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CONSTITUTIVE BEHAVIOR OF MODEL FCC, BCC, AND HCP METALS: EXPERIMENTS, MODELING AND VALIDATION

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CONSTITUTIVE BEHAVIOR OF MODEL FCC, BCC, AND HCP METALS: EXPERIMENTS, MODELING AND VALIDATION

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ABSTRACT - The stress-strain responses of a half-hardened copper and an annealed tantalum as a function of temperature and strain-rate were investigated. The rate-dependent yield stress and work-hardening behavior were described satisfactorily by the Mechanical Threshold Strength (MTS) model which is based on thermally-activated plasticity and evolution. Excellent agreement was obtained comparing experiments and calculations of Taylor cylinder impact tests.

INTRODUCTION: The mechanical properties of materials under high-strain-rate deformation are essential to many defense-related and industrial applications. The stress/strain behaviors of several metals encompassing three common crystal structures, namely fcc, bcc, and hcp, have been investigated as a function of temperature and strain rate. The dominant deformation mechanisms can be dislocation slip, mechanical twinning, or both operating in series or parallel. The development of a more physically-based constitutive strength model capable of describing the very complex mechanical responses of these metals is important.

Taylor cylinder impact tests (Taylor [1948], Maudlin et al. [1998]) are relatively easy and inexpensive to perform. Depending on the initial impact velocity and the material strength, a very wide range of strain rates, temperatures (due to adiabatic heating), and strains can be achieved from a single test. The Taylor test provides a straight forward set of experimental data from which to validate the implementation, the accuracy and predictability of a constitutive model in a large finite element code.

PROCEDURES, RESULTS AND DISCUSSION: The mechanical responses of several metals were measured in compression using solid-cylindrical samples 5 mm in diameter by 5 mm in length lubricated with molybdenum disulfide grease. The deformation behavior and constitutive modeling fit for a half-hardened copper rod (hhCu), provided by J. House at Eglin Air Force Base, and an annealed tantalum (Ta) plate are presented in this paper and are shown in Fig. 1 and Fig. 2 respectively. Comparing the yield stress at 25°C and 0.1/s shown in Fig. 1 to a previous study (Chen and Kocks [1991]) on the same material in an annealed condition, it was estimated that about 50-60% plastic work had been retained from the original processing. This pre-strained structure leads to a low work-hardening rate upon further deformation as observed in Fig. 1. The current material "structure" was characterized by reloading the material at various temperatures and strain rates. The mechanical threshold, defined as the flow stress at 0K, and the rate sensitivity of this "structure" were then determined by plotting the measured yield stresses as a function of strain rate and temperature. The remaining parameters used in the MTS model were held to the same values as those previously published for an annealed Cu (Follansbee and Kocks [1988]). This model is capable of capturing the effects of deformation-path change as demonstrated by the excellent agreement between the experiments and model fits shown in Fig. 1.

The yield stress and work hardening as a function of strain rate and temperature of Ta are plotted in Fig. 2. It is seen that the yield and flow stresses exhibit very high strain-rate sensitivities which is typical in bcc materials at low temperature or at high strain rate. The strain-hardening behavior within the current testing conditions is seen to be independent of strain rate and temperature. The MTS model, using a high rate-dependent parameter describing the yield behavior and a rate-independent parameter representing the structure evolution, is shown to accurately capture the overall mechanical response (Fig. 2).

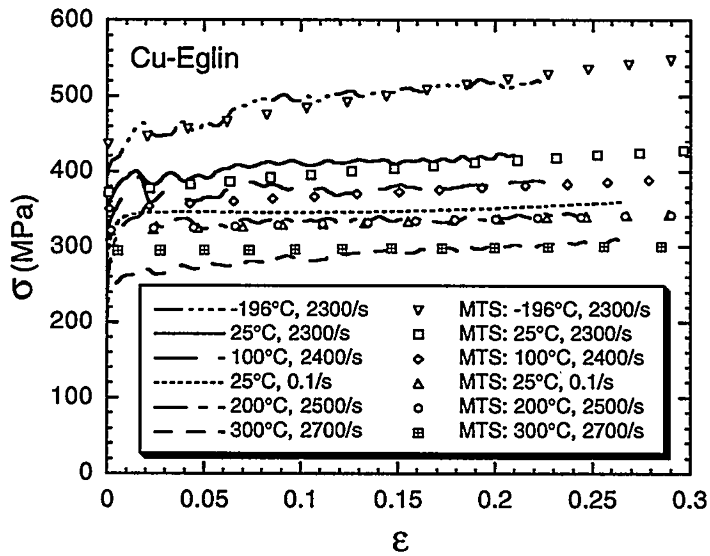

Fig. 1 Stress-strain curves of a half-hardened copper (curves) showing the fit to the MTS model (symbols).

Taylor cylinder impact testing has been shown to be an effective constitutive model validation test due to the gradients of stress, strain, strain rate, and temperature (as a result of adiabatic heating under high-rate deformation) which this integrated test provides. Recently we have designed and constructed a facility to conduct this type of test. A gas breech filled with He was used to accelerate the sample through a 30-caliber barrel. High-pressure He propulsion has the advantage of quick turn-around time, minimal environmental impact, and more precise velocity control over the traditional powder-driven systems. The nominal dimension of the sample is 51.8 mm in length by 7.62 mm in diameter. The hhCu sample was tested at Los Alamos National Laboratory. The Ta test, with a dimension of 38.1 mm in length by 7.62 mm in diameter, was conducted at Eglin Air Force Base (Maudlin et al. [1998]). Rod velocity is measured using parallel laser beams crossing the flight path. They were 178 m/s for the hhCu and 175 m/s for Ta, respectively.

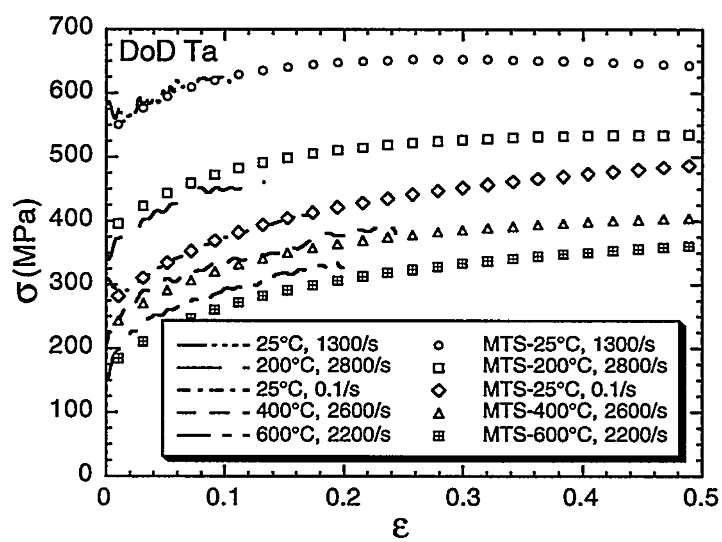

Fig. 2 Stress-strain curves of DoD Ta (curves) showing the fit to the MTS model (symbols).

Comparisons of Taylor cylinder impact experimental results and simulations are shown in Figs. 3 and 4. As a result of the processing history, the extruded hhCu rod with an initial axial-symmetric fiber texture exhibited almost perfectly round footprint (not shown in Fig. 3). The Ta sample was machined from a rolled and recrystallized plate in the in-plane direction. The retaining rolling texture with ~4 times greater intensity than random caused the material to exhibit anisotropic deformation as evidenced by the elliptical footprint of the deformed cylinder (Fig. 4(a)). Finite-element simulations of the Taylor tests were calculated using an explicit Lagrangian finite element code, utilizing a complete description of the MTS constitutive modeling to capture the flow stress, and a Hill (Hill [1950]) quadratic function to represent the anisotropic yield surface of the material. The calculated side profile cut along the middle plane of the hhCu is shown in Fig. 3(b). The final length, the axial distribution of plastic strain, and the size of the footprint agree very well with the experiment result (solid circles in Fig. 3(b)). The use of the mechanical threshold, representing the current "structure", as an internal state variable in the MTS model successfully describes the flow behavior upon deformation-path change. In this case, the "structure" has evolved from an annealed state to a deformed one via a complex straining path. By characterizing the current "structure" that serves as input to the model, the strain-rate and temperature sensitivities of further structure evolution under new deformation paths can be predicted based on the parameters derived for the annealed Cu.

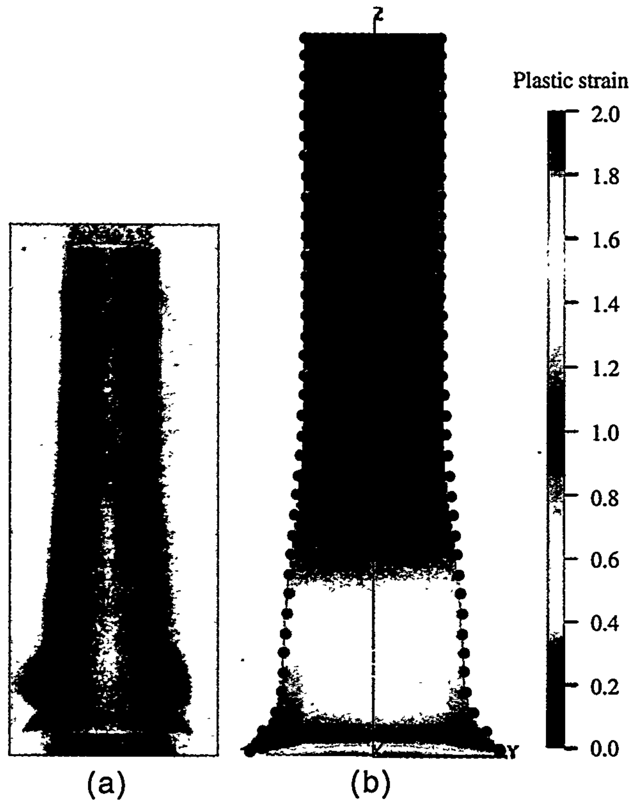

Fig. 3 Comparison of Taylor cylinder impact (a) experimental result, and (b) simulation for a half-hardened copper. The digitized experimental post-test shape is shown in (b) as solid circles.

The calculated elliptical footprint of Ta shown in Fig. 4(b) has an eccentricity (ratio of major to minor diameters) of about 1.20. This compares well with the experimental footprints from Fig. 4(a). The side profile compared in Figs. 4(c)-(d) indicates that the final length agrees well with the post-test sample length and the axial distribution of plastic strains also track very well with the experimental profile. The axial distribution of plastic strains in a Taylor test is essentially controlled by the flow stress model. The good agreement between the experiment and simulation implies that the MTS flow stress characterization accurately captures the size of the yield surface in absolute stress space.

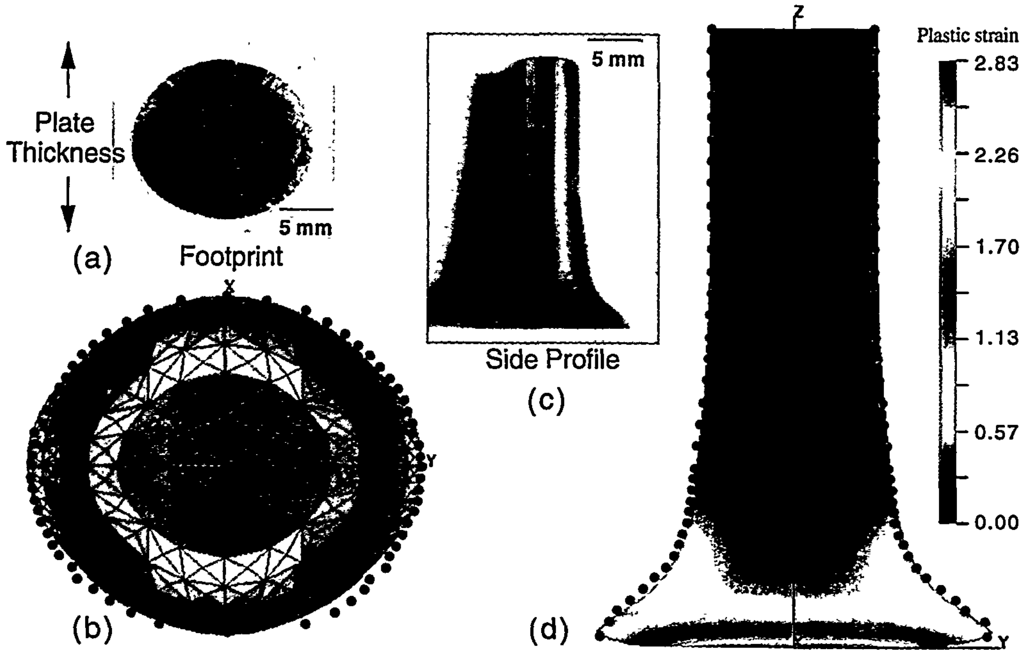

Fig. 4 Comparison of experimental and simulation results for a Taylor cylinder test. (a)-(b) footprint view, and (c)-(d) side profile. The simulation results shown in (b) and (d) capture the overall shape after impact and the eccentricity as a result of material anisotropy.

CONCLUSIONS: Mechanical properties of metals can be well characterized using compression testing under carefully selected deformation conditions which yield the temperature and strain-rate sensitivities. Constitutive behavior is then fitted to a physically-based model to capture the essential mechanical responses observed in the experiment with confidence in extrapolating the model to conditions which are not directly measurable. The Taylor test provides validation on the accuracy of the constitutive model prediction.

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