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13. ABSTRACT (Maximum 200 words)

Broadly, the results under this grant are:
The thermoviscoplastic behavior of pure polycrystalline tungsten at high rates of deformation was measured. This is the basis for some models of tungsten-based composites.

- The mechanical behaviors of two modified tungsten phases (made at Penn State and ARDEC) were measured at high rates and high temperatures. A model was developed for this behavior.
- **The mechanical behavior of an alternate matrix material (hafnium) was measured over a wide range of strain rates.**
- **The mechanical behavior of a tungsten-hafnium composite was measured using a wide range of strain rates and deformation modes. A model was developed to describe the observed constitutive response, based on the behaviors of the individual phases.**
- A technique was developed for the recovery of samples in high-strain-rate pressure-shear experiments.

of a material to adiabatic shear localization under superimposed hydrostatic pressure.

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Final Progress Report: ARO Award DAAH049510417

Introduction

This technical report describes the work performed under ARO Award DAAH0495104172 to Professor K.T. Ramesh and the Johns Hopkins University. The award was used to fund research within the Laboratory for Impact Dynamics and Rheology working under the supervision of Professor K.T. Ramesh, and (through a subcontract) to fund research at Pennsylvania State University under the supervision of Professor R.M. German. The technical work was linked to research performed under an AASERT Award DAAH049510272 to Professor K.T. Ramesh.

Objectives

The specific objectives of this research program were the following:

- The development of a modified tungsten phase for use within advanced WBCs, through a complete experimental evaluation of the deformation mechanisms within a modified polycrystalline tungsten at high shear rates coupled with a modeling effort. This was to be complemented by studies of pure polycrystalline tungsten being performed under contract with ARL.
- The design and evaluation of an advanced WBC for penetrator applications, using the modified (dispersion-controlled) tungsten phase in conjunction with a new binder/matrix phase.

Students Supported

S. Yadav, Ph.D. Currently at Fermilab, IL.
D. Jia, Ph.D. expected Dec. 2000.
Y. Li, postdoctoral fellow, for very short periods.
Andrew M. Lennon, Ph.D. Currently at Applied Physics Laboratory, MD.
Several undergraduate research assistants.

Results and Discussion

The technical work under this grant has been linked to research performed under the associated AASERT Award on "Susceptibility of materials to adiabatic shear localization under superimposed pressure" as well as to research performed under the auspices of the Army Research Laboratory on "Adiabatic Shear Localization in BCC Metals."

Broadly, the results under this grant are:

- A technique was developed for the measurement of the dynamic properties of materials at high rates and high temperatures.
- A model was developed for the effect of particle shape and aspect ratio on the high-rate deformations of metal-matrix composites.
- The thermoviscoplastic behavior of pure polycrystalline tungsten at high rates of deformation was measured. This is the basis for some models of tungsten-based composites.

- The mechanical behaviors of two modified tungsten phases (made at Penn State and ARDEC) were measured at high rates and high temperatures. A model was developed for this behavior.
- The mechanical behavior of an alternate matrix material (hafnium) was measured over a wide range of strain rates.
- The mechanical behavior of a tungsten-hafnium composite was measured using a wide range of strain rates and deformation modes. A model was developed to describe the observed constitutive response, based on the behaviors of the individual phases.
- A technique was developed for the recovery of samples in high-strain-rate pressure-shear experiments.

Some of these results are summarized in the following subsections.

A Technique for Measuring the Dynamic Behavior of Materials at High Temperatures

A new experimental technique has been developed for the performance of high temperature, high-strain-rate experiments in the compression Kolsky bar (split-Hopkinson pressure bar or SHPB). The new technique (referred to as the High Temperature Compression Kolsky Bar or HTCKB) uses an infra-red spot-heater to rapidly heat the specimen to the desired temperature, and an electropneumatic actuation system to minimize the development of temperature gradients in the sample. The technique is cheap and relatively easy to implement and yet provides accurate, repeatable results. As an illustration of the application of the technique, we have examined the high-temperature response of the BCC metal vanadium at high strain rates. Stress-strain curves are obtained for the material at strain rates of $4\text{x}10^3$ s^{-1} and at temperatures ranging from 300 to 1100 K (27 to 800 °C). Quasistatic (10^{-3} s^{-1}) experiments have also been performed on vanadium over a slightly smaller range of temperatures, and the results are compared with the new high-temperature, high-strain-rate data. It is observed that the rate of thermal softening is a function of the strain rate. These results illustrate the importance of including the coupling between temperature and strain rate in thermoviscoplastic constitutive models.

The Mechanical Behavior of Polycrystalline Hafnium: Strain Rate and Temperature Dependence

The mechanical behavior of polycrystalline hafnium has been investigated over a wide range of strain rates (10^{-4}–10^5 s^{-1}) and temperatures (298–1023 K). Hafnium specimens are tested in compression and shear using servohydraulic machines, the compression Kolsky bar, and pressure-shear plate impact. The hafnium compression specimens show an unusual strain-hardening behavior, with strong but constant strain hardening for strains less than 10%, then very strong and increasing hardening up to strains of about 25%, and finally decreasing hardening until the stress reaches a maximum (in compression). The maximum in the compressive stress-strain curve is associated with the onset of strongly inhomogeneous deformation in the specimen. At larger strains (beyond that corresponding to the maximum stress), the cylindrical hafnium compression specimens fail by localized shearing deformations involving the nucleation, growth, and coalescence of microvoids. The flow stress sustained by hafnium is found to be strongly dependent on the rate of deformation over the range of strain rates investigated in this work. Further, the degree of strain hardening is also found to be larger at high strain rates. A 150% increase in flow stress is observed for a change in strain rate over eight orders of magnitude. Twinning is an important deformation mechanism in hafnium and increases with an increase in strain or strain rate. However, at high temperatures deformation occurs entirely by dislocation activity and no twinning is observed. Finally, it is shown that the compressive behavior of hafnium up to a strain of 10% can be modeled reasonably well using a modified form of the Zerilli & Armstrong model (for fcc materials) for a broad range of temperatures (298–1023 K) and strain rates (10^{-4}–10^{3} s^{-1}).

High-Strain-Rate Pressure-Shear Recovery: A New Experimental Technique

A new experimental technique is presented that allows for the recovery of a sample that has been subjected to a single well-characterized high-rate shear loading and a single well-characterized longitudinal pulse within a pressure-shear plate impact configuration. Pressure-shear plate impact experiments are traditionally used to investigate the behavior of materials under conditions of very high rate (10^5 - 10^6 s^{-1}) simple shearing under high hydrostatic pressures. The new technique - known as High-Strain-Rate Pressure-Shear Recovery or HSRPSR - is valuable for the investigation of microstructural influences on the plastic flow of materials under these conditions. Several successful experiments have been performed at strain rates of 10^5 s^{-1} using the HSRPSR technique. The recovered specimens are compared with specimens obtained after deformation within conventional pressure-shear plate impact experiments. As an example of the utility of this recovery technique, the paper presents the microstructural characterization of specimens of alpha-titanium after deformation at strain rates of 10^5 s^{-1} and under superimposed hydrostatic pressures of several GPa.

Influence of Particle Volume Fraction, Shape and Aspect Ratio on the Behavior of Particle-Reinforced Metal-Matrix Composites at High Rates of Strain

The compressive plastic deformation of particle reinforced metal matrix composites (A359/SiC_p) is investigated through experiments and numerical modeling at high rates of strain. The experiments are performed using an MTS servohydraulic machine and a compression Kolsky bar. The numerical modeling is performed using axisymmetric unit cell models, with the particles treated as elastic ellipsoids or cylinders embedded within a rate dependent matrix. The constitutive behavior of the matrix material is obtained from independent experimental results on the A356 aluminum alloy. The strain rate hardening is characterized as power-law with parameters obtained from experiment. The flow stress of the composites was predicted for different volume fractions of particles and for varying particulate aspect ratios over a range of strain rates. The results show that both the flow stress and the strain rate hardening increase with increasing volume fraction of the reinforcement. It is also shown that the rate-dependent flow stress is influenced not only by particle aspect ratio but also by particle shape (ellipsoidal or cylindrical) and particle aspect ratio. In terms of aspect ratio, disk shaped particles are stronger reinforcements than needle shaped particles if the particles are ellipsoidal; however, the reverse is true for cylindrical particles. Comparison of the experimental and numerical results for a single volume fraction indicates reasonable agreement, although particle damage (which occurs in the real composite in compression but which is not incorporated in the model) results in a lower experimental strain hardening than predicted by the model.

The Thermoviscoplastic Response of Polycrystalline Tungsten in Compression

The thermomechanical response of commercially pure polycrystalline tungsten was investigated over a wide range of strain rates and temperatures. The material was examined in two forms: one an equiaxed recrystallized microstructure and the other a heavily deformed extruded microstructure that was loaded in compression along the extrusion axis. Low strain rate (10^{-3} to 10^{0} s^{-1}) compression experiments were conducted on an MTS servohydraulic load frame equipped with an infra-red furnace capable of sustaining specimen temperatures in excess of 600 °C. High strain rate (10^{3} to 10^{4} s^{-1}) experiments were performed on a compression Kolsky bar equipped with an infra-red heating system capable of developing specimen temperatures as high as 800 °C. Pressure/shear plate impact experiments were used to obtain shear stress vs. shear strain curves at very high rates ($\sim 10^{4} - 10^{5}$ s^{-1}). The recrystallized material was able to sustain very substantial plastic deformations in compression (at room temperature), with a flow stress that appears to be rate-dependent. Intergranular microcracks were developed during the compressive deformations. Under quasistatic loadings a few relatively large axial splitting cracks were formed, while under dynamic loadings a very large number of small, uniformly distributed microcracks (that did not link up to form macrocracks) were developed. The rate of nucleation of microcracks increased dramatically with strain rate. The extruded tungsten is also able to sustain large plastic deformations in compression, with a flow stress that increases with the rate of deformation. The strain hardening of the extruded material is lower than that of the recrystallized material, and is relatively insensitive to the strain rate. High-temperature experiments at low and high strain rates show that the strain hardening is also insensitive to the temperature over this temperature range. The flow stress is shown to be strongly temperature-dependent at low homologous temperatures.

The Mechanical Behavior of Modified Tungsten Phases

The project examined novel tungsten-based composites in which the tungsten phase is itself a nanocomposite of pure tungsten with small particles of another material and including alternative matrix phases. Modeling studies were conducted on such "advanced tungsten phases" in order to guide materials processing. Two such materials were examined experimentally. The first material produced specifically as a result of our computational modeling was an advanced tungsten phase containing glassy silica inclusions (made by R.M. German at Penn State). Samples of the material were deformed in compression at low rates (10^{-5} s^{-1}), at high rates (10^{3} s^{-1}) and at high temperatures and high rates (up to 600 °C at 10^{3} s^{-1}) using a locally developed experimental technique. The new material was shown to sustain the same flow stresses as pure polycrystalline tungsten at both low and high rates, to sustain the same initial flow stress at various temperatures, but to show substantial softening during high-rate, high-temperature deformations. The material is promising as a modified tungsten phase. Since the material also has a lower thermal conductivity as a result of the glassy inclusions, we are quite hopeful that the susceptibility to shear localization will increase. However, we were never able to obtain samples of sufficient size to conduct the shear localization experiments. The second modified tungsten phase that was studied was a tungsten-hafnium carbide composite made by ARDEC, which had shown some promise in ballistic testing. This material showed impressive dynamic strength (much higher than anticipated) but some lack of toughness.

Summary

The ARO award has been used to develop a complete characterization of the constitutive response of polycrystalline tungsten, an alternate matrix material, two modified tungsten phases, and a novel tungsten-based composite. The results have greatly expanded our understanding of the high-rate deformations of these materials. There is not as yet a definitive answer to the question of high-performance alternatives to DU, because the development of novel tungsten-based composites for penetrator applications is processing-limited. However, the combination of advanced matrices such as the hafnium alloys with a modified tungsten phase such as the tungsten-hafnium carbide material may provide the necessary improvement, if processing difficulties can be overcome.

Publications resulting from the Award:

1. Yadav, S. & Ramesh, K.T., "The Mechanical Behavior of Polycrystalline Hafnium: Strain Rate and Temperature Dependence," Materials Science & Engineering A, Vol. 246, pp. 265-281, 1998.
2. Li, Y., & Ramesh, K.T., "Influence of Particle Volume Fraction, Shape and Aspect Ratio on the Behavior of Particle-Reinforced Metal-Matrix Composites at High Rates of Strain," Acta Materialia, Vol. 46, No. 16, pp. 5633-5646, 1998.
3. Lennon, A.M., & Ramesh, K.T., "A Technique for Measuring the Dynamic Behavior of Materials at High Temperatures," International Journal of Plasticity, Vol. 14, No. 12, pp. 1279-1292, 1998.
4. Jia, D. Lennon, A.M., & Ramesh, K.T., "High-Strain-Rate Pressure-Shear Recovery: A New Experimental Technique," International Journal of Solids & Structures, Vol. 37, No. 12, pp. 1679-1699, 2000.
5. Lennon, A.M., & Ramesh, K.T., "The Thermoviscoplastic Response of Polycrystalline Tungsten in Compression," Materials Science & Engineering A, Vol. 276, pp. 9-21, 2000.
6. Lennon, A.M. & Ramesh, K.T., "The Influence of Crystal Structure on the Dynamic Behavior of Materials at High Temperatures," International Journal of Plasticity, accepted for publication.
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8. Yadav, S., Zhang, Y. & Ramesh, K.T., "The Dynamic Behavior of a Tungsten-Hafnium Composite for Kinetic Energy Penetrator Applications," 1997 International Conference on Tungsten, Refractory Metals and Alloys, Metal Powder Industries Federation, Princeton, NJ, 1997.