Some Observations on the Effects of Hydrostatic Pressures to 20,000 Atm on the Structure of Polycrystalline Bismuth

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This report deals with a study of the effects of extreme hydrostatic pressure on a polycrystalline material which exhibits a high degree of elastic anisotropy. Metallographically prepared polycrystalline bismuth samples were subjected to pressure levels up to 20,000 atm in a piston type gas-liquid system. The observed structural changes consisted of deformation localized along the grain boundaries, which appears to be a boundary migration phenomena, and widespread slip and cross slip. Subsequent deformation is progressive with increased pressure, and is substantially different in type from the deformation characteristic of uniaxial compression.

A large amount of interest has been shown in recent years in the effects of extreme pressure on metals. In this connection, many investigations into the effects of pressure on physical and mechanical properties and reactions have been undertaken. Due primarily to the experimental difficulties involved, there has not been a great deal of study of the structural changes resulting from exposure of metals to extreme pressure. It has been difficult, for instance, to produce a true hydrostatic stress state in many of the extreme pressure devices used, and also to directly examine specimens metallographically before and after pressurization. The results of a preliminary investigation into one of the effects of extreme pressure, and its associated true hydrostatic stress state, on the structure of metals are discussed herein.

Metals exhibit varied degrees of anisotropy in their physical and mechanical properties. Significant among the anisotropic properties is the modulus of elasticity, which varies by a factor of as much as three in some of the fcc metals, and by much larger factors in some of the less symmetrical elements. As a result of the variation of the modulus of elasticity with crystallographic direction, shear stresses will be induced in polycrystalline samples under true hydrostatic compression. Depending on several factors, these shear stresses could become of sufficient magnitude to cause localized plastic deformation.

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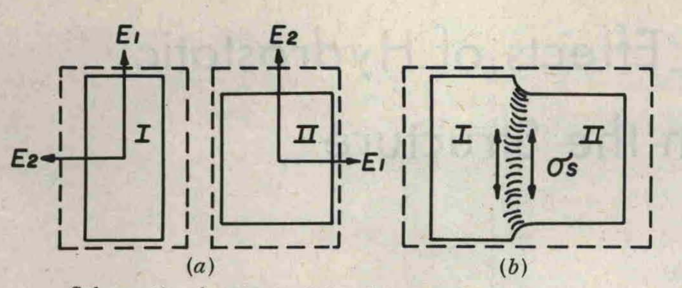
Presented herein are some of the structural changes observed in polycrystalline bismuth as a result of exposure to hydrostatic pressures of up to 20,000 atm. Although several other materials in both bicrystal and polycrystalline form are also currently under investigation, bismuth was chosen initially, due to its low symmetry and moderately high degree of anisotropy in the elastic properties.

The fact that extreme hydrostatic pressure can induce structural changes in some elements in the polycrystalline state is of importance in itself. However, it may also be a factor in many of the other extreme pressure effects. For instance, this localized plastic deformation could substantially lower the recrystallization temperature, thus altering the effects of extreme pressure on this phenomenon. Also, as commented on by Bridgman,[1] the hysteresis in the polymorphic transition of polycrystalline bismuth under extreme pressures could possibly be attributed to structural changes brought about by unequal compressibility. Therefore, to accurately determine the true effects of extreme pressure on metallic substances, one first must determine if any structural changes due to hydrostatic compression are also simultaneously occurring.

The purpose of this work has been to determine whether the shear stresses induced by hydrostatic pressure in an anisotropic polycrystalline material, such as bismuth, could reach a magnitude great enough to cause plastic deformation and to study the resultant structural changes and effects.

THEORY

In a metallic crystal, the elastic properties are dependent upon the crystallographic direction and plane. Depending upon the degree of anisotropy of the elastic properties and other factors, internal shear stresses of sufficient magnitude to cause localized plastic deformation may be induced in polycrystalline material by true hydrostatic compression. The following highly simplified two-dimensional model of two adjacent grains in a polycrystalline aggregate under hydrostatic pressure serves to schematically demonstrate how these shear stresses arise in an anisotropic material.



Schematic showing origin of internal shear stresses.

In (*a*), the approximate elastic dimensional changes of Grain I and II under hydrostatic compression are shown separately. For the purposes of the diagram, the maximum and minimum modulus of elasticity are shown to be normal, which, of course, is usually not the case, and E_1 is assumed to be much larger than E_2. (*b*) shows Grain I and II with a common boundary. Assuming the continuity of material across the boundary, the source of the shear stresses at the boundary due to accommodation is obvious.

The model shown is highly simplified as compared to the three dimensional case of a polycrystalline aggregate. From the two dimensional model, however, one can readily see how shear stresses can arise in the polycrystalline aggregate under hydrostatic pressure.

The magnitude of the induced shear stresses will depend on several factors. The stresses will be proportional to the applied hydrostatic pressure up to the point where plastic deformation occurs, and will be related to the degree of anisotropy of the material, the magnitude of the elastic modulus, and to the relative orientation between the adjoining grains of primary interest. As an example, for most cubic materials the maximum and minimum modulus of elasticity lie along the (111) and (100) directions respectively. Considering only two grains then, the maximum shear stress would occur when the (111) direction in one grain is parallel to the (100) direction in the adjoining grain.

Whether the induced shear stresses are of sufficient magnitude to cause localized plastic deformation will, of course, depend upon the lattice symmetry of the material and whether the critical resolved shear stress for slip or twinning has been exceeded. How all of these variables affect the magnitude of the shear stress and the amount of plastic deformation are subjects of other current investigations.

Based on the above considerations, hydrostatic pressure induced plastic deformation has a substantial probability of occurring in a material such as bismuth since it has low lattice symmetry (rhombohedral), a rather low modulus of elasticity and a reasonably high degree of anisotropy which is estimated to be a factor of 2.9 between the maximum and minimum elastic moduli based on the work of Wachtman[2] for rhombohedral corundum.

PROCEDURE

Specimen. The bismuth specimens used in this investigation were of 99.95 pct pure material which was obtained commercially in the as-cast lump form. For the actual specimens, this as-cast material was cast into 3/4-in.-diam, 1-in.-long cylinders, which were then extruded into 0.155-in.-diam rod. To enhance the actual extrusion process and soundness of the resultant material, the extrusion was performed at 220°C. The final specimens, which were 0.125 in. in diam and 0.200 in. long, were machined from the extruded rod.

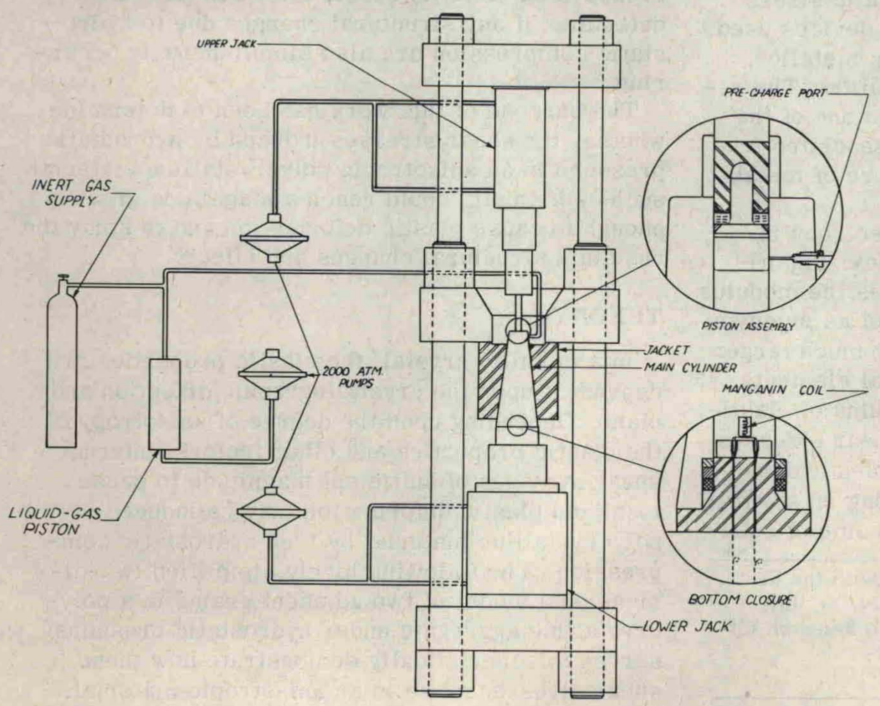


Fig. 1—Schematic of 30,000 atm pressure system.