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# INFLUENCE OF STRAIN RATE AND TEMPERATURE ON THE MECHANICAL BEHAVIOR OF BERYLLIUM

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# INFLUENCE OF STRAIN RATE AND TEMPERATURE ON THE MECHANICAL BEHAVIOR OF BERYLLIUM

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The compressive stress-strain response of three grades of beryllium were studied as a function of strain rate and temperature. Grades S200D, E, and F represent a historical perspective of beryllium processing from the 1960's through 1990's technology. The purpose of this study was to measure the mechanical behavior of beryllium over a range of deformation conditions for constitutive model development and to obtain microstructural evidence for deformation mechanisms. The compressive stress-strain response was found to be independent of grade and strongly dependent on the applied strain rate between 0.001 and 8000 s<sup>-1</sup>. The strain-hardening response displayed a moderate temperature dependence between 77°K and 873°K. Because distinct yield was not observed, the intercept-stress from linear strain-hardening fits was analyzed and was found to be only weakly dependent on strain rate and temperature above ambient. Microstructural examination of SHPB specimens revealed that twinning was extensive at strains between 7-22%. A SHPB sample deformed to over 20% strain contained both extensive twinning and grain boundary microcracking.

## INTRODUCTION

Beryllium metal has many excellent structural properties in addition to its unique radiation characteristics, including: high modulus, low Poisson's ratio, low density, and excellent melting point. However, it suffers from several major mechanical drawbacks: 1) high anisotropy - due to its hexagonal lattice structure and its susceptibility to crystallographic texturing; 2) susceptibility to impurity-induced fracture - due to grain boundary segregation; and 3) low ductility for ambient temperature fabrication. Commercial beryllium has undergone processing improvements over the last 30 years to control impurity content, minimize crystallographic anisotropy, and maximize mechanical properties. Grades S200D, E, and F (Brush Wellman, Inc., Elmore, OH) represent a historical perspective of beryllium processing from the 1960's through 1990's technology.

Knowledge of the influence of temperature, strain rate, microstructure, and chemistry on mechanical response is necessary for accurate constitutive

model development for current and earlier grades which are still in service.

While numerous studies have investigated the low-strain-rate constitutive response of beryllium, the combined influence of high strain rate and temperature on the mechanical behavior and microstructure of beryllium has received limited attention over the last 30 years (1-4). In general, prior studies have focussed on a single material (1,4), the tensile behavior (2), or limited conditions of dynamic strain rate and/or temperature (1-4).

The goal of this study was to measure the stress-strain response of three commercial grades of polycrystalline beryllium over a wide range of temperatures and strain rates and to use microstructural evidence to identify dominant deformation mechanisms. The mechanical response will be considered in terms of the strain-hardening rate, the initial yield behavior, and the rate sensitivity. The strain-hardening behavior is generally the most important response for modeling constitutive behavior to large strains and is influenced by impurity level, grain size, and the extent of deformation twinning.

## EXPERIMENTAL TECHNIQUES

This investigation was performed on three grades of vacuum-hot-pressed powder beryllium: S200D, E, and F (Brush Wellman, Inc. Elmore, OH). These grades represent commercial beryllium available in the 1960's, 1980's and 1990's, respectively. Table 1 shows the impurity content and grain size parameters of the different grades. The total impurity content has improved with each grade (2.037%, 1.158%, and 0.983% for the D, E, and F grades, respectively) along with a small reduction in the grain size. A description of the processing differences between grades S200E and S200F can be found elsewhere (5). Due to its age, no detailed processing information is available for the S200D material. The initial microstructure of all three grades can be characterized as having equiaxed grains, an extensive grain size distribution, and few residual twinned grains.

Uni-axial processes such as die filling, hot-pressing, and hot-rolling are known to preferentially align plate-like grains generated by easy basal plane cleavage in beryllium during grain size reduction. Preferred texture is important because it results in orientation-dependent constitutive properties. The crystallographic texture of the three grades of beryllium was recently measured using neutron diffraction (6). Moderate axisymmetric (fiber) texture was observed in (0001) pole figures oriented along the hot-pressing direction. Texture maxima of 2.0, 1.68, and 1.73 m.r.d. (multiples of random distribution) were reported for the 200D, E, and F grades, respectively.

For this study, samples were machined only for compression along the basal-textured, hot-pressing axis of each plate. A split-Hopkinson pressure bar (SHPB) was used to conduct dynamic testing on 5-mm diameter by 5-mm long specimens as a function of strain rate, 1500-8000 s<sup>-1</sup>, and temperature, 77°K, 223°K, 293°K, and 473°K to 873°K (in 100 degree increments). Samples were machined to minimize surface damage which is known to reduce tensile ductility, but no additional treatments were used to remove residual machining damage. The dynamic results were compared to quasi-static compression tests conducted on similarly prepared 13-mm diameter by 19-mm long specimens at strain rates of 0.001, 0.01, and 0.1 s<sup>-1</sup> and at temperatures of 423°K to 873°K (5).

SHPB tests were conducted in a hazardous materials containment chamber to minimize

potential exposure to beryllium dust in the event of specimen failure. Samples were cooled with liquid nitrogen to achieve temperatures of 77°K and 223°K. A resistance furnace was used to heat samples above room temperature in an argon gas atmosphere.

TABLE 1. Composition (wt%) and Grain Size (μm)

Element/Grade	200D	200E	200F
Beryllium	98.80	99.19	99.28
BeO	1.70	0.860	0.720
Fe	0.13	0.070	0.090
C	0.07	0.080	0.072
Al	N/A	0.036	0.038
Mg	0.03	0.020	N/A
Si	0.04	0.031	0.025
Others combined	0.067	0.061	0.038
Avg. Grain Size	N/A	13.4	11.4
Max. Grain Size	N/A	56	50

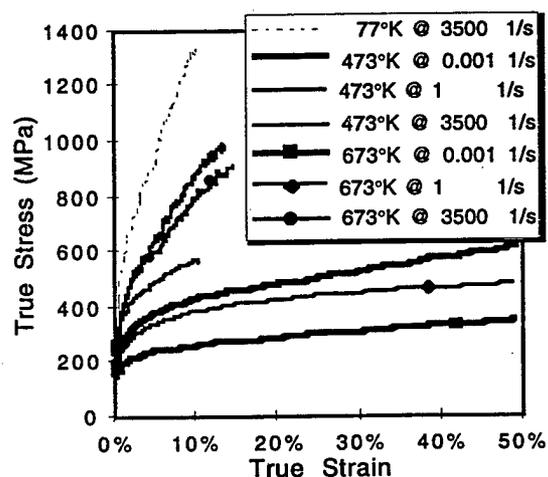


FIGURE 1. Compressive true stress-true strain response of S200F beryllium showing moderate temperature and strain rate dependence.

During high temperature SHPB testing, the lubrication condition of the sample-bar interfaces was observed to substantially affected the flow stress and reproducibility of the stress-strain behavior (although the strain-hardening rate was virtually unaffected). Specifically, specimen barreling was observed and the flow stress of poorly-lubricated specimens was typically 50 to 100 MPa higher than well-lubricated values, as previously observed during quasi-static testing (5). A combination of boron nitride (spray-coated) and

molybdenum sulfide grease produced reproducible stress-strain results without sample "barreling" up to 773°K.

After SHPB testing, selected specimens were sectioned (parallel to the loading axis) and prepared by conventional polishing for cross-polarized light optical metallography.

## RESULTS AND DISCUSSION

The compressive stress-strain behavior of the beryllium exhibits a gradual transition to linear strain-hardening behavior after a few percent strain as shown in Fig. 1 for a wide range of temperatures and strain rates. The strain-hardening behavior was obtained by fitting linear equations to the data over the range of 4% to 9% strain (a range common to both SHBP and quasi-static data sets, but beyond initial yield). Quasi-static failure occurred with little ductility at temperatures below 420°K which precluded measurement of the strain hardening behavior in this regime.

All three grades were nearly identical in their compressive stress-strain behavior as illustrated in Fig. 2a. The strain-hardening rate (= slope of the linear fit) increases with increasing strain rate or decreasing temperature as shown in the semi-log plot of Fig. 2b. Empirical power-law fits of both dynamic and quasi-static hardening data are offset which suggests that different deformation mechanisms control the strain hardening behavior in these two strain rate regimes.

Because a distinct yield point is not observed under either quasi-static or SHPB conditions, the yield stress-intercept value from the linear strain-hardening fits of the stress-strain curves were instead compared as a function of strain rate and temperature as shown in Fig. 3. The strain-rate sensitivity of the intercept-stress varied from about 0.09 at SHPB strain rates to about 0.04 at quasi-static strain rates which again suggests the operation of different deformation mechanisms.

Microstructural examination of SHPB-deformed specimens reveals that twinning is extensive. Fig. 4a is a micrograph of a specimen deformed at room temperature to 7% strain at a strain rate of 1500 s<sup>-1</sup>. Twins are present in the majority of grains. Twinning was not prevalent in the microstructure of quasi-statically deformed specimens which were tested above 423°K. Hence, the strain-hardening and yield behavior differences between high rate and

low strain rates may be due to dislocation- versus twinning-dominated deformation mechanisms.

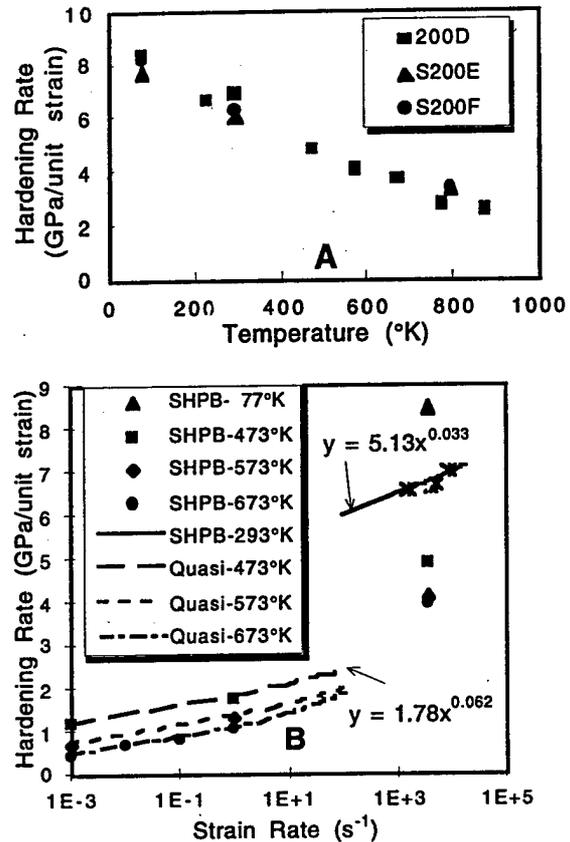


FIGURE 2. a) Strain-hardening behavior is virtually identical for grades S200D, E, and F. b) Strain-hardening as a function of strain rate and temperature is distinctly offset between high and low strain rates.

Figure 4b shows a sample deformed at room temperature to over 20% strain and a peak stress of 1.48 GPa at 8000 s<sup>-1</sup>. The microstructure contains both twins and a sizable distribution of microcracks. The microcracks are primarily observed at grain junctions, but are also present within some grains. The advent of microcracking can be correlated to the end of linear strain-hardening behavior and a peak in the flow stress. The deviation from linear strain-hardening in this specimen begins at 15% strain with a peak in the flow stress at 18% strain. This response was not associated with a change in the strain rate or with barreling effects due to interfacial friction.

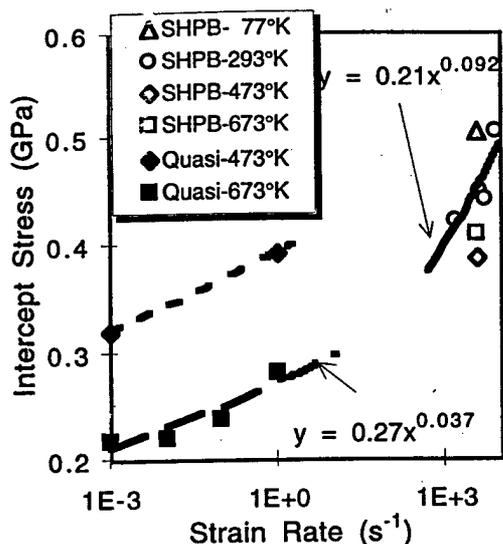


FIGURE 3. Yield stress behavior is analyzed using the strain-hardening intercept stress as a function of temperature and strain rate.

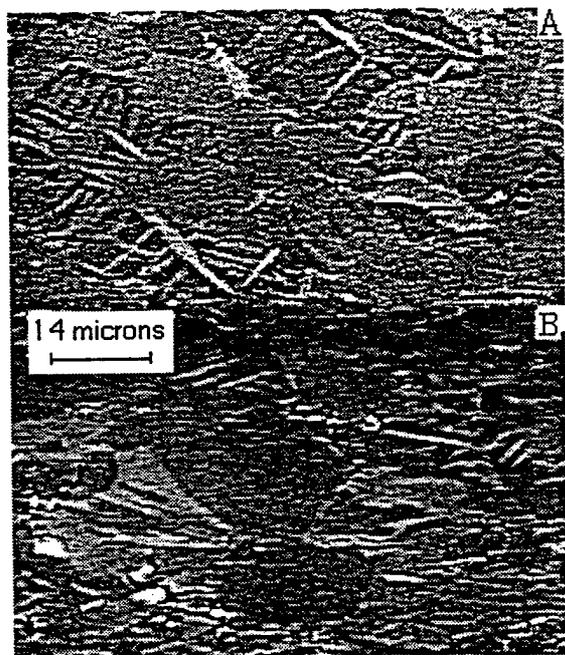


FIGURE 4. a) SHPB specimen deformed to 7% strain reveals twinning as a dominant deformation mode. b) SHPB specimen with 20% strain also shows microcracking at grain junctions.

Similar linear hardening response and twin formation under high-strain-rate loading has been observed in other hexagonal metals (7). Twinning is also known to depend on grain size and texture. The grain size and moderate basal texturing of the three grades of beryllium appears to favor twinning for compression along the hot-pressing direction.

## SUMMARY AND CONCLUSIONS

A study of the compressive deformation response of three grades of hot-pressed beryllium was conducted as a function of strain rate and temperature. The following were concluded: 1) the high-strain-rate compressive behavior of grades S200D, E, and F are virtually identical; 2) the strain-hardening and the yield intercept stress increase with higher strain rate and lower temperature; and 3) twinning contributes substantially to plastic flow at high strain rates, followed by microcracking at large strains (>15%).

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