2A_Small Scale Fracture

Overview

Nanoscience is needed to understand why small scale objects, for example optical fibers of a small diameter and thin films are much "stronger" than engineering scale entities (like a bicycle frame).

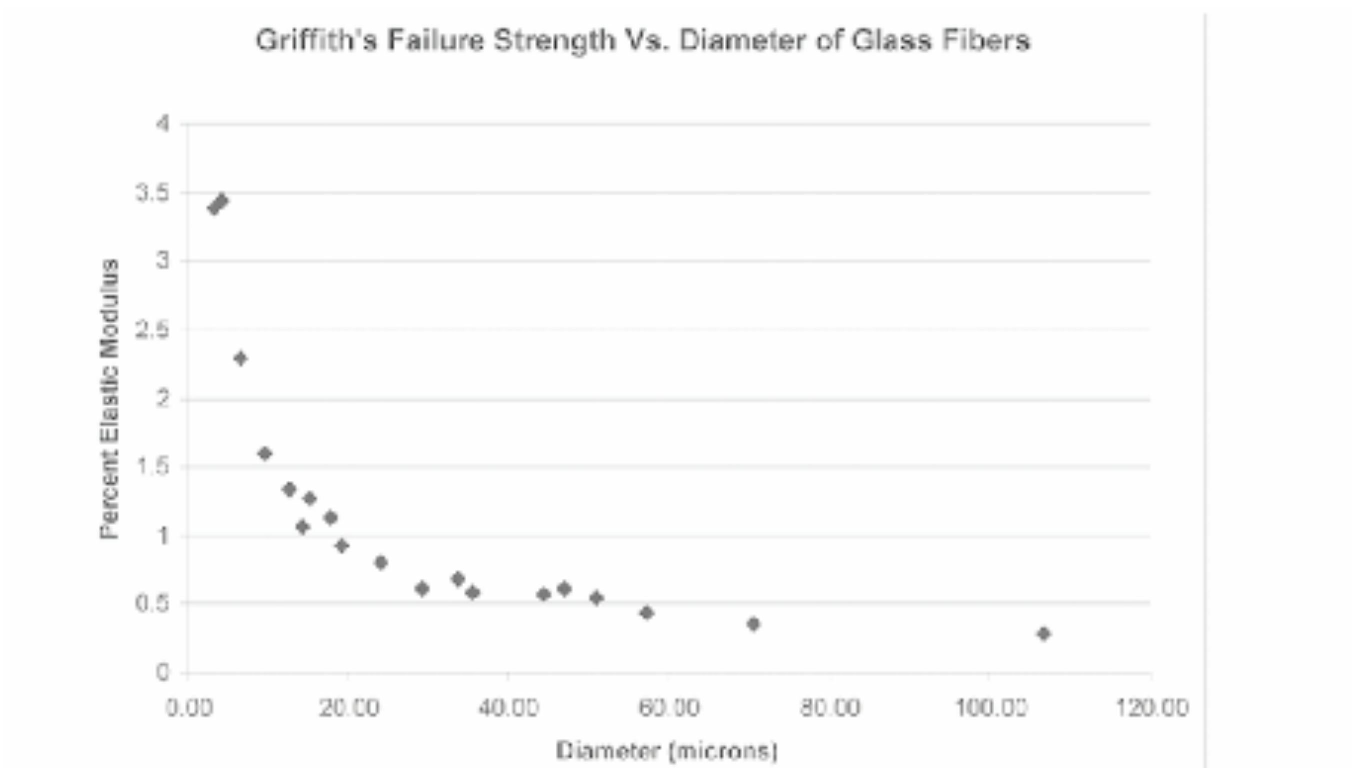
•Influence of "size" on "fracture"

•We need a method for normalizing the engineering strength with "ideal" strength

Glasses and Ceramics

Tensile fracture in silica fibers as a function of the fiber diameter

In glass fibers the fracture strength rises non-linearly with size. At a diameter of 1μm, the strength rises far above the nominal value.



Note in the above figure that the tensile strength is plotted *as a percent of the tensile modulus* (the Young Modulus).

Example, silica fibers:

$E_{silicsa}$=80 GPa

Strength at 1μm is 4 GPa, about 5% of the elastic modulus, which is huge, since the typical fracture strength is only 250 MPa.

The length scale of 1μm is a good number to keep in mind for engineering design requiring high strength.

Fracture in thin films of glass

The method

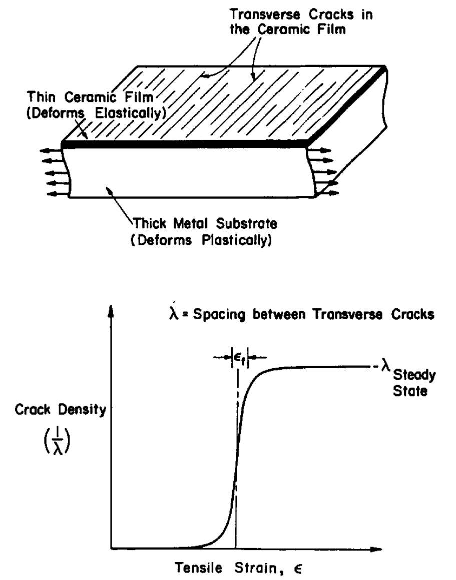


Fig. 1. Illustration of the experimental technique (top). A schematic of the increase in crack density in the silica film with the strain applied to the copper substrate (bottom).

As shown on the right a thin film of silica glass (a brittle material) is deposited on a ductile metal (copper). When the copper substrate is pulled in tension it deforms "plastically" that is in a ductile fashion. However, the silica film, being brittle can deform only elastically. When the fracture strength is reached the film begins to fracture creating many cracks. Thus the fracture strength can be measured in the form of an elastic strain such that

$$\sigma_F = \varepsilon_F E$$

The equation related the fracture stress to the strain at fracture multiplied by E, the elastic modulus of the glass (similar to the measurement of fracture in glass fibers).

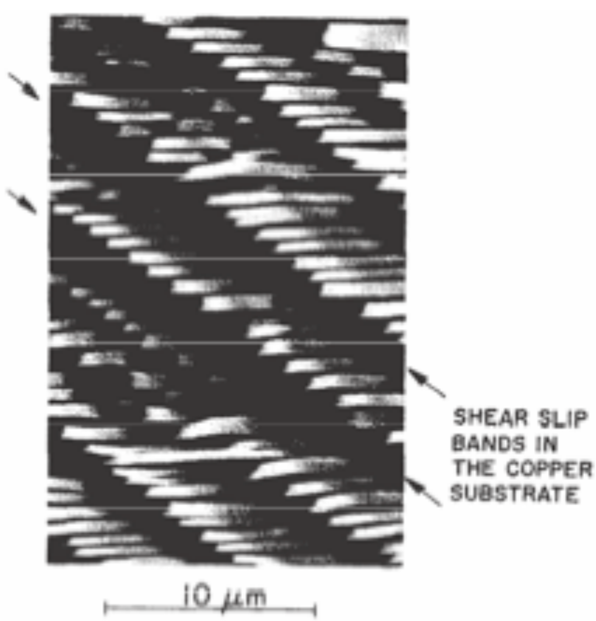


Fig. 3. The shear slip bands in the copper appear as relief in the silica film. However, the crack spacing is not influenced by the orientation and the localization of the slip bands. ε = 25%.

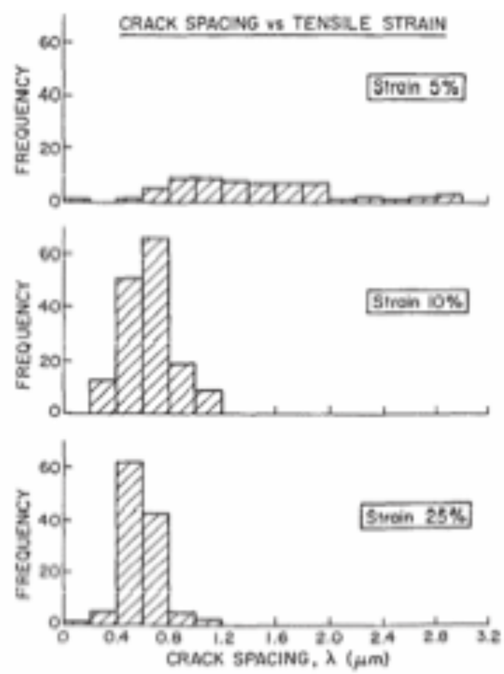


Fig. 4. The distribution of crack spacing, λ, obtained at applied tensile strain of 5, 10 and 25%.

When the ductile substrate is pulled, a tensile stress it exerted on the film which can deform only elastically. Beyond the certain strain the film develops cracks. In the figure just above the onset of cracks is measured as the frequency of cracks (which is inversely related to the spacing between them). The histogram shows that only a few cracks form at an elastic strain of 5%, and many more at 10%, which then reach a maximum density at 25% elastic strain.

These thin films were < 100 nm thick. Therefore, they had very high strength.

The Rationale (for high strength in small dimensions in brittle materials)

(i) The fracture strength is determined by the presence of defects on the surface, like a scratch. Stress concentrations produced by flaws can cause the fracture strength to degrade.

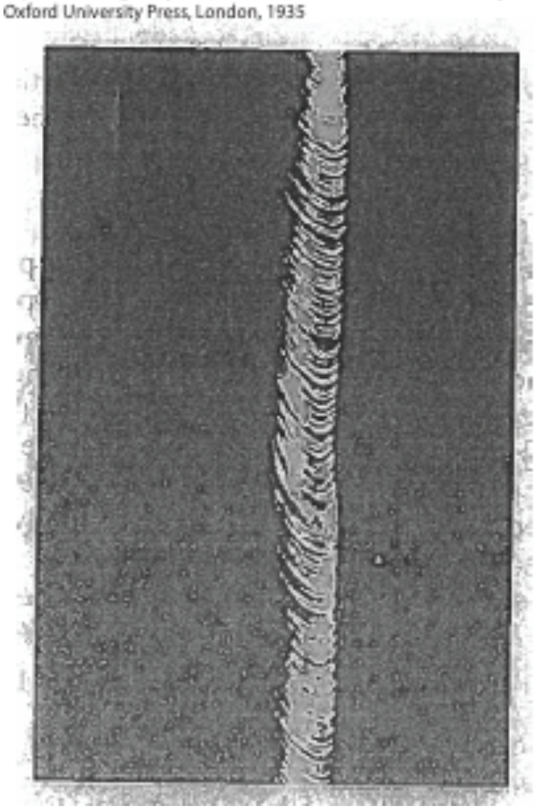
(ii) The fracture strength therefore is expected to depend on the "flaw size". A larger flaw can produce a more severe stress concentration causing failure at a lower value of the applied stress.

(iii) Knowledge of the relationship between the fracture strength and the flaw size can help us understand the why smaller fibers have a higher fracture strength.

Metals

Metals are ductile when pulled in tension. Fundamental information about the deformation mechanism can be obtained from experiments with single crystals. A picture of a Zn single crystal deformed in tension is shown just below.

Slip in Zinc Single Crystal (C. F. Elam, the Distortion of Metal Crystals, Oxford University Press, London, 1935

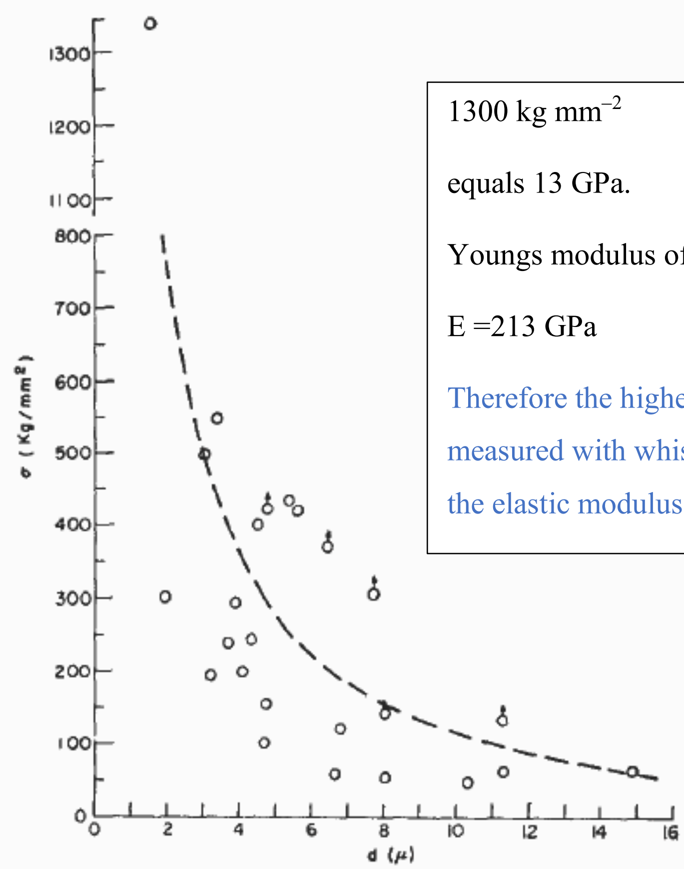


Note that crystal becomes longer by sliding on specific crystallographic planes, all parallel to one another, like a pack of cards. The spacing between these planes can be measured. It is in the range of 1 to 10 μm. One can therefore, draw an inference that the length scale of the defects within the crystal that can lead to sliding, or slip as it is called, is of the order of about 1 μm.

It can be further imagined that if the specimens had a diameter of less than about 1 μm then they would be unable to deform plastically, and would fracture without significant plastic deformation, as was confirmed in experiments described below.

Tensile strength thin fibers of single crystals of metals, called whiskers

The tensile strength of single crystals whiskers of iron of various diameters measured by Brenner in 1956, is shown below,



1300 kg mm^{-2}

equals 13 GPa.

Youngs modulus of iron

E =213 GPa

Therefore the highest tensile strength measured with whiskers was about 6.5% of the elastic modulus

FIG. 6. The effect of size on the strength of iron whiskers. ♂ fracture occurred at or near grips. True fracture stress may have been higher.

Summary

Both brittle and ductile materials (glasses and ceramics versus metals) show a dramatic rise in strength at length scales near 1 μm. That both classes show the transition at a similar length scale is fortuitous since the origin of weakness is quite different: it is a physical flaw in brittle materials, and a defect within the crystal structure in metals.