MASTER COPY — KEEP THIS COPY FOR REPRODUCTION PURPOSES

REPORT DOCUMENTATIO[N PAGE]

AD-A281 377

[Form App]roved, [OMB No.] 0704-0188

1. AGENCY USE ONLY (Leave blank)	2. REPORT DATE	3. REPORT TYPE AND DATES COVERED
	2/28/94	FINAL TECHNICAL 9/1/86-8/31/93

4. TITLE AND SUBTITLE

CENTER FOR ADVANCED MATERIALS OF HIGH QUALITY DYNAMIC PERFORMANCE (Fellowships)

5. FUNDING NUMBERS

DAAL03-86-G-0196

6. AUTHOR(S)

Dr. Siavouche Nemat-Nasser
Principal Investigator

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)

UNIVERSITY OF CALIFORNIA, SAN DIEGO
DEPARTMENT OF APPLIED MECHANICS AND ENGINEERING SCIENCES
9500 GILMAN DRIVE, LA JOLLA, CA 92093-0411

8. PERFORMING ORGANIZATION REPORT NUMBER

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)

U.S. Army Research Office
P.O. Box 12211
Research Triangle Park, NC 27709-2211

10. SPONSORING/MONITORING AGENCY REPORT NUMBER

ARO 24619.1-MS-UIF

11. SUPPLEMENTARY NOTES

The views, opinions and/or findings contained in this report are those of the author(s) and should not be construed as an official Department of the Army position, policy, or decision, unless so designated by other documentation.

12a. DISTRIBUTION/AVAILABILITY STATEMENT

Approved for public release; distribution unlimited.

12b. DISTRIBUTION CODE

13. ABSTRACT *(Maximum 200 words)*

Under the designation of this fellowship grant, seven URI fellows were supported in the pursuit of their Masters Degrees and Ph.D.'s. This final report identifies the degrees conferred, placement of the fellows and brief description of research. These research topics have been reviewed during the ARO panel annual reviews and their status and progress have been reported in the yearly technical reports which were distributed during the ARO URI site visits. (Copies are available upon request).

94-21056

14. SUBJECT TERMS

15. NUMBER OF PAGES

15

16. PRICE CODE

17. SECURITY CLASSIFICATION OF REPORT	18. SECURITY CLASSIFICATION OF THIS PAGE	19. SECURITY CLASSIFICATION OF ABSTRACT	20. LIMITATION OF ABSTRACT
UNCLASSIFIED	UNCLASSIFIED	UNCLASSIFIED	UL

Center for Advanced Materials of High Quality Dynamic Performance (Fellowships)

FINAL TECHNICAL REPORT

for the period
September 1, 1986 - August 31, 1993

Principal Investigator: Dr. S. Nemat-Nasser

U.S. Army Research Office
ARO Proposal Number: 24619-MS-UIF
Grant No.: DAAL03-86-G-0196

University of California, San Diego

1.0 DEGREES AWARDED FOR WORK COMPLETED

1.1 Ph.D. Degrees

(a) **M. Rashid** (1990) Thesis: High-Strain-Rate Plastic Flow in Metallic Single Crystal

Period of Support: 10/87 - 6/90

Status:: Was a post-graduate researcher at UCSD's CEAM and then a Sr. Member of Technical Staff, Division of Engineering Mechanics and Material Modeling, Sandia National Laboratories, Albuquerque, New Mexico.
Current Status: Assistant Professor, University of California, Davis

Publications:
Rashid, M.M. and S. Nemat-Nasser, " Modeling Very Large Plastic Flows at Very Large Strain Rates for Large-Scale Computation", Computers and Structure, Vol. 37, No. 2 (1990), pp. 119-132.

(b) **M. Zikry** (1990) Thesis: High-Strain-Rate Deformation and Failure of Crystalline Materials

Period of Support: 10/86-7/90

Current Status: Assistant Professor, Department of Applied Mechanics North Carolina State University

Publications:
Zikry, M.A. and S. Nemat-Nasser, "High Strain-Rate Localization and Failure of Crystalline Materials", Mechanics of Materials, Vol. 10, No.3 (1990), 215-237.

(c) **B.S. Altman** (1992) Thesis: Dynamic Deformations and Analysis of a Metal Matrix Composite

Period of Support: 6/89 - 9/91

Current Status: Staff Researcher, Advanced Munitions Department, Sandia National Laboratories, Albuquerque, New Mexico

Publications:
S. Nemat-Nasser, M. Hori, J. E. Starrett, B. Altman, S. Chang and J. Isaacs, "Ductile Failure by Void Collapse and Void Growth," *Impact Loading and Dynamic Behavior of Materials* (eds. C. Y. Chiem, H.-D. Kunze, and L. W. Meyer) **1**, Verlag: DGM Informationsgesellschaft (1988), pp. 343.

K. T. Ramesh, B. Altman, G. Ravichandran, and S. Nemat-Nasser, "Failure Mode and Mechanism in Cermets Under Stress-Wave Loading," *Advances in Fracture Research* (eds. K. Salama, K. Ravi-Chandar, D. M. R. Taplin, P. Rama Rao) **1**, (1989), pp. 811-817

B. Altman, S. Nemat-Nasser, K. S. Vecchio, and J. Isaacs, "Homogeneous Deformation of a Particulate Reinforced Metal-Matrix Composite," to be published in the *American Physical Society 1991 Topical Conference on Shock Compression in Matter.*

(b) **D. Owen** (1993) Thesis: An Investigation into the Free Sintering and Sinter Forging Behavior of Single and Dual Phase Alumina-Zirconia Ceramics

Period of Support: 7/1/91 - 6/30/93

Current Status: Research Fellow Aeronautics, California Institute of Technology, Pasadena

Publications:

S.K. Ganapathi, D.M. Owen and A.H. Chokshi, "The Kinetics of Grain Growth in Nanocrystalline Copper," *Scripta Metall. et Mater.*, 25, (1991), pp. 2699-2704.

D.M. Owen and A.H. Chokshi, "A Comparison of the Tensile and Compressive Creep Behavior of a Superplastic Yttria-Stabilized Tetragonal Zirconia - 20 wt% Alumina Composite," *Superplasticity of Advanced Materials*, (S. Hori, M. Tokisane and N. Furushiro, eds) Osaka, Japan, Japan Society of Research on Superplasticity (1991), pp 215-220.

D.M. Owen and A.H. Chokshi, "Microstructural Aspects of Superplastic Deformation in a Yttria Stabilized Zirconia and a Zirconia-Alumina Composite," *Proceedings of European Ceramic Society, Second Conference*, in press , (1992)

D.M Owen and A.H. Chokshi, " An Evaluation of the Densification Characteristics of Nanocrystalline Materials," *Nanostructural Materials*, Vol. 2 (1993), pp. 181-187.

D.M. Owen and A.H. Chokshi, "Observations of Primary Regions in the Tensile Creep Deformation of a Superplastic Zirconia-Alumina Composite," *Scripta Metallurgica et Materialia*, Vol. 29, (1993), pp. 869-874.

D.M. Owen and A.H. Chokshi, "Observations of Transitions in Creep Behavior of a Superplastic Yttria-Stabilized Zirconia.", *Science and Technology of Zirconia*, (S.P.S. Badwal, M.J. Bannister, and R.H.J. Hannink, eds.), Technomic Publishing, Lancaster, PA. (1993), pp 432-439

T.G. Nieh, T.C. Chou, J. Wadsworth, D. Owen and A.H. Chokshi, "Crep of a Niobium Beryllide, Nb_2Be_{17}", Journal of Materials Research, Vol. 8, (1993), 757-763.

1.2 M.S. Degrees

(a) **B.S. Altman** (1989) Project: Normal Plate Impact Recovery Experiments onB_4C/Al Cermet

Period of Support: 10/86 - 5/89

(b) **D. Owen** (1991) Thesis: An Investigation into the Microstructural Evolution and Creep Deformation at Elevated Temperatures of a Superplasticity Zirconia-Alumina Composite.

Period of Support: 9/1/90 - 6/30/91

(c) **T. Winter** (1991) Masters Degree by Examination

Period of Support: 9/89 - 6/90

(d) **B. Crafts** (1992) Thesis: High Strain Rate Efects in Tungsten Quasi-Single Crystals

Period of Support: 10/91 - 3/92

Current Status: Was at the Language Internship Program, Yonsei University, South Korea. Now working in the United States.

2.0 CONTINUING PH.D. GRADUATE STUDENTS

J. LaSalvia **Ph.D.** **3/31/94**
(Stipend and tuition/fees supported: 5/92 - 3/31/93)

Publications:

J.C. LaSalvia, L.W. Meyer, and M.A. Meyers, "Densification of Reaction Synthesized Titanium Carbide by High-Velocity Forging," *J. Am. Ceram. Soc.*, Vol. 75, (1992), pp. 592-602

K.S. Vecchio, J.C. LaSalvia, M.A. Meyers, and G.T. Gray III, "Microstructural Characterization of Self-Propagating High Temperature Synthesis/Dynamically Compacted and Hot-Pressed Titanium Carbide," , *Metall. Trans.*, **23A** (1) (1992), pp. 87-97.

M.A. Meyers, J.C.LaSalvia, L.W. Meyer, D. Hoke, and A. Niiler,"Reaction Synthesis/Dynamic Compaction of Titanium Carbide and Titanium Diboride," in *Shock-Wave and High Strain-Rate Phenomena in Materials*, edited by M.A. Meyers, L.E. Murr, and K.P. Staudhammer, Marcel Dekker, New York, NY, (1992), pp. 261-270.

M.A. Meyers, J.C.LaSalvia, L.W. Meyer, D. Hoke, and A. Niiler, "Reaction Synthesis/Dynamic Compaction of Titanium Carbide and Titanium Diboride,", *J. De Physique IV*, **1** (1991), C3-123-C3-130.

J.C. LaSalvia, M.A. Meyers, and D.K. Kim, "Combustion Systhesis/Dynamic Densification of TiC-Ni Cermets," *J. Mat. Synthesis Processing*, (1994), in press.

3.0 ABSTRACTS OF PH.D. DISSERTATIONS

ABSTRACT OF THE DISSERTATION

High-Strain-Rate Plastic Flow in

Metallic Single Crystals

by

Mark Marwan Rashid

Doctor of Philosophy in Engineering Sciences (Applied Mechanics)

University of California, San Diego, 1990

Professor Siavouche Nemat-Nasser, Chair

A numerical algorithm is developed for the integration of the constitutive equations of rate-dependent crystal plasticity theory. The algorithm is based on a weighted residual method, and employs a modified Newton-Raphson iterative solver to achieve reliable and efficient convergence. The algorithm has been implemented in an explicit finite element code for the purposes of analyzing the response of face-centered cubic crystals to high-strain-rate deformations This finite element code was used to simulate the deformation of carefully oriented copper single crystals that were dynamically indented using the split Hopkinson pressure bar. In the experiment, slab-like crystals were subjected to a high-rate edge-indentation by means of a precisely contoured indenter. For comparison, one specimen was subjected to a similar, but quasistatic, edge-indentation. Scanning electron microscopy performed on the deformed specimens revealed that plastic flow occurred by crystallographic slip on a pair of

slip systems oriented approximately 70 degrees apart. Additionally, the quasistatic specimen exhibited bands of concentrated deformation that were absent from the dynamically deformed crystals. The comparison between the computational and experimental results indicates that proper characterization of the rate-dependence of plastic flow is crucial if realistic numerical predictions are to be obtained. In particular, both the computational and the experimental results indicate that the formation of localized modes of deformation is extremely sensitive to strain rate history effects. Accordingly, a Hopkinson bar experiment is proposed for the separation and measurement of instantaneous rate sensitivity and strain rate history effects.

Also, a new theoretical framework for the plastic flow of metallic single crystals is developed. This construct takes explicit account of the dislocation structure responsible for inelastic deformation through the use of dislocation distribution functions. The central relation in the theory is a conservation equation for these distribution functions. This equation accounts for convective motion of dislocations as well as for generation, annihilation, and cross-slip. It is thought that this theory may be of some use in the analysis of sub-grain-sized microstructural features in metals.

ABSTRACT OF THE DISSERTATION

High Strain-Rate Deformation

and Failure of Crystalline Materials

by

Mohammed A. Zikry

Doctor of Philosophy in Engineering Sciences (Applied Mechanics)

University of California, San Diego, 1990

Professor Siavouche Nemat-Nasser, Chairperson

Theoretical and computational models are introduced to study the micromechanical high strain-rate failure mechanisms of shear-strain localization, void collapse and void growth in monocrystalline f.c.c. structures. The micromechanics of plastic flow are based on a constitutive model for the high strain-rate finite deformation of rate-dependent single crystals. A proposed explicit finite-element algorithm is introduced for the integration of the numerically stiff constitutive visco-plastic slip-relations. The combined effects of strain hardening, strain-rate sensitivity, strain-rate history, geometrical and thermal softening and specimen geometry on crystalline failure are studied.

The study consists of six parts. In the first part, the theoretical framework for the rate-dependent constitutive relations, and the computational scheme for the integration of the numerically stiff constitutive relations, are developed. In the second part, numerical examples are presented to illustrate the effects of accuracy, stability and stiffness on the integration of the

constitutive slip-relations. In the third part, high strain-rate tensile localization of copper monocrystals, is studied. Shear-band formation is shown to be due to the thermal and geometrical softening mechanisms surmounting the strengthening mechanisms of the single crystal. In the fourth part, the high strain-rate torsional deformation of monocrystalline aluminum is studied. The computed results show a strong correlation with experimental results for the torsional deformation of aluminum. The high strain-rate compression-induced collapse of a single void is studied in the fifth part, and the high strain-rate tensile growth of a single void is studied in the sixth part. Criteria for the formation, the retardation, and the exclusion of shear-band formation, in monocrystalline copper, are developed. Large stress concentrations, in combination with limiting values of dislocation densities, dislocation velocities, plastic strain-rates and temperatures are shown to lead to the expansion or collapse of the void into a crack. Fundamental differences, between the large inelastic deformation of a dynamically expanding void and a dynamically collapsing void, are elucidated. Based on the present analysis and the experimental corroboration of the computed results, it is shown that the material failure mode is governed by the competition between the strengthening and the softening mechanisms of the crystalline structure.

ABSTRACT OF THE DISSERTATION

Dynamic Deformations and Analysis of a Metal Matrix Composite

BY

BRAD STEWART ALTMAN

Doctor of Philosophy in Engineering Sciences (Applied Mechanics)

University of California, San Diego, 1992

Professor Siavouche Nemat-Nasser, Chair

Deformation of a model particulate reinforced metal-matrix composite is studied over strain rates ranging from 10^{-3} to 10^3/s in compression and 10^{-3} to 10^2/s in tension. The material is 2014 aluminum alloy with alumina particulate reinforcement of 10 and 20 volume percent. Tests are also performed on 2014 aluminum to provide a baseline for comparison. Micromechanical models are used to predict material response. All tested specimens are examined via scanning and transmission electron microscopy to characterize the differences in microstructural evolution and failure modes.

ABSTRACT OF THE DISSERTATION

An Investigation into the Free Sintering and Sinter Forging Behavior of

Single and Dual Phase Alumina - Zirconia Ceramics

by

David McCormick Owen

Doctor of Philosophy in Materials Science

University of California, San Diego, 1993

Professor Atul H. Chokshi, Chair

The elimination of detrimental flaws, such as voids, cracks, and large grains, is essential to the fabrication of highly reliable ceramics. Agglomerates, large aggregates of smaller crystallites, are one of the primary heterogeneities that exist in ceramic powders. Recently, colloidal processing techniques have been developed as a means to improve the reliability of ceramics by facilitating the removal of agglomerates from a dilute liquid-powder slurry. Concurrent shear deformation may assist also in the elimination of flaws as well as enhance the densification rate. Sinter forging is a technique in which shear deformation is introduced by the application of a uniaxial compressive stress without lateral constraint. This dissertation describes an experimental and analytical evaluation of the densification and deformation behavior of single phase and dual phase composite ceramics. Sintering experiments were conducted on several compositions in the zirconia - alumina system under free sintering conditions without stress, and sinter forging conditions with a uniaxial compressive stress. It was demonstrated that the applied stress enhances significantly the rate of densification; however, the mechanisms associated with densification during free sintering and sinter forging are similar. Also, the deformation characteristics of the porous single phase compacts were similar to those observed in fully dense material. The sintering behavior of dual phase materials was shown to depend on the second

phase solubility and particle packing characteristics for low second phase volume fractions, whereas at higher volume fractions the changes in the sintering behavior were determined by the change in the characteristic diffusional path length. The activation energies for either densification or deformation of several compositions were found to be 750±150 kJ mol^{-1}, which varied independently of composition. The similarity of the activation energies for densification and deformation implied that the rate of both processes may be controlled by the diffusion of the same ionic species. An analytical model for pore shrinkage by diffusion along multiple grain boundary paths was developed for free sintering and stress assisted densification. The validity of the model was assessed critically using quantitative pore size measurements on material containing uniform porosity introduced by the pyrolization of polystyrene spheres.

4.0 SUMMARY OF GRADUATE STUDENT RESEARCH:

4.1 *"High Strain Rate Effects in Tungsten Pseudo Single Crystals"* *by: Robert Crafts*

Faculty Advisor: *S. Nemat-Nasser*
Technical Advisor: *J. Isaacs*

Focus of Research:

Bob Crafts research has consisted of the study of tungsten pseudo-single crystals under high strain rate uniaxial compression, low strain rate uniaxial compression, and the related sample preparation and microscopy. He has been involved with the testing of many different varieties of samples – heat treated and non-heat treated, relatively large and small diameter specimens, and different orientations of the preferential grain growth. In the process he has learned to operate the Instron low strain rate testing machine and the Split Hopkinson Compression bar with a momentum trap designed and developed at CEAM. He has learned to use the scanning electron microscope and metallograph. The aim of his research was to characterize the strain rate dependency of the strength of the material and the modes of deformation in these pseudo-single crystals. The samples were grown by a technique related to chemical vapor deposition. At the time of his research the samples with texture orientation in the [100] direction show great ductility, to strains of ~70% true strain, while the samples with texture orientation in the [110] direction demonstrate a high yield stress and relatively low strains, ~ 10%, before failure (i.e., breaking into multiple pieces). One very interesting point to note is that the surfaces of the [100] samples were very badly cracked, but after polishing, relatively little damage is seen. This leads to the conclusion that, after the samples become very hot during the high strain rate experiments (too hot to hold in a bare hand), the steel Hopkinson bars, in essence, quench the sample. This great internal heat is probably partially responsible for the presence of large strains without much evidence of slip deformation or twins, though some cracking is seen. An interesting feature of some of this cracking process is that the cracks are not typical of compression induced cracks which run parallel to the loading direction. Rather there are several examples of the cracks running perpendicular to the loading direction, seemingly along a grain growth transition layer. When the CVD samples are grown, several passes are made. This is clearly visible in both tested and untested samples as two distinct regions termed transition layers. The cracks that are formed in compression testing tend to run along these transition layers. This suggests that the easiest bonds to break are along these transitions. Through his research he endeavored to explain why this occurs; the flow stress, and the deformation mechanisms present in these pseudo-single crystals as compared to those in real single crystals as reported in the literature. Future research will be a continuation of this project. Four samples will be tested in compression using the split Hopkinson bar. The samples will then be prepared for investigation using the transmission electron microscope.

4.2 *"Production of Titanium Carbide and Titanium Carbide Based Composites by Reaction Synthesis and Dynamic Forging"* *by: Jerry LaSalvia*

Faculty Advisor: *M. Meyers*

Technical Advisor: *J. Isaacs*

Current Status and Focus of Research:

The research Jerry La Salvia is currently conducting involves the synthesis of dense titanium carbide and titanium carbide-based composites. The synthesis process that he uses is called self-propagating high temperature synthesis (SHS). This process has been extensively researched by scientists in Russia. It has been estimated that researchers in Russia have produced over 300 different compounds (many of which are produced on a commercial level) by this process.

Materials produced by the SHS process are inherently porous(as high as 50% porosity) due to outgassing of volatile impurities, density differences between the reactants and the products, and due to the initial green porosity. Thus, one of the goals of his research has been to show that dense materials can be produced by combining the SHS process with a simultaneous densifying step.

Due to the energy evolved during the exothermic reaction between titanium and carbon, the final product (i.e. titanium carbide) is raised to an extremely high temperature. In fact, this temperature can approach the melting point of the material(approximately 3000°C). Titanium carbide exhibits a brittle-to-ductile transition temperature. This temperature, depending upon grain boundary impurities lies between 800°C and 1200°C. Thus, the titanium carbide produced by the SHS process is therefore in a ductile state. The structure of the material appears to resemble a foam-like structure, that is, it is highly distended. Because the matrix is in a ductile state, this foam-like structure may be easily collapsed, thereby producing a dense body. The technique by which the foam-like structure is collapsed involves the use of a gas-propelled hammer machine. This machine is called the Dynapak, and has traditionally been used in the aerospace industry for the manufacture of titanium-alloy parts.

To date, he has been successful in producing 10cm diameter titanium carbide disks approximately 0.5 cm thick with densities greater than 97% of the theoretical. The microstructure consisted of equiaxed titanium carbide grains with a mean grain size of about 44 μm. The only limit in size of the disks that can be produced, besides forging die material, is the energy of the machine. Our machine is rated at approximately 17kJ of energy, which is small in comparison to most machines of this type (there are MJ machines).

While he has been successful in producing dense titanium carbide, the technique is not without its share of problems. Because of the experimental set up, thermal shock has been a problem. The problem stems from both the low fracture toughness of titanium carbide and the resulting grain size. To increase the fracture toughness and decrease the grain size, an experiment was conducted with 25 wt % nickel added to the original reaction. The resulting microstructure showed spheroidal titanium carbide grains approximately 10 μm in size embedded in a nickel matrix. Thermal shock did not seem to be a problem with this composition. Future experiments will be conducted with both titanium-carbon-nickel and titanium-carbon-nickel-molybedenum compositions. These materials will be characterized by optical and electron-optical techniques. In addition, mechanical characterization will be conducted. Commercially produced materials can be used as standards for comparison.

He is also currently working on developing a constitutive law for this material. Jerry have concluded thus far that the material behaves like a perfectly-plastic(or viscoplastic) foam over much of the densification process. In the later stages of densification, the material will probably behave as a plastic(or viscoplastic) material containing isolated voids.

Continued research (experimental and theoretical) is included in both the basic sciences of ceramic and ceramic composites, as well as the practical applications of these materials to problems in energy related areas. I would hope to continue this work at either a national laboratory or university.

Jerry's work has been published in journals or has been presented at conferences. Above is a list of publications based upon this research. This work has been presented at the 1991 Annual MTS Conference in New Orleans, Louisana; 1991 DYMAT Conference in Strasbourg, France; 1990 Annual Ceramic Society Conference in Dallas, Texas; 1990 Explomet Conference in San Diego, California; and the First Scientific Workshop on "Forced SHS Compaction" held in Chernogolovka, RussiA, 1992.