
Fracture: Microscopic Aspects

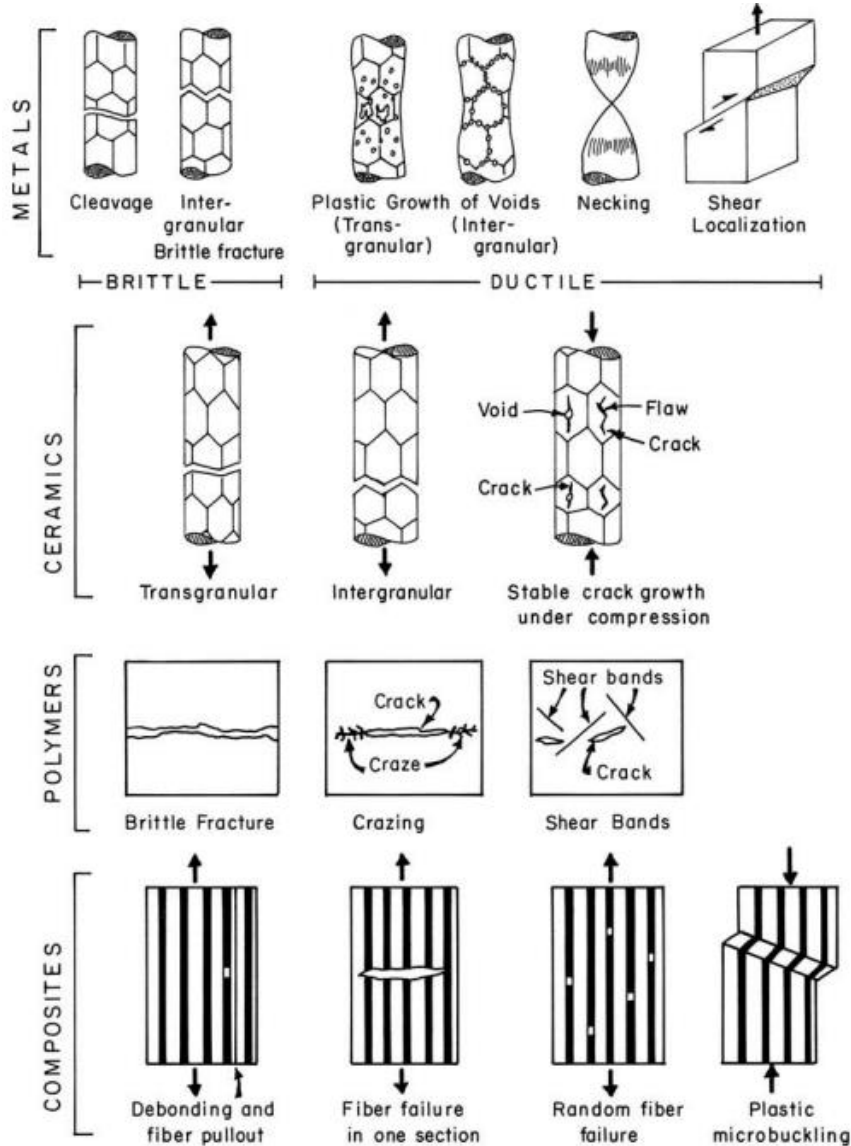
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Fracture Morphologies and Processes



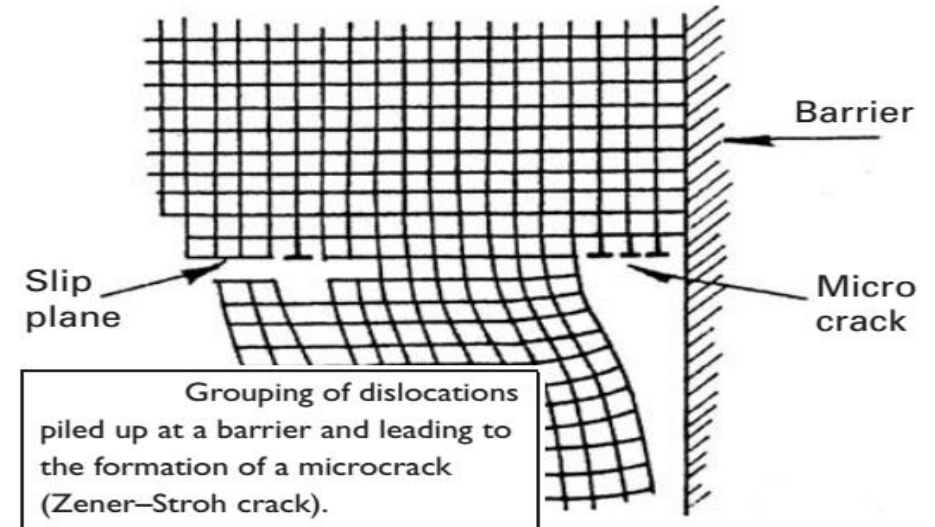
Metals fail by two broad classes of mechanisms: *ductile and brittle*. *Ductile* failure occurs by (a) the nucleation, growth, and coalescence of voids, (b) continuous reduction in the metal's cross-sectional area until it is equal to zero, or (c) shearing along a plane of maximum shear.

Brittle fracture is characterized by the propagation of one or more cracks through the structure. While totally elastic fracture describes the behavior of most ceramics fairly well, metals and some polymers undergo irreversible deformation at the tip of the crack, which affects its propagation.

Composites -- especially fibrous ones -- can exhibit a range of failure modes that is dependent on the components of the material (matrix and reinforcement) and on bonding. If the bond strength is higher than the strength of the matrix and reinforcement, the fracture will propagate through the latter. If the bonding is weak, one has debonding and fiber pullout. In compression, composites can fail by a kinking mechanism, also shown in the figure; the fibers break, and the entire structure rotates along a band, resulting in a shortening of the composite. This mechanism is known as *plastic microbuckling*.

Fracture in Metals

Crack nucleation mechanisms vary according to the type of material: brittle, semibrittle, or ductile. The brittleness of a material has to do with the behavior of dislocations in the region of crack nucleation. In highly brittle materials the dislocations are practically immobile, in semibrittle materials dislocations are mobile, but only on a restricted number of slip planes, and in ductile materials there are no restrictions on the movement of dislocations other than those inherent in the crystalline structure of the material.

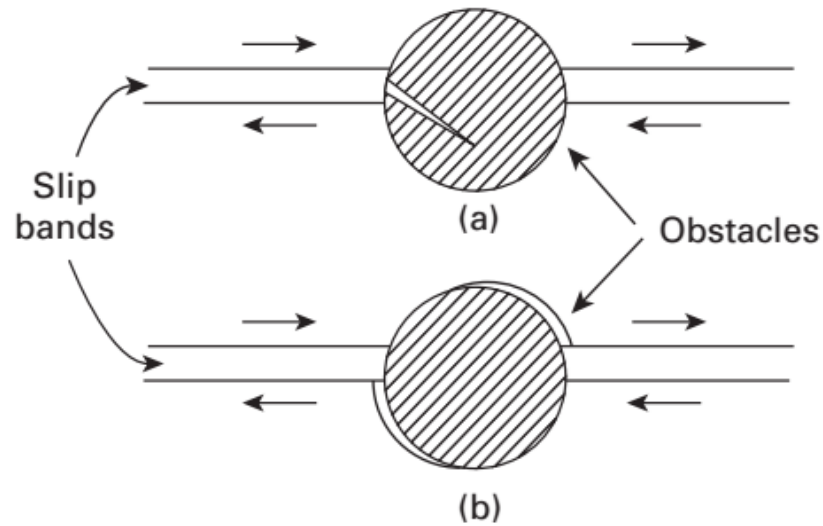


Materials of Various Degrees of Brittleness

Type	Principal Factors	Materials
Brittle	Bond rupture	Structures of type diamond, ZnS, silicates, alumina, mica, boron, carbides, and nitrides
Semibrittle	Bond rupture, dislocation mobility	Structures of type NaCl, ionic crystals, hexagonal close-packed metals, majority of body-centered cubic metals, glassy polymers
Ductile	Dislocation mobility	Face-centered cubic metals, some body-centered cubic metals, semicrystalline polymers

Fracture in Metals

Nucleation of a cavity at a second-phase particle in a ductile material. (Adapted with permission from B. R. Lawn and T. R. Wilshaw, *Fracture of Brittle Solids* (Cambridge: Cambridge University Press, 1975), p. 40.)



If the second-phase particles are brittle and the matrix is ductile, the former will not be able to accommodate the large plastic strains of the matrix, and consequently, these brittle particles will break in the very beginning of plastic deformation. In case the particle/matrix interface is very weak, interfacial separation will occur. In both cases, microcavities are nucleated at these. Generally, the voids nucleate after a few percent of plastic deformation, while the final separation may occur around 25%.

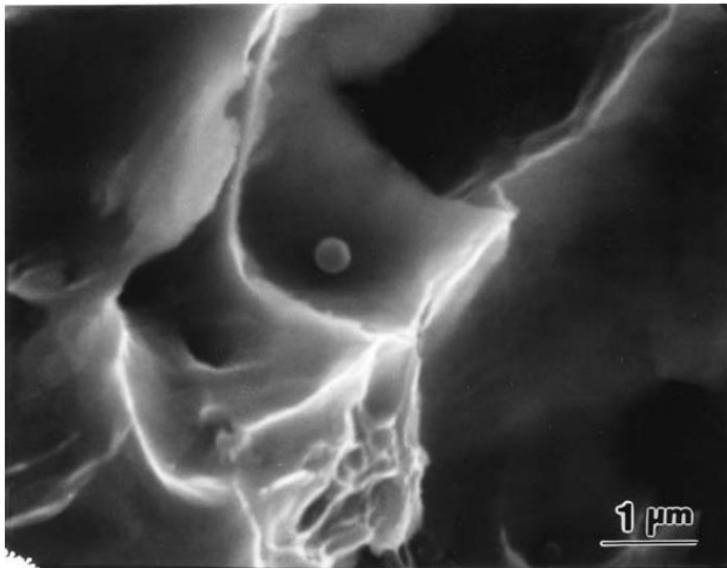
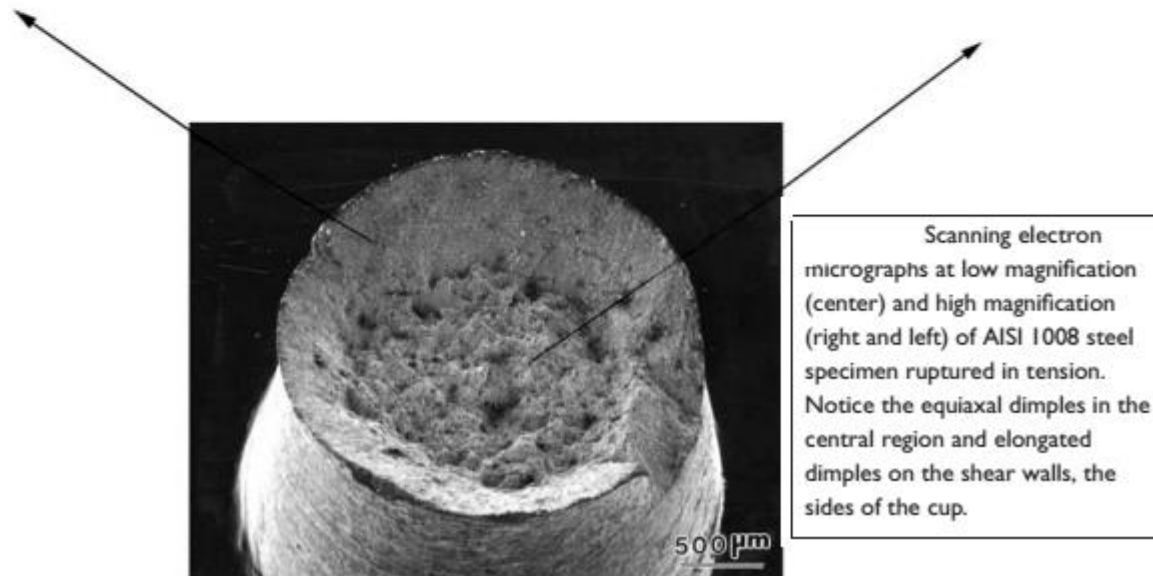
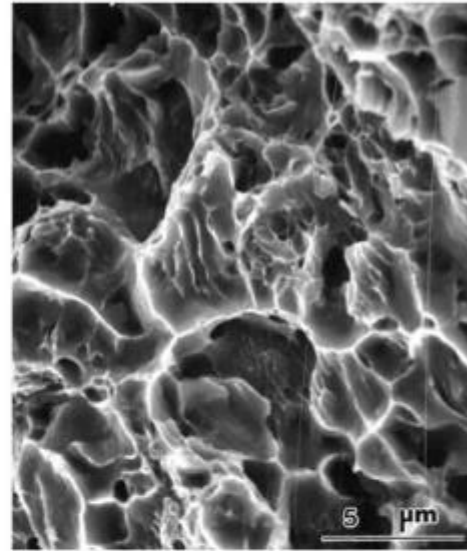
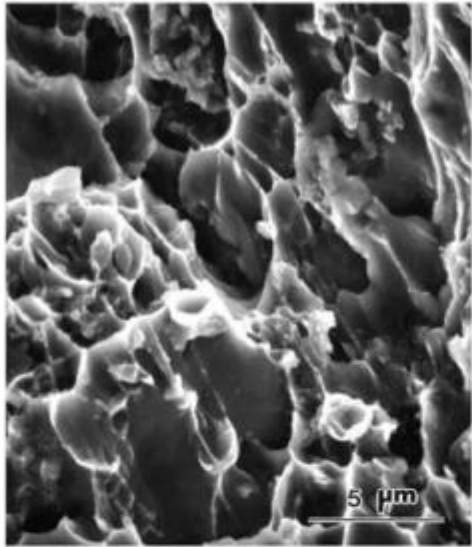


Fig. 8.12 Scanning electron micrograph of dimple fracture resulting from the nucleation, growth, and coalescence of microcavities. The micrograph shows an inclusion, which served as the microcavity nucleation site.

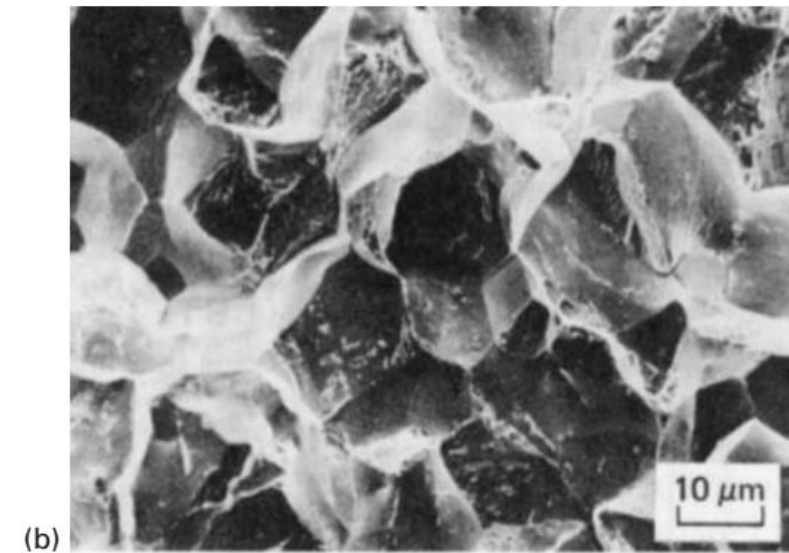
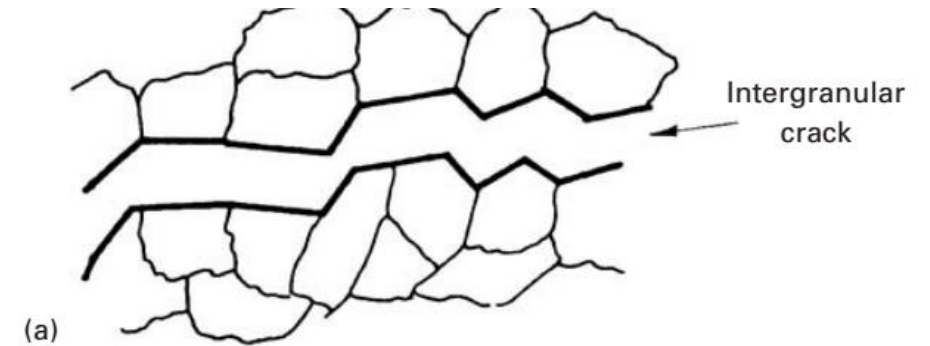
Fracture in Metals



Voids nucleate and grow in the interior of the specimen when the overall plastic strain reaches a critical level. The voids grow until they coalesce. Initially equiaxial, their shape changes in accordance with the overall stress field. As the voids coalesce, they expand into adjoining areas, due to the stress concentration effect. When the center of the specimen is essentially separated, this failure will grow toward the outside. Since the elastic--plastic constraints change, the plane of maximum shear (approximately 45° to the tensile axis) is favored, and further growth will take place along these planes, which form the sides of the cup.

Fracture in Metals

The most brittle form of fracture is cleavage fracture. The tendency for a cleavage fracture increases with an increase in the strain rate or a decrease in the test temperature of a material. Cleavage occurs by direct separation along specific crystallographic planes by means of a simple rupturing of atomic bonds. Iron, for example, undergoes cleavage along its cubic planes (100). This gives the characteristic flat surface appearance within a grain on the fracture surface. There is evidence that some kind of plastic yielding and dislocation interaction is responsible for cleavage fracture. Earlier, we mentioned that cleavage occurs along specific crystallographic planes. As in a polycrystalline material, the adjacent grains have different orientations; the cleavage crack changes direction at the grain boundary in order to continue along the given crystallographic planes. The cleavage facets seen through the grains have a high reflectivity, which gives the fracture surface a shiny appearance. Sometimes the cleavage fracture surface shows some small irregularities -- for example, the river markings. What happens is that, within a grain, cracks may grow simultaneously on two parallel crystallographic planes. The two parallel cracks can then join together, by secondary cleavage or by shear, to form a step.

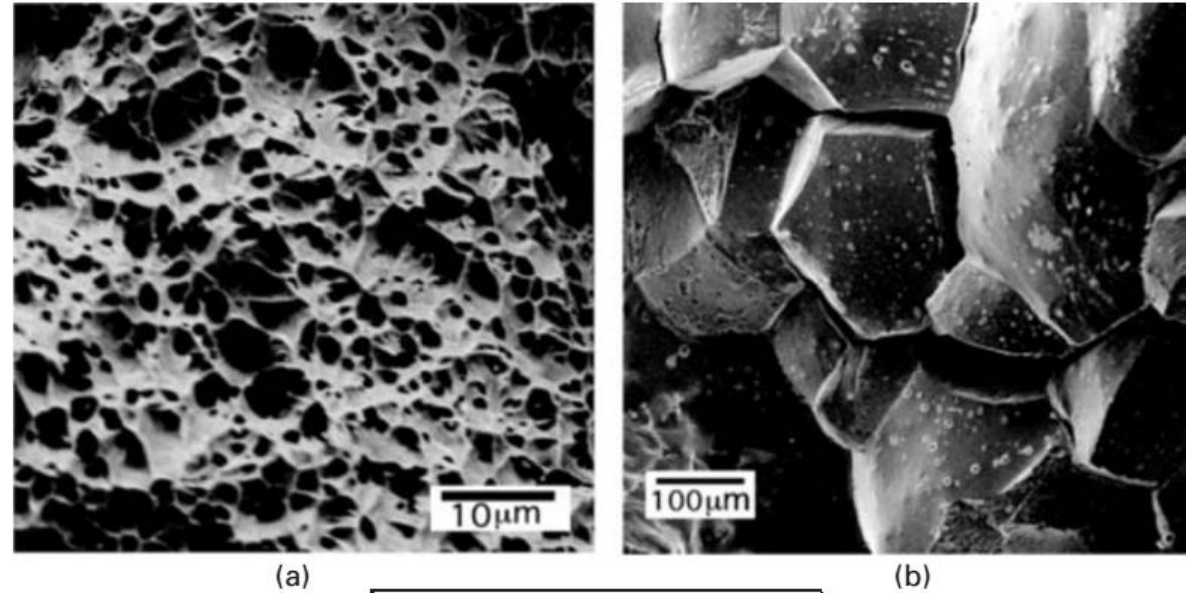


(a) An intergranular fracture (schematic). (b) Intergranular fracture in steel (scanning electron micrograph).

Fracture in Metals

Under normal circumstances, face-centered cubic (FCC) metals do not show cleavage. In these metals, a large amount of plastic deformation will occur before the stress necessary for cleavage is reached. Cleavage is common in body-centered cubic (BCC) and hexagonal close-packed (HCP) structures, particularly in iron and low carbon steels (BCC). Tungsten, molybdenum, and chromium (all BCC) and zinc, beryllium, and magnesium (all HCP) are other examples of metals that commonly show cleavage.

The grain boundary and segregation of undesirable elements to the boundary play a role in many brittle fractures. Minute amounts of additions can completely change the fracture mechanism and morphology. The impurities often segregate to the grain boundaries, changing their strength. A few parts per million (ppm) of impurities are sufficient to decrease the grain boundary cohesion. Figure-a shows a ductile fracture in copper, characterized by dimples and void nucleation and growth. Figure-b shows a fracture surface in copper to which 20 ppm Bi was added. The two morphologies are completely different.

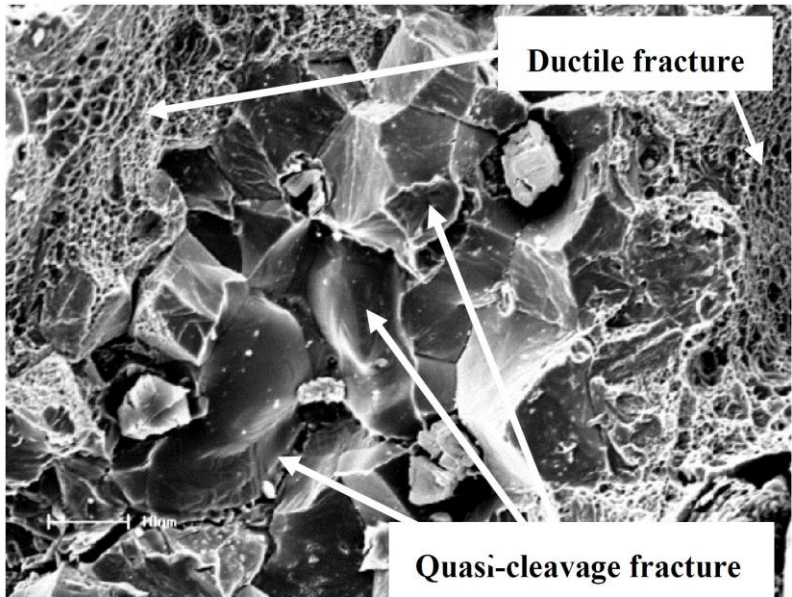


SEM images of the fracture surface of (a) pure Cu and (b) Cu doped with 20 ppm Bi. (From D. B. Williams, M. Watanabe, C. Li, and V. J. Keast, in *Nano and Microstructural Design of Advanced Materials*, (Elsevier, Oxford, 2003).)

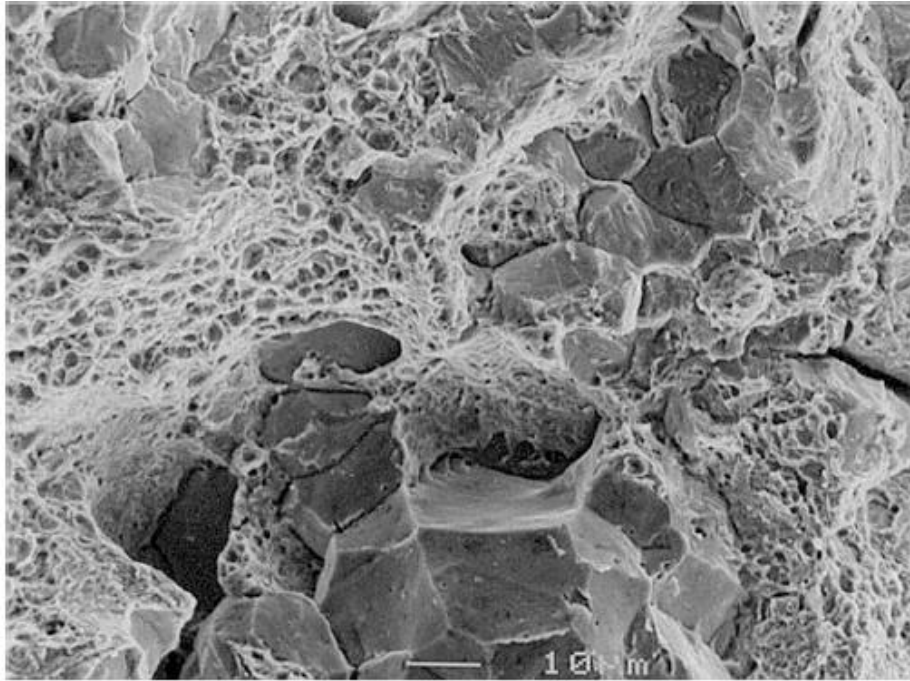
The role of fractography in Failure analysis



- Delta river patterns upon crossing grain and subgrain boundaries in the cleavage fracture. Cleavage plane in the previous grain can be seen in the Fig. As it crosses the grain boundary the little plane facet can be distinguished in the picture. Why is that so ? Because the orientation is different from one crystal to the other then the different cleavage planes are activated in the second crystal. The crack goes between different crystals which are parallel to each other. Each of the shear steps absorbs the energy then delta reduces itself to main direction.
- Quasi-cleavage fracture is more complex which takes place in crystals such as martensite (as-quenched alloy steel). The process is more complex. Why is that so? In the cleavage facets there are small holes that come from the cohesion of the metal matrix from the small nonmetallic particles. The surface isn't straight and so absorbs more energy and increases fracture toughness.



Ductile-Brittle Combined Fractures



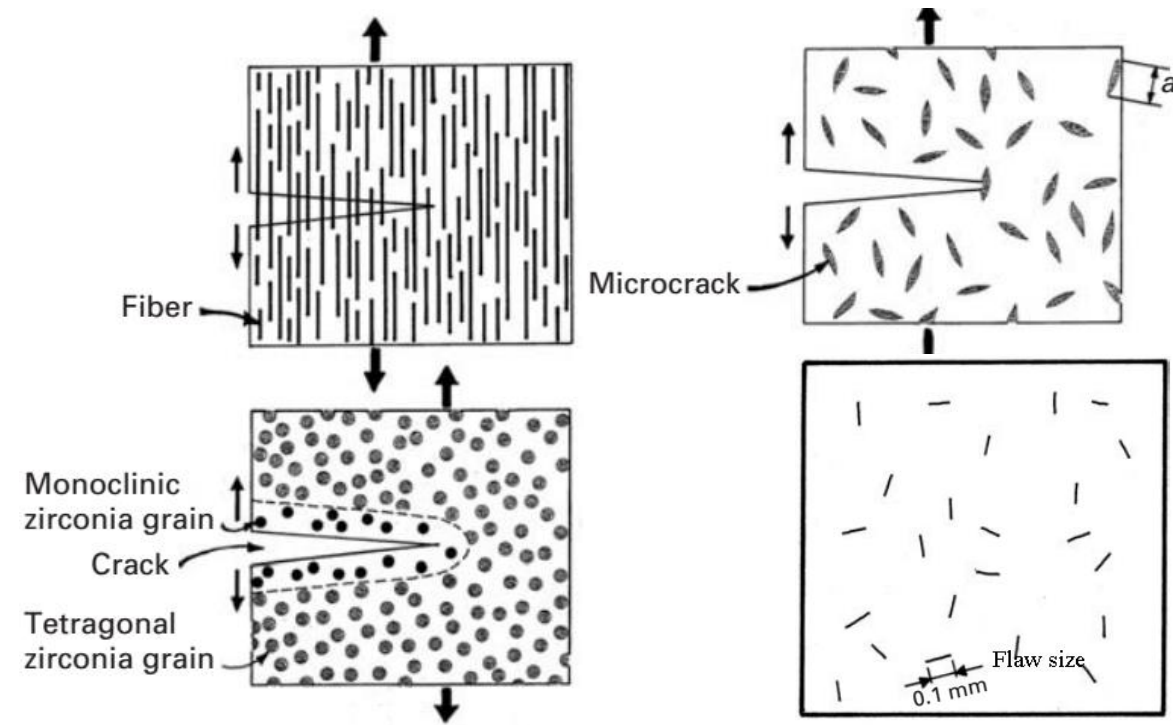
Combination of fracture mechanisms at the microscopic scale: ductile fracture by micro-voids, combined with brittle fracture cleavage and intergranular fracture

Due to microstructure variations, changes in mechanical properties and different states of stress, among other factors, at the local level in engineering materials, it is common to find combinations of brittle and ductile fractures at the microscopic scale in the same fractured surface, as shown in the example in Fig. The fractographer must be careful when drawing conclusions about determining the main cause of fracture when this combination occurs, since the criterion that the most abundant type of fracture indicates the main fracture mechanism may not necessarily be correct. This may be the case when, for example, if a mixture of cleavage facets and dimples are observed on the fractured surface, with a majority of ductile fracture dimples, it may not be said that the mechanism that initiated the failures was a ductile one, because fractures most likely initiate at the brittle phases, so the cause of failure is brittle fracture.

Fracture in Ceramics

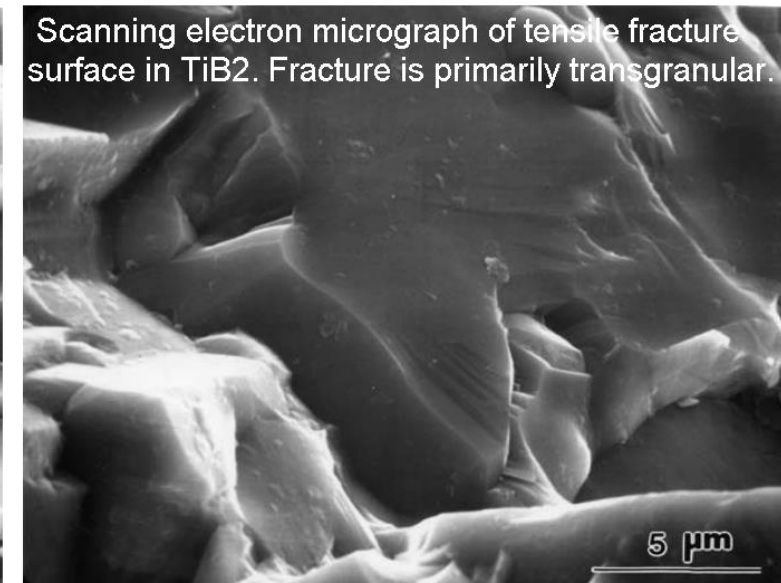
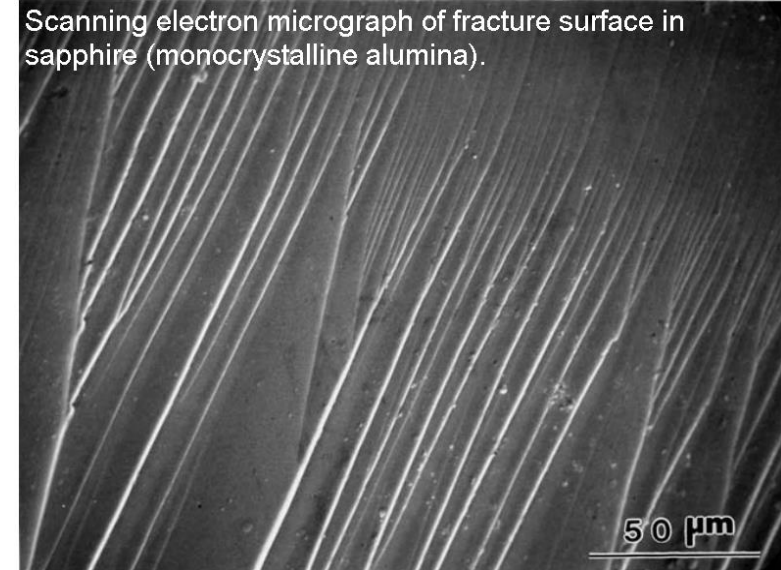
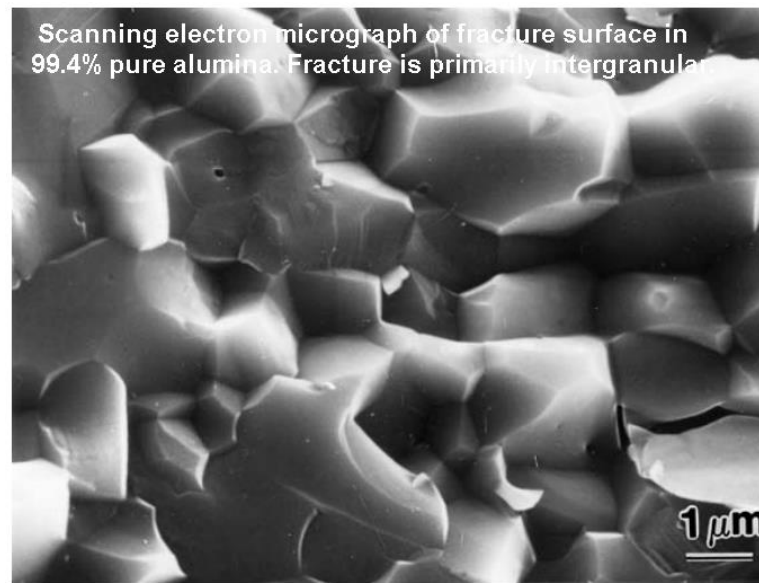
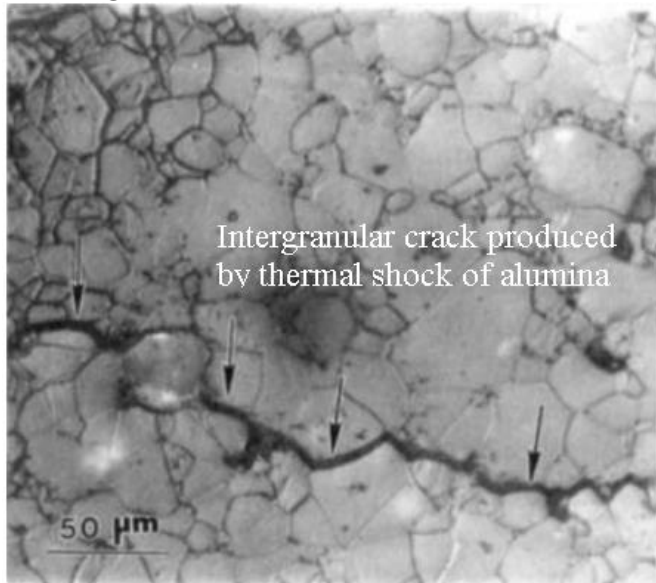
Ceramics are characterized by high strength and very low ductility. Among the approaches developed to enhance the ductility (and, consequently, the fracture toughness) of ceramics are:

1. The addition of fibers to the ceramic to form a composite, making crack propagation more difficult because of crack bridging, crack deflection, fiber pullout, etc.
2. The addition of a second phase that transforms at the crack tip with a shear and dilational component, thus reducing the stress concentration at the tip of the crack.
3. The production of microcracks ahead of the crack, causing crack branching and distributing the strain energy over a larger area.
4. Careful processing in such a manner that all flaws of a size greater than the grain size are eliminated.



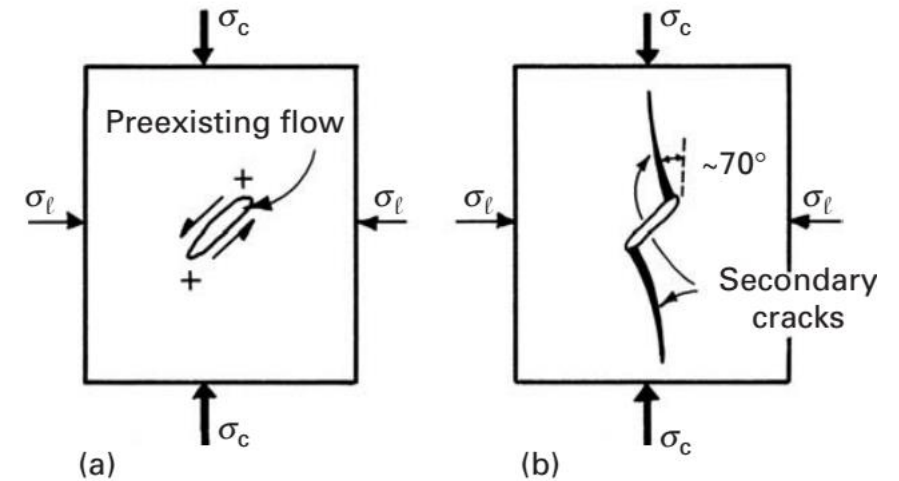
Fracture in Ceramics

The surface morphology of fractures in ceramics tends to present some markedly different features from those appearing in metals. Usually, failure begins at a flaw and propagates slowly. As it accelerates, its energy release rate increases, and there is a tendency for branching. When crack branching (bifurcation) starts, the fracture surface becomes increasingly irregular, because, on separation, different fracture planes become interconnected. In ceramics, the flaws are extremely important, and their concentration and size determine the strength of the ceramic.



Fracture in Ceramics under Compression

Several mechanisms have been proposed, and they all involve the formation of localized regions of tension in the material, caused by the interaction of the externally applied compressive stresses with microstructural defects. Griffith was the first to propose a mechanism for the compressive fracture of brittle materials. The mechanism is based on a pre-existing crack of length $2a$ oriented at an angle ψ to the highest compressive stress (σ_c). This compressive stress will cause a shear stress acting on the opposite faces of the pre-existing flaw. Thus, sliding of the two surfaces will take place. At the ends of the flaw, this sliding is prevented. This will lead to a localized tensile stress ahead of the flaw that will, eventually, nucleate two cracks. Initially, the cracks will grow at an angle of 70° to the face of the flaw and will then align themselves with the direction of the maximum compressive stress.



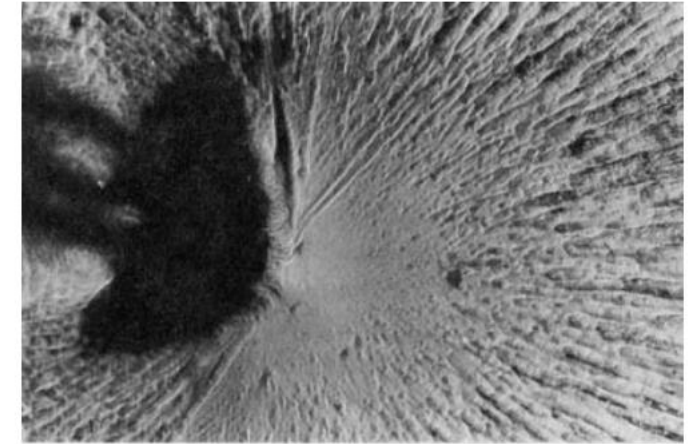
Fracture in Polymers

Many polymers fracture in a brittle manner below their glass transition temperature. This is particularly true of polymers having large, bulky side groups or a high density of cross-links. Under either of these circumstances, the molecular chain structure of the polymer becomes so rigid, that chain disentanglement and/or slipping becomes very difficult. Examples of such polymers are thermosets, such as epoxy, polyester, and polystyrene. The stress—strain curve of these polymers is quite linear to fracture, and the strain to failure is typically less than 1%.

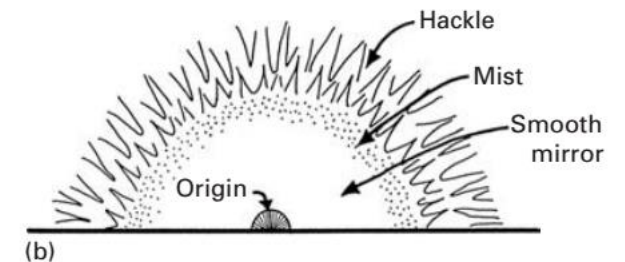
There are three regions:

1. A mirrorlike, or specular, region adjoining the crack nucleation site, indicating slow crack growth.
2. A coarse and flat region indicative of fast crack growth; sometimes this region is called the region of *hackle*, and one can see that the crack has propagated on different levels over small areas. When hackle is elongated in the direction of crack propagation, the pattern is called “river markings.”
3. A transitional region between the preceding two that has a *misty* appearance and no resolvable features.

(a) Brittle fracture in a highly cross-linked thermoset (polyester). (b) The three different regions that compose the brittle fracture surface in (a).



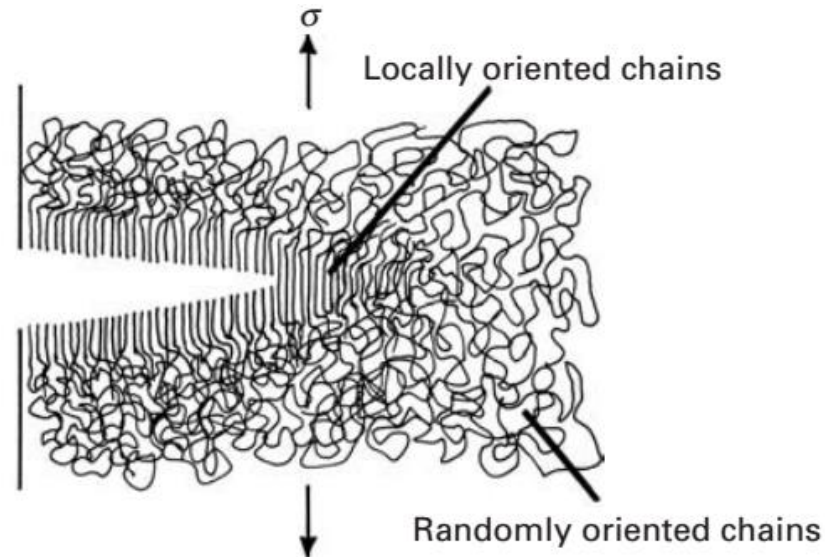
(a)



(b)

Fracture in Polymers

Frequently, the phenomena of crazing and shear yielding precede actual fracture in a polymer. Both these phenomena involve a localization of the plastic deformation in the material. The major difference between the two is that crazing occurs with an increase in volume, whereas shear yielding occurs at constant volume. In glassy polymers, one can regard crazing and shear yielding as competing processes. In brittle glassy polymers, such as polymethyl methacrylate (PMMA) or polystyrene (PS), crazing precedes the final brittle fracture. In comparatively more ductile polymers (for example, polycarbonate or oriented polyethylene), which have flexible mainchain linkages, shear yielding is the dominant mode of deformation, and the final fracture is ductile.



A series of crazes produced in a tensile specimen of polycarbonate. (Used with permission from R. P. Kambour, *Polymer*, 4 (1963) 143.)

