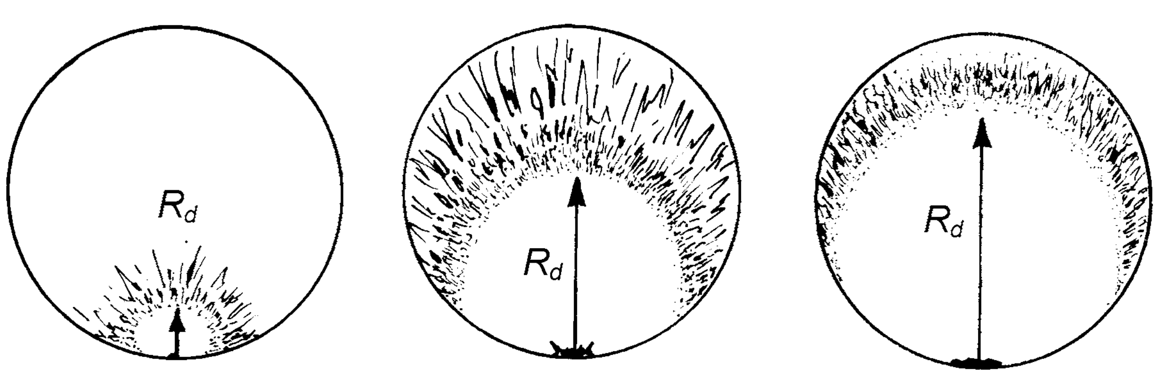
$$\sigma_a = \frac{A}{\sqrt{R}} \tag{2}$$

where σ_a is the stress at the origin site, A is the mirror constant, and R is the mirror radius in the direction of constant stress. A is the slope of the regression line. Separate regressions should be done for mirror-mist and mist-hackle boundaries for glasses for A_i and A_o estimates, respectively.

6.11.3 Plot the data with a vertical axis (the ordinate) of stress at the origin with units of MPa and a horizontal axis (the abscissa) of $1/\sqrt{R}$ where R is in meters. Use linear regression methods to obtain A in accordance with Eq 2 with a forced zero intercept as shown in Fig. 7a.

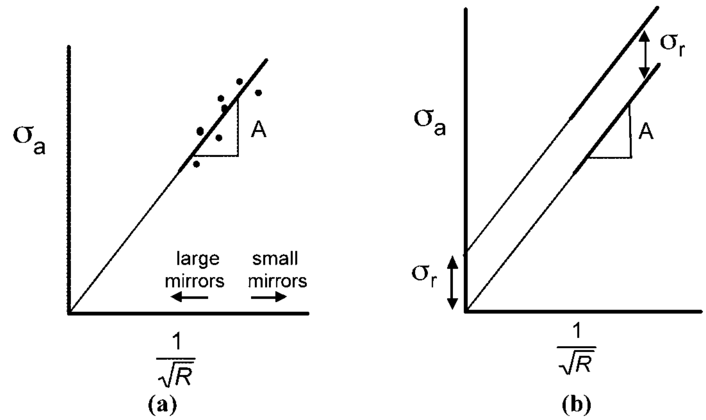
NOTE 2—The mirror constant A is a slope and is easily visualized. In addition, a nonzero intercept as shown in Fig. 7b may be conveniently interpreted as an effective residual stress as discussed in Annex A3.

NOTE 3—If the mirror is measured in mm or μm, the radii should be converted to meters before plotting and regressing. Otherwise, if the appropriate conversion factors are added later they can cause confusion,



NOTE—Measure both the mirror-mist radius and mist-hackle radii into the depth.

FIG. 6 Mirrors Surrounding Surface Origins in Rods or Fibers Loaded in Direct Tension.



NOTE—(a) shows the trend for residual stress-free parts; (b) shows it for parts with residual stresses. Compressive residual stresses move the locus up with a positive intercept σ_r, but with the same slope. Tensile residual stresses shift the data downwards with a negative intercept (not shown).

FIG. 7 Plot of Applied Stress σ_a(at the Origin) Versus $1/\sqrt{R}$.

since the square root of a conversion factor of 1000 (e.g., meters to mm) is an odd value.

NOTE 4—If stresses are measured in ksi, then measure mirror radii in inches. These units are not recommended.

6.11.4 If stresses are in units of MN/m^2(MPa), and the mirror size is measured in meters, then the mirror constant A has units of $MN/m^{1.5}$ or $MPa\sqrt{m}$.

NOTE 5—If stresses are measured in ksi, and the mirror radii in inches, then the mirror constants have units of $ksi\sqrt{in}$. These units are not recommended.

6.11.5 Use some judgment in the regression analysis since fracture mirror data frequently has moderate scatter. If the data do not appear to fit a trend that has a zero intercept, regress the data with a non-zero intercept as shown in Fig. 7b. Again use some judgment in the interpretation, since a strict linear regression fit may produce implausible outcomes, particularly if the data are collected over a limited range of mirror sizes and stresses.

6.11.6 Report the intercept if it deviates significantly from zero (> 10 MPa for glasses or > 50 MPa to 100 MPa for ceramics). Investigate possible residual stresses or specimen size or shape issues if the intercept deviates significantly from zero. See Annex A3 for more information on the effects of residual stresses and their interpretation.

6.12 Mirrors sizes should be collected over a broad range of sizes and fracture stresses if possible. Data from different specimen types and sizes may be combined.

6.12.1 Data from many small specimens may be complemented by judicious testing of a few large specimens.

6.12.2 Another common procedure to vary mirror sizes is to anneal or fine grind/polish some specimens to obtain high strengths, but also abrade or damage others to obtain low strengths. Sometimes the mode of loading can be changed to alter the fracture stress. For example, large four-point and small three-point flexure specimens may be used. Some specimens may be tested in inert conditions and others in conditions conducive to slow crack growth.

7. Report

7.1 Report how the mirrors were measured. Show at least one photo with arrows or lines marking the mirror size.

7.2 Report the microscope that was used. Confirm that the interpretation was made while looking through the microscope. Report whether photos had to be used and, if so, approximately what magnifications were used. The directions in which the mirror radii were measured should be recorded. The approximate shape of the mirrors (semicircular, circular, or elliptical) should be noted. It should also be noted whether the mirrors were an appreciable fraction of the size of the cross section or not. Lastly, and most importantly, the judgment criterion used should be reported.

7.3 Show a graph of stress versus inverse square root mirror size with the fitted regression line if multiple mirrors have been measured for laboratory strength type specimens.

7.4 Whenever possible, provide information on the test specimen material and the testing conditions including composition, microstructure, phase content, processing, conditioning, and mode of loading.

8. Keywords

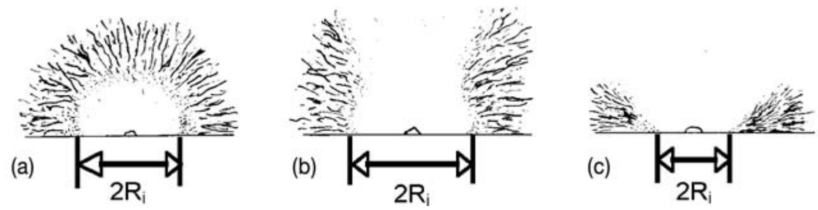
8.1 ceramics; fractography; fracture mirror; fracture strength; fracture stress; fracture surface; glasses; hackle; microscope; mist; origin; residual stresses

ANNEXES

(Mandatory Information)

A1. Elongated and Incomplete Fracture Mirrors

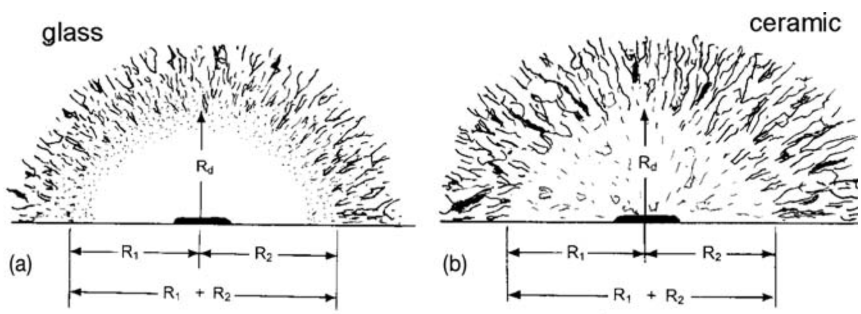
A1.1 Fracture mirror shapes are commonly affected by stress gradients in a plate or a beam in bending. Mirror radii are elongated in the direction of decreasing stress. Examples are shown in Fig. A1.1 and Fig. 2, Fig. 4, and Fig. 5. In such cases, measure the mirror radius along the tensile surface where the stress is constant. Do not measure the mirror radii into the gradient. Even with this precaution, there is considerable evidence that the data begin to depart from the stress-mirror size relationship when the mirror radii approach the cross-section thickness in bending loadings. For example, if the mirror radius is greater than a plate's thickness and the radii are measured along the plate surface (such as shown in Fig. A1.1c), the radii will be larger than they would be if they were completely within a large part in uniform tension. Mirror elongations into the interior may also be caused by surface tensile residual stresses if they exist as described in Annex A3, paragraph A3.1.



NOTE—If the mirror is small relative to the part size, then the mirror may be semicircular, as shown in (a). Weaker parts have larger mirrors that flare into the interior and are incomplete, as shown in (b) and (c). Measure the mirror size (R_i or $2R_i$ for the mirror-mist in the illustrations here) in the direction of constant stress.

FIG. A1.1 Elongated Mirrors in Bending Stress Fields.

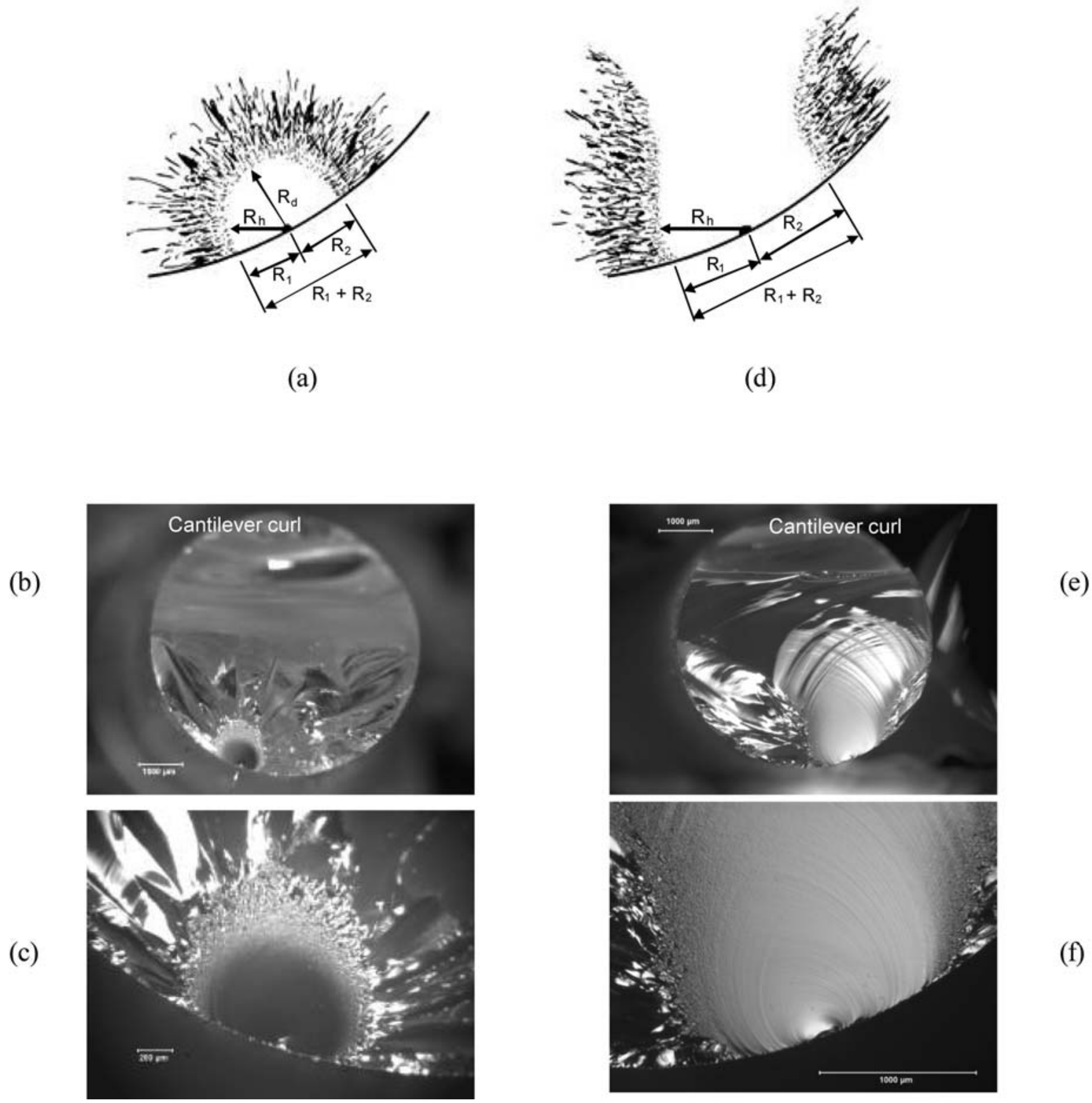
A1.2 A trend for mirrors to elongate the opposite way, along the external surface of a specimen, occurs with long grinding cracks or scratches as shown in Fig. A1.2.



NOTE—(a) shows a schematic of such a mirror with the mist-hackle boundary marked in glass, and (b) shows a comparable image in a polycrystalline ceramic. The ceramic has some intrinsic microstructural roughness inside the mirror. The mirror-hackle boundary is marked. Use an average radius: R_{avg}= $\{(R_1+ R_2+ R_d\}/3$.

FIG. A1.2 Grinding Cracks and Scratches Causing Mirror Elongations along the Surface (even in Bend Bars with Stress Gradients).

A1.3 In some cases, it may be difficult to measure mirrors in directions of constant stress. The two sides of a fracture mirror may have unequal lengths, since the stresses are different on either side of the mirror. Fig. A1.3 shows examples of round rods broken in flexure. Origins may not necessarily be at the rod bottom where the stresses are a maximum, but part way up the side of the specimen. Specimen orientation may be easily determined from observation of the cantilever curl (also known as the compression curl), which marks the compression side of the specimen. The maximum tensile stress on the bottom of the specimen is on the rod directly opposite the cantilever curl. The mirror radii have obviously different lengths due to the stress gradient. A radius in the direction of constant stress, R_h, should be measured as shown in Fig. A1.3, if the mirror is centered on a well-defined origin site. If there is any doubt, then an average radius may be computed. Use $R_{avg}= (R_1+ R_2+ R_d) / 3$ if the mirror is nearly semicircular. Use $R_{avg}= (R_1+ R_2) / 2$ if the mirror is elongated into the interior and R_d is large or is incomplete. For origins located in the interior of a rod or bar broken in flexure, only use the radii in the direction of constant stress.



NOTE—The maximum tensile stress is at bottom center. The cantilever curl or compression curl (at the top of b and e) provides a convenient reference to determine the bending stress distribution. Fractures started at flaws part way up the sides of the rods, causing the mirrors to have unequal radii. One rod (a,b,c) was sufficiently strong that a nearly semicircular mirror formed, albeit with unequal radii due to the stress gradient. Use $R = R_h$ in the horizontal direction if the origin and mirror center is distinct. Otherwise use $R_{avg} = (R_1 + R_2 + R_d) / 3$ if the mirror is nearly semicircular. Use $R_{avg} = (R_1 + R_2) / 2$ if the mirror is elongated into the interior and R_d is large. A second but weaker glass rod is shown in (d,e,f). Use $R = R_h$ if the origin and mirror center are distinct, otherwise use $R_{avg} = (R_1 + R_2) / 2$ and truncate surface cusps as discussed in Annex A2.

FIG. A1.3 Fracture Mirrors in Two Rods Tested in Flexure.

A2. Surface Cusps in Glass Fracture Mirrors

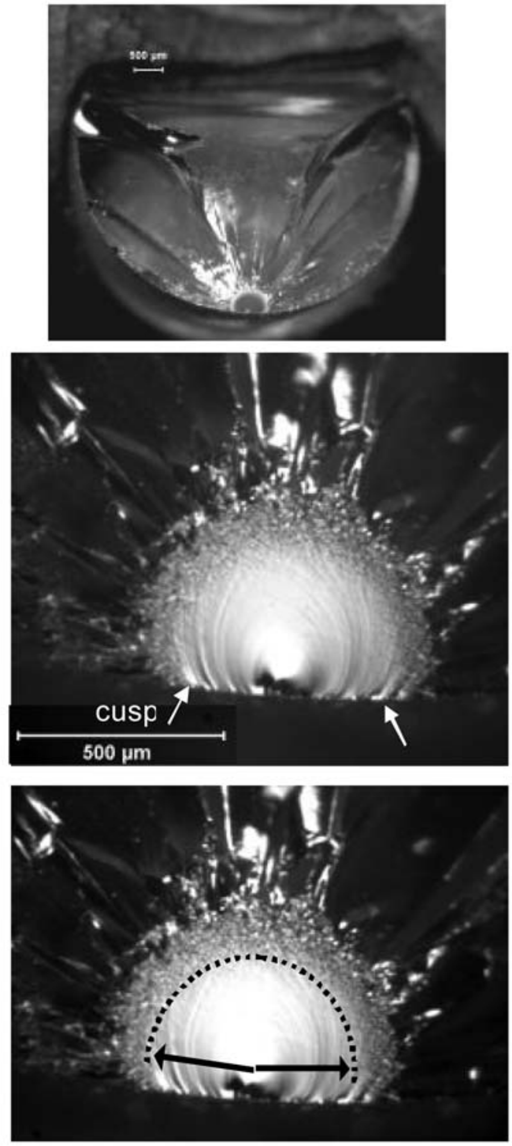
A2.1 Mirrors located on a specimen external surface in glasses have small cusps at the intersection with the outer surface, as shown in Fig. A2.1 and Fig. A2.2. Such cusps are rarely if ever discerned in polycrystalline ceramic mirrors. The small cusp is a consequence of fracture mechanics. A small element of material near the tip of a crack at the specimen exterior surface experiences greater stress intensity (K_I) than a similar element buried in the interior, whereby neighboring elements can "share the load." The slightly-greater stress intensity at the surface triggers the mirror markings a bit sooner than for interior elements.

A2.2 Another reason to be wary of measurements right along the surface is that surface roughness, machining damage, or other surface irregularities also may trigger mist or hackle formation a bit earlier at the surface than in the interior.

(a)

(b)

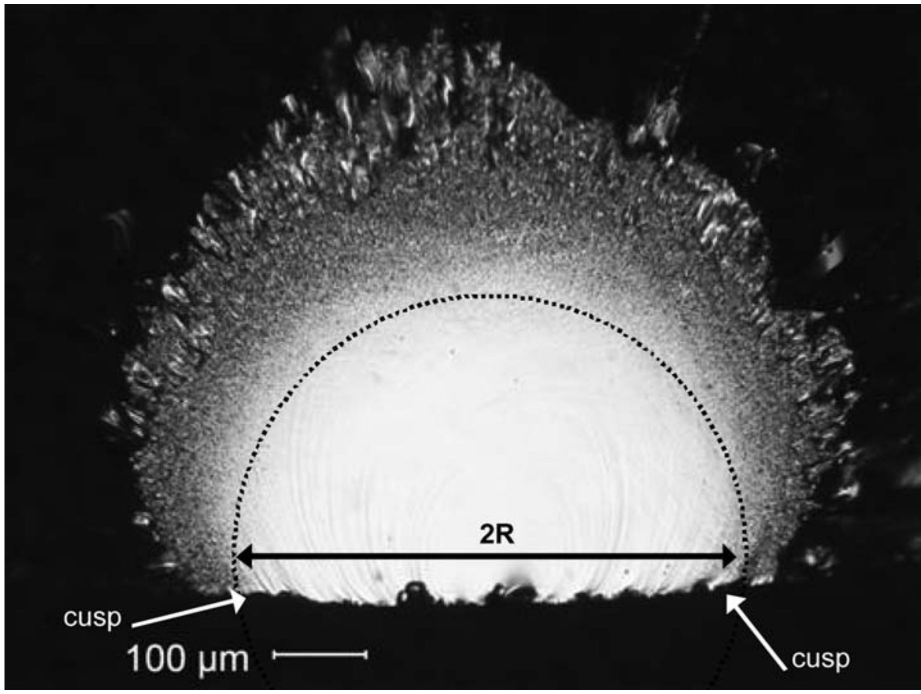
(c)



NOTE—Mirror measurements should not include the inward bend of the mirror and may be made as shown in (c).

FIG. A2.1 Fracture Mirror in a Fused Silica Rod (a), Illustrating the Cusps in the Mirror Near the Outer Surface (b).

A2.3 Truncate the cusps as shown in Fig. A2.1 and Fig. A2.2. Extend the semicircular (or other mirror shape) arcs as shown in these figures. Other examples of mirrors with cusps are shown in Fig. 1 and Fig. A1.3.

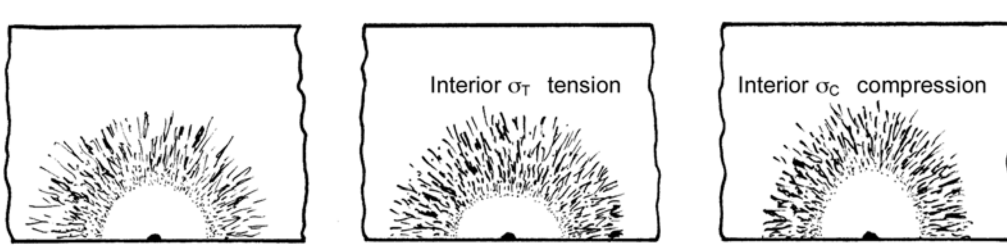


NOTE—Fracture mirrors centered on surface origins in glass have inward tilting cusps. These should be truncated and a mirror site measured by using the arc of the overall mirror shape. This mirror is slightly elongated into the interior due to a bending stress gradient.

FIG. A2.2 Fracture Mirror in a Fused Silica Rod (116 MPa).

A3. Effects of Residual Stresses on Fracture Mirrors

A3.1 Residual stresses affect the size and shape of fracture mirrors. If the fracture mirror is very small relative to the stress gradient, the mirror shape may remain circular if in the interior or semicircular if on the surface. On the other hand, if the mirror is larger or the stress gradient is steep, then the gradient alters the mirror shape, as shown in Fig. A3.1. Fig. A3.1a shows an annealed plate that requires an applied stress of $\sigma_a = \sigma_f$ to cause fracture. Fig. A3.1b shows the case where the same plate has residual compression stress $\sigma_r = \sigma_c$ on the outer surface from ion exchange or thermal tempering, so that an applied stress to cause fracture is $\sigma_a = \sigma_f + \sigma_c$. In other words, the applied stress must be increased to overcome the residual surface stress. Nevertheless, the net stress at the surface at the moment of fracture is $\sigma = \sigma_a - \sigma_c = (\sigma_f + \sigma_c) - \sigma_c = \sigma_f$, the same stress as in the annealed plate. Hence the mirror radii along the surface are unchanged compared to the annealed plate. In contrast, in the direction into the interior, tensile stresses combine with the applied tensile stress to cause the mirror markings to form sooner, at a shorter radius into the interior than in the annealed plate. In this example, the mirror shape is flattened to a semiellipse. Mirror radii should be measured only along the surface (or just beneath the surface if there is a cusp)



NOTE—σ_a is the applied stress to cause fracture, and σ_f is the fracture stress in an annealed plate in tension. (a) shows a surface mirror in an annealed plate. (b) shows the mirror shape in a plate with surface compression stresses that decrease into the interior and become tensile. (c) shows a mirror in a plate with surface tensile stresses that diminish into the interior and become compressive.

FIG. A3.1 Surface Residual Stresses Altering a Mirror Shape.

in these cases. Fig. A3.1c shows that surface residual tensile stresses have the opposite effect: mirror radii are elongated into the interior. Mirror radii again should only be measured along the surface, since again the net stress to cause fracture is $\sigma = \sigma_f$.

A3.2 There are two possible paths for analysis if there are residual stresses.

A3.2.1 The fracture mirror is measured on a component. The applied stress and the residual stresses are unknown. In this instance, the net stress s at the origin can be evaluated from R and Eq 1. If the stress estimate from fracture mirror analysis differs from a stress estimate from an independent analysis, then residual stresses may be present. (Alternatively, the independent analysis may be incorrect.) The shape of the mirror may be interpreted for signs of residual stresses, although applied stress gradients may also cause mirror shape distortions

A3.2.2 The mirrors are collected in laboratory strength test conditions. Usually specimens are tested such that the apparent origin stresses, σ_a, from applied stresses are known. Usually many specimens are tested and matched pairs of σ_a and R are obtained. Graphical analysis shown below in Fig. 7b and discussed in A3.3 reveals the existence of residual stresses and allows an estimate of their magnitude.

A3.3 A nonzero intercept may be conveniently interpreted as an effective residual stress on a graph of applied stress versus inverse square root of mirror size, as shown in Fig. 7b. If residual stresses σ_r are present in addition to the externally applied stress, σ_a, then the net stress acting on the origin site is:

$$\sigma_{net} = (\sigma_a + \sigma_r) = \frac{A}{\sqrt{R}} \tag{A3.1}$$

and:

$$\sigma_a = \frac{A}{\sqrt{R}} - \sigma_r \tag{A3.2}$$

An intercept below the origin corresponds to a net tensile residual stress. A positive intercept corresponds to residual compressive stress, since the usual sign convention is for compressive stresses to have a negative sign.

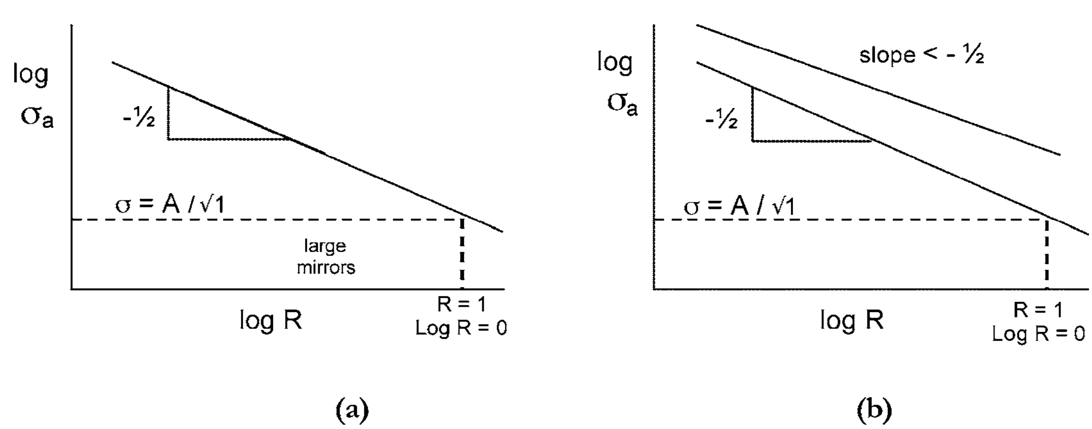
A3.4 Some caution is advised, since residual stresses are often nonuniform. The estimate from the intercept is an effective residual stress, which in reality may vary in magnitude through the mirror region. Once again it is prudent to measure mirror radii in directions of constant stress. For example, if the mirror is in a heat-strengthened or tempered piece (where stress may be constant along the surface, but change dramatically through the thickness) the mirrors should only be measured along the surface (or just underneath to avoid the cusp). Residual stresses from an indentation or impact site are very local to the origin and may have very little effect on a mirror size.

APPENDIX

(Nonmandatory Information)

X1. ALTERNATIVE REGRESSION ANALYSIS

X1.1 One popular alternative analysis method is based on plotting the data on a log-stress versus log-radius graph as shown in Fig. X1.1. This method of showing the results and calculating a mirror constant was common in the older technical literature[1,2] and is occasionally still found today. Graphs of this type were used when researchers were not sure whether Eq 2 with the $\sqrt{R}$ relationship was appropriate. Forty years of research have shown it is, so there no longer is a need to test



NOTE—Compressive residual stresses move the locus upwards as shown in (b), but with a different slope and intercept. Tensile residual stresses move the loci below the baseline curve (not shown).

FIG. X1.1 Plot of log σ_a Versus log R for Parts with No Residual Stresses (a), and Parts with Residual Stress (b).

for the trend. From Eq 2:

$$log\ \sigma_a = -\frac{1}{2} log\ R + log\ A \quad (X1.1)$$

X1.2 If stresses are in units of MN/m^2(MPa), and the mirror size is measured in meters, then the mirror constant A has units of MN/m$^{1.5}$ or MPa$\sqrt{m}$. If the mirror size is 1 m, then log R = 0. Then log σ = log A and hence, σ = A. Hence, the mirror constant A corresponds to the value of stress that creates a mirror of size 1 m. (The mirror constant A corresponds to the value of stress for a mirror of size 1 in. if the mirror constant has units of ksi$\sqrt{in}$ and stress is in ksi.) Since most mirrors are usually much smaller than unit size, it is apparent from Fig. X1.1 that the mirror constant (or the stress for R = 1) lies beyond the range of data usually collected. Deviations from the linear relationship on the log – log plot occur when residual stresses are present but unaccounted for, or when the mirror size is large relative to the component size, or when there are stress gradients. The residual-stress deviations cause the line to have a slope other than –½ , as shown in Fig. X1.1. Attempts to compute the residual stresses may then be made by guessing values of the residual stresses σ_r, replotting the data, and checking the goodness of fit of a line of slope –½ . This is a cumbersome process and the recommended σ versus 1/$\sqrt{R}$ procedure is much simpler. The two analyses put different weights on large and small mirror measurements. In one case the mirror constant is a slope of a line, in the other it is an intercept at R = 1. Some of the variability in published mirror constants probably is due to the use of the two different curve-fitting schemes.

X1.3 Regression analyses on the log – log graph are more vulnerable to deviations of the data from the correct trends when mirror sizes are large. Upward deviations from the log stress – log radius graphs have been noted in a number of studies. Regression lines "chase" the upward deviations and dramatically alter the estimate of the mirror constant.

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