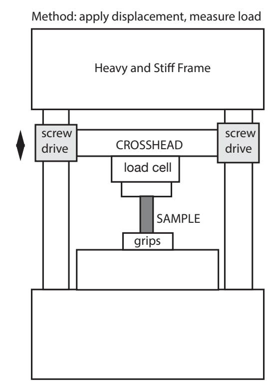
02A_Plasticity: An Introduction

Topics:

1. Phenomenology (shear, Poisson's Ratio and Tensile Yield Strength)
2. Characterization of the length scale of plastic flow
3. Plastic deformation in a single crystal
4. Plastic flow in a polycrystal (The Hall Petch Equation)

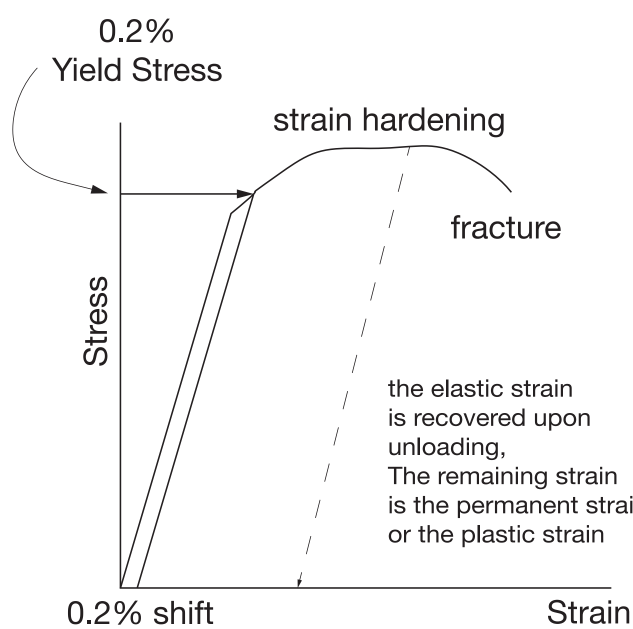
1. The stress-strain curve



The Instron

Notes:

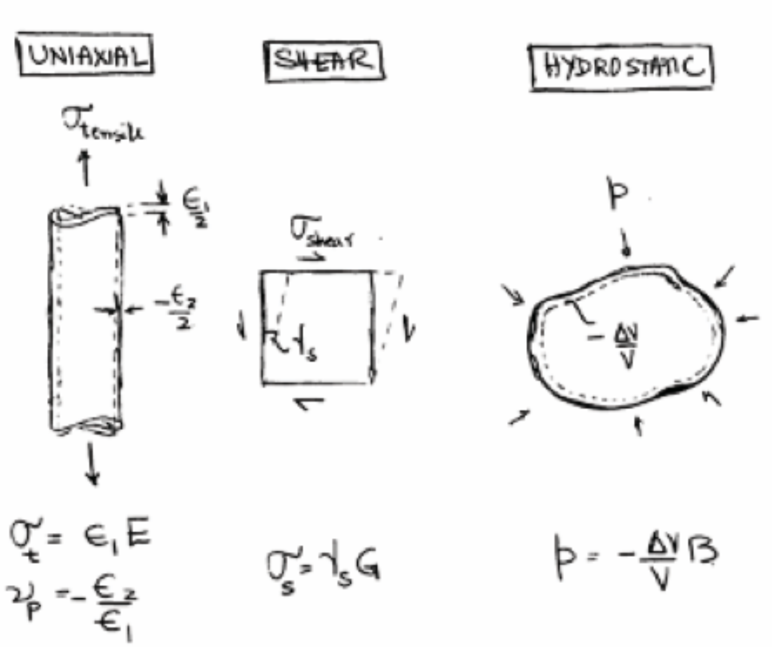
1. The Instron machine, in the ideal case, would have infinite stiffness (a big machine for a tiny specimen so that all of strain, and the elastic strain energy) is concentrated in the sample.
2. The early stress-strain curve is linear AND reversible.
3. Beyond a certain limit the curve bends over at the onset of plastic deformation.
4. As the plastic deformation continues the yield stress continues to increase: a phenomenon known as strain hardening.
5. The yield stress goes past a maximum and then the specimen (goes off the cliff) and fractures.
6. The maximum in the stress occurs when plastic flow begins to localize in a small section of the length of the sample (called "necking").
7. 0.2% yield stress: the transition from elastic to plastic deformation is often washed out. A consistent way to characterize the engineering value of the yield stress is as shown.



8. Recall that in most practical situations (excluding situations where the samples are very small - about one micrometer) the highest elastic strain that can be applied is of the order of 1%.
9. Here we have defined: (i) the yield stress, (ii) the rate of strain hardening - strain hardening coefficient, (iii) the ultimate stress - the maximum in the stress-strain curve, and (iv) unloading always follows the slope of the elastic modulus.

2. Plastic flow is a shear phenomenon (constant volume)

Plastic deformation is necessarily a constant volume deformation phenomenon. Constant volume means plastic deformation occurs in pure shear (since a hydrostatic component will produce a change in volume).



The question is how do we characterize constant volume deformation in a uniaxial tensile test. Recall that the volume change is given by the sum of the three principal strains:

$$\frac{\Delta V}{V} = \varepsilon_1 + \varepsilon_2 + \varepsilon_3 = \varepsilon_1 + 2\varepsilon_2 \text{ , since } \varepsilon_2 = \varepsilon_3 .$$

By definition, $\nu = -\frac{\varepsilon_2}{\varepsilon_1}$

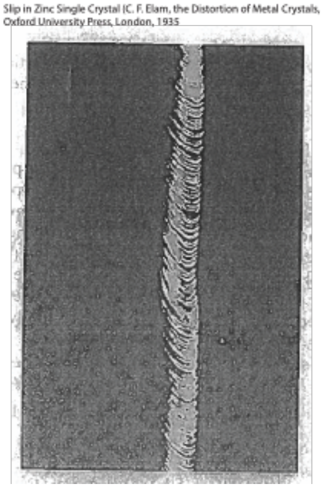
$$\frac{\Delta V}{V} = \varepsilon_1 + 2\varepsilon_2 = \varepsilon_1 - 2\nu\varepsilon_1 = \varepsilon_1(1-2\nu)$$

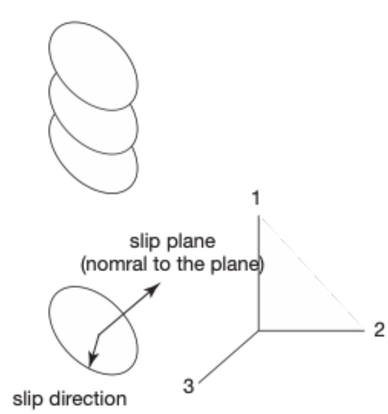
Therefore for plastic deformation where the volume change is zero, $\nu = 0.5$.

3. Plastic flow in a single crystal

Single crystal of zinc pulled in uniaxial tension:

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





Notes:

1. Relative sliding at the crystal planes leads to plastic deformation. There is a specific geometrical relationship between the crystal planes that slide and the uniaxial pulling direction. The tensile yield stress therefore depends on the orientation of the crystal. The "apparent" yield stress will be the lowest when the "slipping" crystal planes are aligned for maximum shear stress, that is at 45° with respect to the tensile axis.

2. There is apparently a distance between the "slip planes", this number is typically between 1 μm and 10 μm. This length scale means that yield stress depends on specimen size. If the specimen is "microscale" then it may not yield at all! That is why thin films in microelectronics are so "strong" because they are smaller than the characteristic spacing between slip planes.

3. In addition to a specific slip plane the sliding occurs also within the plane in a specific direction, called the slip direction.

4. The combination of slip plane and the slip directions, both of which are characteristic of the crystal structure, is called a "slip system".

5. The slip system consists of a specific crystallographic plane and a specific slip direction, which necessarily lies in the slip plane (therefore the slip direction and the slip plane, which is described by a vector that is normal to the plane, are orthogonal to each other (that is the dot-product of these two vectors is equal to zero)

   Mr. Brenner (in the 1960s) measured the tensile yield of "whiskers" (are wire like single crystals)

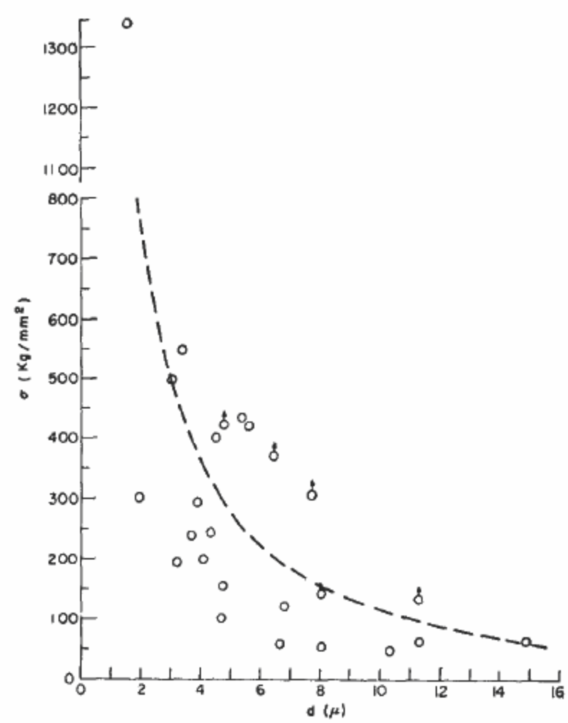
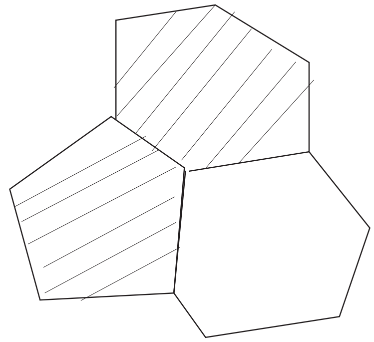


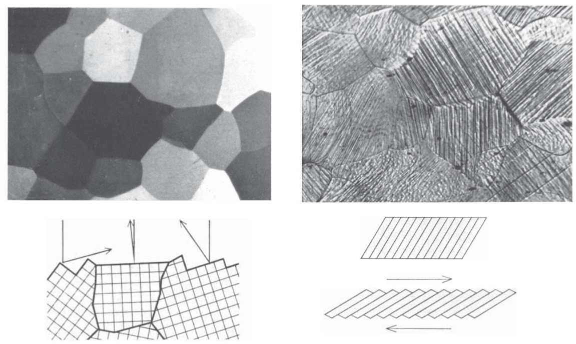
FIG. 6. The effect of size on the strength of iron whiskers. ♂ fracture occurred at or near grips. True fracture stress may have been higher.

The question is what is then the upper bound for the yield stress of a "perfect" whisker without active slip planes?

4. How do polycrystals deform?

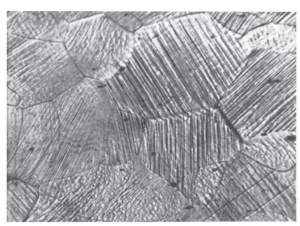
A polycrystal is a fully packed aggregate of small crystals. The crystallites are described as "grains" and their typical length scale is called the grain size. The grain size is a key parameter in relating the mechanical properties of the polycrystal to the microstructure. For example consider the following schematics:





Note that the different orientations of the slip planes in adjacent grains in a polycrystal hamper the overall plastic deformation in the polycrystal.

The barrier for the slip to transmit from one grain into the adjacent grain is overcome by the stress concentration that slid produces at the grain boundary. The larger the grain size, the stronger is this stress concentration, and therefore the lower is the overall yield stress of the polycrystal. Thus, there is "some kind" of an inverse relationship between the yield stress of the polycrystal and the grain size. This relationship is given by the Hall-Petch equation.



$$\sigma_{Yield} = \sigma_o + \frac{k_{HP}}{d^{1/2}}$$

Hall-Petch Equation
for grain size dependence of the yeild stress