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Compressive stress-strain measurements in the pre-macroyield region have been made on 99.999 percent pure copper single crystals purchased from Research Crystals, Inc. The test specimens were cylinders that measured approximately 0.375 in. in diameter by 0.750 in. high and were oriented so that the end faces were (100) planes. Testing was done in a special high sensitivity apparatus that will be described in detail in a future publication. An initial stress bias of 0.45 g/mm^2 was a necessary condition in the testing procedure. Specimens were compressed at a constant strain rate of 4.5×10^{-5} sec^{-1}. Applied load versus specimen deflection was plotted directly with an X-Y recorder, and since only specimen deflections were measured, no corrections were required in computing specimen strain.

A representative set of cyclic loading-unloading curves for a single specimen are shown in Fig. 1. The number at the top of each curve denotes the loading-unloading cycle. Several modulus values are shown at various stress levels. These were calculated from the tangents to the curves shown by the dashed lines. The following specific features are apparent in Fig. 1: (1) both the loading and unloading curves are nonlinear with a concave upward curvature, (2) the first few cycles show open hysteresis loops (residual strain), (3) after a number of cycles to loads equal to or less than the maximum of the first cycle, closed loops result (cycle 10), (4) a change in slope occurs when the load exceeds the maximum of previous cycles (cycles 11 and 16), and (5) a nonuniform strain increment detectable at the instant of crosshead reversal in the first few cycles disappears with successive cycling.

In a study of the stress-strain behavior of several ionic single crystals, it was found that closed hysteresis loops could be made to open by subjecting the specimen to low amplitude mechanical oscillations.[1] The results of this study suggested the following experiment. The specimen used to produce the curves of Fig. 1 was placed upright on a PZT transducer, which measured 0.5 in. in diameter by 1.0 in. high, that was driven by a variable frequency oscillator whose output was set at 40 v rms. After the specimen was shaken for 25 min at various frequencies from 100 to 5000 cps, it was returned to the compression apparatus, and the loading-unloading cycles (cycles 20 to 32) were executed. These results are shown in Fig. 2, where it is readily seen that, for the first few cycles after shaking, open hysteresis loops and the "strain increment" at the instant of crosshead reversal reappear.

The strain increment can be explained as follows. The elastic energy stored in the loading system (machine plus load cell) coupled with still active slip processes in the specimen results in additional strain after the reversal of direction of the imposed strain. The effect decreases with succeeding cycles due to the exhaustion of the active slip processes. The shaking treatment regenerates this effect since it regenerates these slip processes.

The tangent modulus during cycle 1 (Fig. 1) varies from a value several orders of magnitude lower than the elastic value of 3.3×10^{12} dynes/cm^2 to a maximum value on the unloading curve of 1.89×10^{11} dynes/cm^2. After 19 cycles to a maximum resolved shear stress σ_R of 10.5 g/mm^2, the maximum tangent modulus is 2.13×10^{11} dynes/cm^2. This value is nearly a factor of 9 lower than the value of 1.79×10^{12} dynes/cm^2 reported by Rosenfield and Auerbach, who performed static tensile tests on high purity copper single crystals.[2] Cycle 32 in the sequence shown in Fig. 2 has a maximum tangent modulus of 3.2×10^{11} dynes/cm^2, which is a factor of 10 lower than the value calculated from elastic constants.[3]

In addition to the low moduli, the results reported here show that, for initial loading to a σ_R of 10.4 g/mm^2, total strain ϵ_T of 4.4×10^{-4} results, and after 19 cycles, a σ_R of 10.5 g/mm^2 produces an ϵ_T of 3.0×10^{-5}. These large strains at low stress levels and the low tangent moduli are taken to indicate that a dislocation mechanism is operative. This is quite reasonable when one considers that Young has measured the forward motion of dislocations in copper, by an etch pit technique, at stresses of 4 g/mm^2 and the back motion of dislocations at stresses as low as 2 g/mm^2.[4]

The general results reported here for copper are qualitatively identical to observations made on several ionic single crystals.[1] Furthermore, the effect of the low kilocycle shaking is qualitatively similar to the cyclic softening observed in some materials by other investigators.[5,6]

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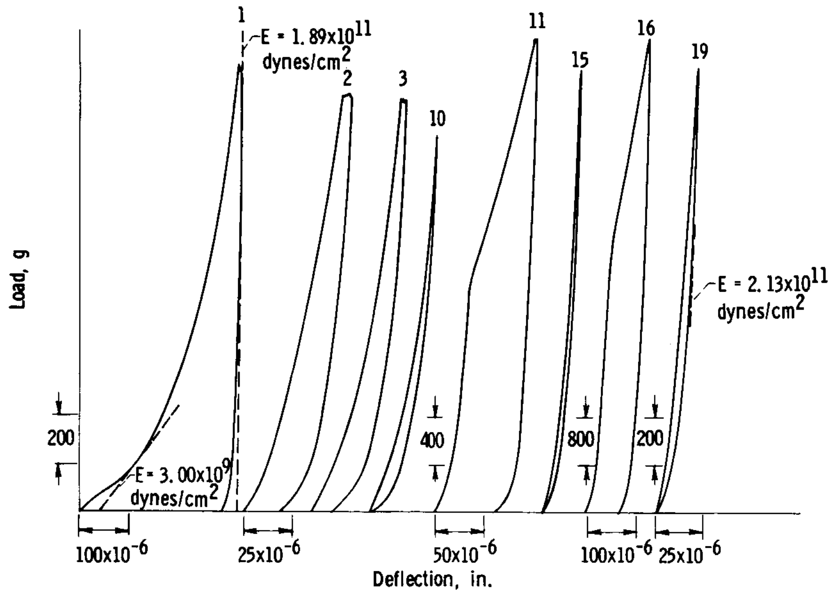

Fig. 1. - Cyclic loading-unloading curves for copper single crystal (no. 211641). Diameter, 0.3774 in.; length, 0.7496 in.; stress bias, 0.45 g/mm^2.

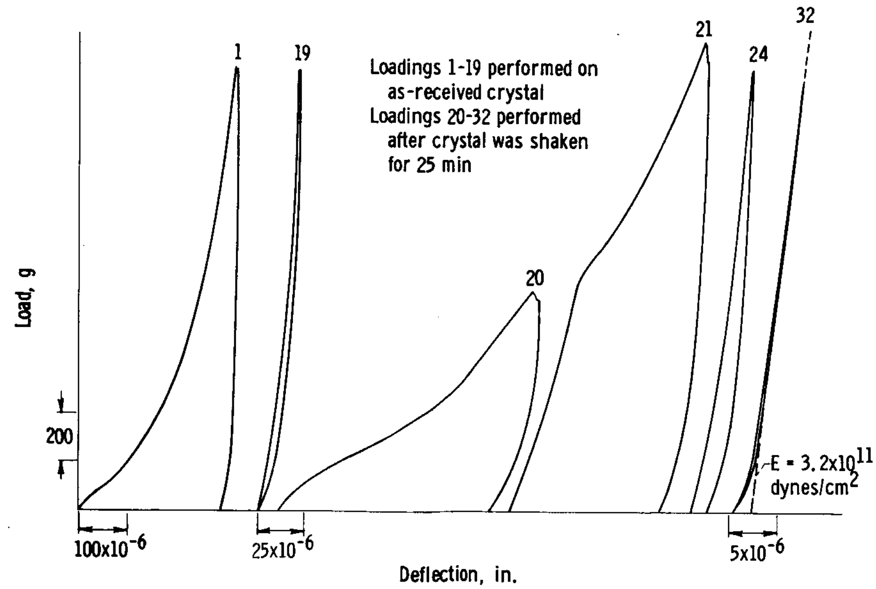

Fig. 2. - Cyclic loading-unloading curves for copper single crystal (no. 211641) after shaking for 25 min. Diameter, 0.3774 in.; length, 0.7496 in.; stress bias, 0.45 g/mm^2.