

# Hydrostatic Pressure-Induced Plastic Flow in Polycrystalline Metals

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*The effects of hydrostatic pressures to 26 kbars on the microstructure of polycrystalline Cd, Zn, Bi, Sn, Zr, Mg, Cu, and Fe were examined. Pressure-induced microscopic plastic flow in the form of boundary migration, slip, multiple slip, or twinning has been observed either singly or in combination in cadmium, zinc, bismuth, and tin. No deformation was observed in zirconium, magnesium, copper, and iron. The occurrence of such deformation, in terms of its intensity and initiation pressure, relates directly to the degree of anisotropy in the linear compressibility. Pressure cycling does not significantly affect the residual tensile properties of a zinc alloy which exhibits pressure-induced deformation similar to that of pure zinc.*

CLASSICAL elastic theory predicts that a superimposed hydrostatic pressure will not induce shear stresses in an ideal material. Thus, in the case of

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Manuscript submitted August 28, 1964. IMD

homogeneous and isotropic materials plastic flow will not occur as a result of pressure exposure, regardless of the magnitude of the pressure, unless some form of phase transformation or permanent density change takes place. However, real materials, such as metals, often vary considerably from the condition of homogeneity and isotropy. For this reason, Vu and Johannin<sup>1</sup> examined and observed hydrostatic pressure-induced microscopic deformation in polycrystalline cadmium and zinc, but not in aluminum, to pressures of 9 kbars and indicated that its occurrence is related to anisotropy in the linear compressibility. In addition, Davidson and Homan<sup>2</sup> have reported pressure-induced deformation in polycrystalline bismuth below the I-II transformation pressure. It becomes apparent then that under certain conditions hydrostatic pressure can induce localized internal shear stresses in some metals of sufficient magnitude to cause plastic flow.

In this work, eight pure single-phase metals of different lattice structures and degrees of elastic anisotropy were examined after pressure exposures of up to 26 kbars in order to establish the conditions under which such deformation occurs and the type of deformation as a function of pressure. The effects of pressure cycling on the mechanical proper-

ties of a metal in which pressure-induced deformation occurs are also examined.

## THEORY

Linear compressibility is defined as the relative change in length of a line per unit increase in hydrostatic pressure. The crystallographic relationships for the linear compressibility of cubic and noncubic structures are:

$$s_{11} + 2s_{12} \quad [1]$$

and

$$s_{11} + s_{12} + s_{13} - \gamma^2(s_{11} + s_{12} - s_{13} - s_{33}) \quad [2]$$

respectively, where the  $s$ 's are the elastic compliances and  $\gamma$  the direction cosine with respect to the "c" axis. In the case of the cubic metals, the relationship does not contain the  $\gamma$  term; thus the linear compressibility is independent of crystallographic direction and one has isotropy with respect to this property. As is evident from the latter relationship, depending upon how much the coefficient of  $\gamma$  differs from zero, noncubic crystals may exhibit high degrees of anisotropy in the linear compressibility.

Since there must be continuity of strain across the grain boundaries of a polycrystalline anisotropic material, exposure to hydrostatic pressure will result in shear stresses at the boundary due to the difference in orientation of adjacent grains. If the superimposed pressure were great enough and/or the grain boundary angle large enough so that the induced shear stresses exceed the critical value for some form of slip, twinning, or boundary migration, then one will observe plastic deformation. In the isotropic case, no discontinuity in the magnitude of the linear compressibility across grain boundaries exists; therefore, no shear stresses nor associated plastic flow will result from a superimposed pressure.

## MATERIALS AND PROCEDURE

The nine polycrystalline metals utilized in this investigation are listed in Table I.

The linear-compressibility ratio shown in Table I represents the ratio of the linear compressibility in the "c" crystallographic direction ( $k_c$ ) to that in the "a" direction ( $k_a$ ) and its deviation from unity is a measure of the degree of anisotropy in this property.

With the exception of zirconium which was in the crystal-bar form, all the above materials were in the hot-worked condition.

In addition to the above samples, single crystals of cadmium and zinc were utilized to detect the presence of any nonhydrostatic stresses during pressurization which would be evident from the deformation of these soft single crystals.

The specimens, approximately 1/8-in.-diam by 1/4-in.-long half cylinders, were metallographically prepared prior to pressurization. The pressure

treatments consisted of half-hour exposures to hydrostatic pressures at various pressure levels for each material, as shown in Table II. Since the pressure-transmitting medium was a 1:1 pentane-isopentane mixture which remained fluid at high pressures, the prepared surface could be directly examined after pressurization without further polishing. However, a very light repolishing and etching was used when questions existed as to whether the deformation observed at the grain boundaries was due to boundary migration.

The pressure system utilized in the work has been previously described.<sup>2</sup>

In order to determine the residual effects on the mechanical properties resulting from the pressure cycling of an anisotropic polycrystalline metal, six zinc-alloy tensile specimens were pressurized to 20 kbars and, along with an equal number of as-received specimens, were subsequently tested in an Instron testing machine at a strain rate of 0.05 in. per min. The zinc alloy was selected on the basis of its being a single-phase alloy having a high degree of elastic anisotropy and a recrystallization temperature above room temperature.

## RESULTS AND DISCUSSION

The results of pressure cycling of the eight pure metals, including additional data for bismuth beyond that previously reported, are summarized in Table II. As can be observed, the severity of the localized deformation varies widely for the materials investigated, ranging from none at the peak pressures to very severe at pressures below 5 kbars. Up to 26 kbars, no deformation was observed in the zirconium, magnesium, copper, and iron polycrystalline samples, nor in the zinc and cadmium single crystals, the latter indicating that hydrostatic pressures were being achieved. Of the metals investigated, only zinc, cadmium, bismuth, and tin exhibited plastic flow. In the case of cadmium, the deforma-

Table I

Material	Crystal Structure	Linear Compressibility Ratio, $k_c/k_a$ *	Purity, pct	Grain Size, mm per grain
Cadmium	Hcp	11.27	99.99	0.29
Zinc	Hcp	7.55	99.99	0.28
Zinc-0.005 Fe, 0.27 Cu	Hcp	7.55 (approx)	Alloy	0.06
Bismuth	Rhombohedral	2.43	99.99+	0.30
Tin	Tetrahedral	1.11	99.99	0.19
Zirconium	Hcp	0.86	99.9+	0.48
Magnesium	Hcp	1.04	99.8	0.12
Copper	Fcc	1.00	99.9	0.10
Iron	Bcc	1.00	99.8	0.04

\*The elastic compliances used for computing  $k_c/k_a$  are given in Ref. 3 and 4.