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DYNAMIC BEHAVIOR OF BERYLLIUM AS A FUNCTION OF TEXTURE

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ABSTRACT- The high-strain-rate stress-strain responses of commercial hot-pressed beryllium and rolled-sheet beryllium were studied as a function of orientation in compression at room temperature. Hot-pressed beryllium exhibits isotropic mechanical properties; whereas 16:1 rolled sheet was highly aniosotropic. Rolled sheet displayed a factor of two difference in strength between the thickness and in-plane (lowest) directions. Twinning is a key deformation mechanism at high rates.

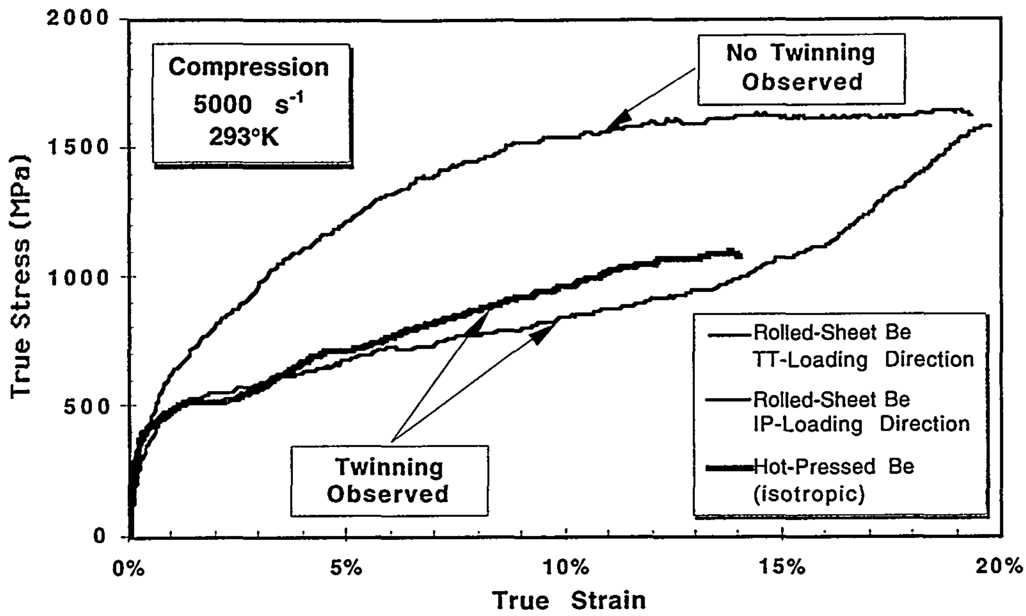
INTRODUCTION: Beryllium has many outstanding mechanical properties in addition to its very low specific gravity. However because it is a toxic material, details of the mechanical behavior and the responsible deformation mechanisms, especially at high strain rates, are incomplete for constitutive model development. Below the melting point, beryllium exhibits a hexagonal close pack (hcp) crystal structure and a lattice parameter ratio (c/a=1.568) similar to titanium, zirconium, and hafnium. In general, hcp metals are mechanically anisotropic due to variations in their elastic constants with orientation and by virtue of relatively easy slip and cleavage on basal planes compared to prism or pyramidal slip. Twinning is an alternate deformation mode that is also mechanically anisotropic and very important in low-symmetry crystal structures at temperatures where five independent slip systems cannot be activated for general deformation or where slip kinetics cannot accommodate the applied deformation rate. For example, at ambient temperatures, hot-pressed beryllium fractures in compression with less than 10% strain. Increasing the temperature above 500°K activates sufficient slip systems to allow compressive strains of 100% (see Abeln, et al. [1995]). On the other hand, increasing the strain rate to 3500 s^{-1} permits over twice as much compressive strain before failure down to at least 75°K (see Blumenthal, et al. [1998]) by activating twinning. The purpose of this study is to examine the high-strain-rate compressive behavior of hot-pressed and rolled-sheet beryllium as a function of orientation using the Hopkinson split-pressure bar (HSPB) for incorporation into constitutive models. HSPB testing may also allow us to isolate and study the mechanism of deformation twinning which cannot be studied at quasi-static strain rates due to the incursion of slip and fracture.

PROCEDURES, RESULTS AND DISCUSSION:

Brush Wellman (Elmore, OH) hot-pressed grades S200D, -E, and -F are a series of beryllium products available from the 1960's through 1990's with processing improvements that include: control of impurity content, grain size, and crystallographic texture (preferred orientations). "Mild" basal plane texturing is still present in hot-pressed beryllium where maxima of 2.0, 1.68, and 1.73 multiples of random distribution along the hot-pressing direction were reported for the S200D, E, and F grades, respectively, by Bennett, et al. [1997] using neutron diffraction. The combined influence of strain rate and temperature on the mechanical behavior of these three grades along the hot-pressing direction was the subject of a previous study by Blumenthal, et al. [1998] which included details of the processing, microstructure, chemistry, specimen preparation, and the SHPB testing procedures. The present study continues this effort by measuring the high strain rate compressive behavior of the three grades in an orientation transverse to the hot-pressing direction to determine the effect of "mild" texture.

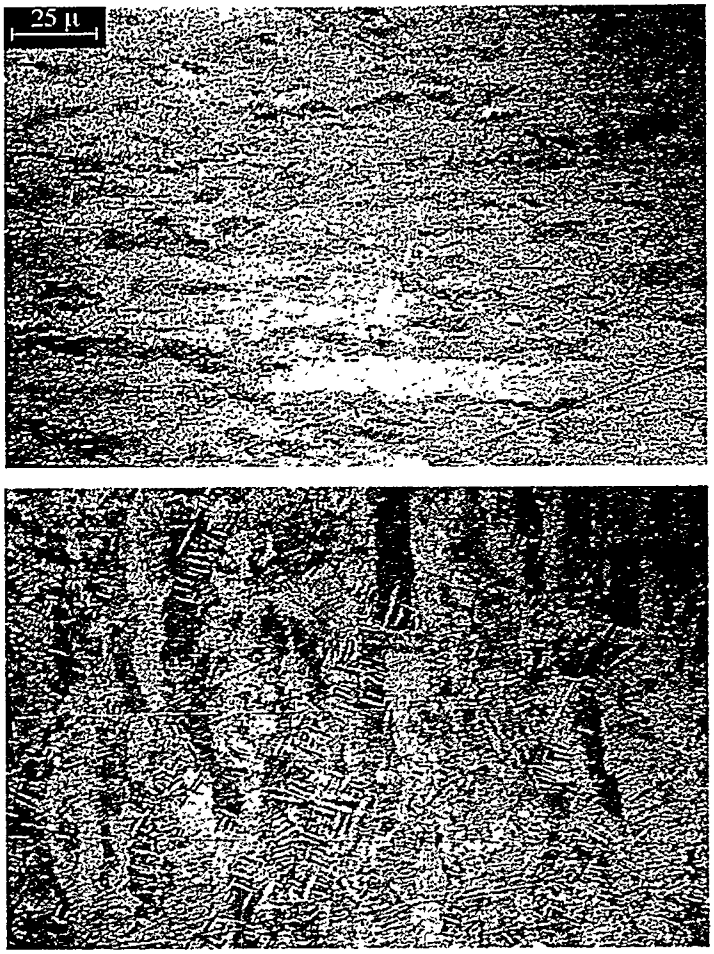
In order to study the effects of "strong" texture in beryllium, a rolled sheet of beryllium was examined as a function of sheet orientation. Brush Wellman produced the sheet in the early 1980's from nominally S200E grade starting powder, but with lower carbon content. The powder was hot-pressed into a large billet and sliced into slabs. The slabs were canned in steel and hot-rolled in a series of passes at approximately 800°C to obtain a reduction-in-height of 4:1, then were cross-rolled to obtain a final reduction-in-height of 16:1. In the present study, cylindrical HSPB specimens nominally 3-mm diameter by 3-mm long were machined along the three principal directions of the plate. Specifically, the through-thickness direction (TT), in-plane rolling direction (IP-RD), and in-plane transverse direction (IP-TD) were the three compression loading directions. Specimens were removed near the edge of the sheet (as opposed to the sheet center). SHPB tests were performed in a HEPA-filtered chamber at room temperature and at a nominal strain rate of 5000 s^{-1}.

Samples both with and without deformation were prepared for optical metallography and neutron diffraction. The microstructures of all three hot-pressed grades are composed of equi-axed grains in a broad size distribution with averages ranging from 11 to 27 micrometers for grade S200F to S200D, respectively. The microstructure of the rolled sheet shows highly elongated and oriented grains stacked in the plane of the sheet with average dimensions of approximately 30 by 7 micrometers. Pre-existing twins were not observed in any of the undeformed materials. Neutron diffraction measurements of the sheet material texture were not completed in time for this paper, however the processing was designed to orient basal-plane normals in or near the TT direction and this texture is supported by our microstructure and property results.



The compressive stress-strain behavior of the "mild" textured, hot-pressed beryllium exhibits no measurable difference as a function of loading orientation; however, the stress-strain behavior of the rolled sheet is a factor of two higher in the TT direction compared to the in-plane directions up to 12% strain as shown in Fig. 1. There is no difference in behavior between the in-plane directions, presumably due to cross rolling, and so this direction is identified only as IP. Above 12% strain the IP flow stress dramatically increases until it converges with the TT curve at about 20% strain. The TT flow stress saturates at about 15% strain and drops-off above 20% strain. All sheet specimens strained above 22% fractured at room temperature.

Microstructural examination of deformed SHPB specimens revealed no twinning in the TT-loading direction of the rolled-sheet as shown in Fig. 2a, but very extensive twinning of apparently a single system in the IP-loaded direction of the rolled sheet (Fig. 2b). Note that the compression direction for both Fig. 2a & 2b is vertical. The behavior of hot-pressed beryllium is very similar to the IP-loaded rolled sheet and also shows significant twinning after high-strain-rate compression between 75°K and 800°K (Blumenthal, et al. [1998]) as compared to quasi-static loading where no twins are observed (Abeln, et al. [1995]). Positive identification of the twinning system was not completed in time for this paper, but based on a review of twinning by Christian and Mahajan [1995] and by the angle between twins within the same grains in Fig. 2b ($\approx 84°$ where the TT direction is horizontal and in the plane of the picture), the twins are of the type $\{10\bar{1}2\} < \bar{1}011 >$ common for hcp metals. The mechanical behavior is analogous to the behavior of textured Mg sheet tested in tension by Reed-Hill [1960] where the flow stress was lower in the TT versus the IP direction.



CONCLUSIONS: It was concluded that under high-strain-rate compression: 1) "mild" textured hot-pressed beryllium is mechanically isotropic; 2) the behavior of roll-textured beryllium was strongly orientation dependent; and 3) twinning contributes substantially to the plasticity of hot-pressed beryllium, but only selectively in the roll-textured beryllium depending on the direction (and mode) of loadingrelativeto the texture. Further testing as a function of temperature is planned.

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