REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

1. AGENCY USE ONLY *(Leave blank)*

2. REPORT DATE
1994

1996 JUL 24 A 9:50

3. REPORT TYPE AND DATES COVERED
Final Report 15 Jan 91-14 Jan 94

4. TITLE AND SUBTITLE
"Investigation of Dynamic Material Response for Model Development"

5. FUNDING NUMBERS
DAAL03-91-G-0025

6. AUTHOR(S)
Rodney J. Clifton

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
Brown University
Division of Engineering
182 Hope Street
Providence, RI 02912

8. PERFORMING ORGANIZATION REPORT NUMBER

19960910 027

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)
U.S. Army Research Office
P. O. Box 12211
Research Triangle Park, NC 27709-2211

ARO 28575.3-MS

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)*

Shear band development in a tungsten heavy alloy has been studied by means of pressure-shear plate impact experiments coupled with finite element calculations. By taking into account the viscoplastic response of the constituents, and by utilizing microstructures obtained by digitizing micrographs of the actual alloy, the principal features of the observed shear band features have been obtained in the calculations. This agreement between theory and experiment has provided insight into the mechanism of shear strain localization in tungsten-based composites. Shear band formation and the resulting microstructures have also been studied in AISI 4330 VAR steel. Transmission electron microscope studies have revealed that the microstructure of the tempered martensite, before and after shear band formation, consists of bcc ferrite grains. The effect of the shear localization is to create thin, highly elongated grains as well as dislocation cell structures. Details of the misorientations between neighboring grains and neighboring cells have been determined.

DTIC QUALITY INSPECTED 3

14. SUBJECT TERMS
shear bands, tungsten heavy alloy, WHA, 4340 VAR steel, tungsten-based composites.

15. NUMBER OF PAGES
8

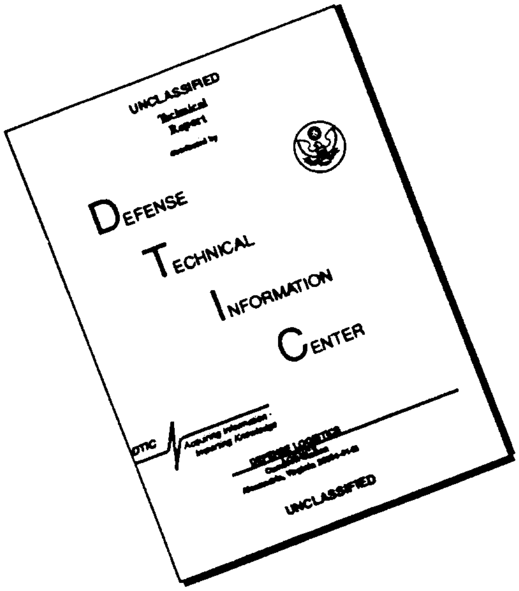
16. PRICE CODE

17. SECURITY CLASSIFICATION OF REPORT
UNCLASSIFIED

18. SECURITY CLASSIFICATION OF THIS PAGE
UNCLASSIFIED

19. SECURITY CLASSIFICATION OF ABSTRACT
UNCLASSIFIED

20. LIMITATION OF ABSTRACT
UL



FINAL REPORT

Title of Proposal: Investigation of Dynamic Material Response for Model Development

Type of Report: Final Report

Author: Rodney J. Clifton

Period Covered by Report: January 15, 1991 - January 14, 1994

Agency: U. S. Army

Contract/Grant Number: DAAL03-91-G-0025

Institution: Brown University
Division of Engineering
Box D
Providence, RI 02912

BRIEF SUMMARY OF RESEARCH FINDINGS

Shear Bands in WHA

Pressure-shear plate impact has been used to study the formation of shear bands in a liquid-phase sintered tungsten heavy alloy (WHA). The experiment (See Fig. 1) involves the shearing of a thin foil specimen sandwiched between two hard tungsten carbide plates. The specimen, which is carefully lapped to thicknesses between 50 μm and 100 μm, is subjected to simple shear for 2 μs at nominal shear strain rates between 10^5 and 10^6 s^{-1}, under pressures of the order of 10 GPa. Plane wave loading is achieved by the impact of a thin specimen, bonded to the front of a tungsten carbide flyer plate, with a stationary anvil plate. Combined pressure and shear loading is obtained by having the parallel impact faces inclined relative to the direction of approach. The stress and strain rate histories are measured by monitoring the impact velocity and the transverse and normal motions of the rear surface of the anvil plate. Stress-strain curves are obtained from the recorded histories of stress and nominal strain rate. The dynamic stress-strain curves obtained (See Fig. 2) show that the flow stress of the alloy is approximately 45 % greater than at strain rates of $10^3 s^{-1}$. Downward slope of the stress-strain curves indicates that thermal softening due to plastic dissipation overcomes strain hardening under dynamic conditions. When the nominal shear strain reaches a critical value, which is between 1 and 1.5, the shear stress sustained by the specimen drops dramatically signifying the onset of shear localization and the formation of a shear band in the specimen.

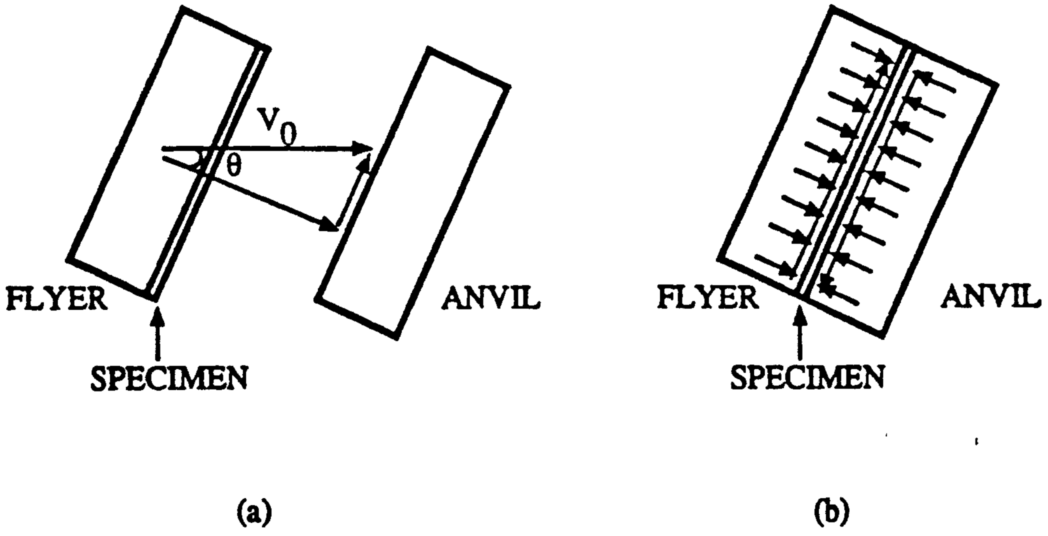


Figure 1: Pressure-shear impact of a thin specimen sandwiched between two elastic plates.

Scanning electron microscopy is used to study the morphology of the shear band. The shear band, located approximately in the middle plane of the thin specimen, is found to be 5 to 10 μm in width and involves both the tungsten grains and the tungsten-nickel-iron (W-Ni- Fe) matrix (binder) phase. (See Fig. 3) The distorted grains form tear-drop shapes. The tails of the tear-drops, together with the neighboring matrix, form the intensely deformed shear band.

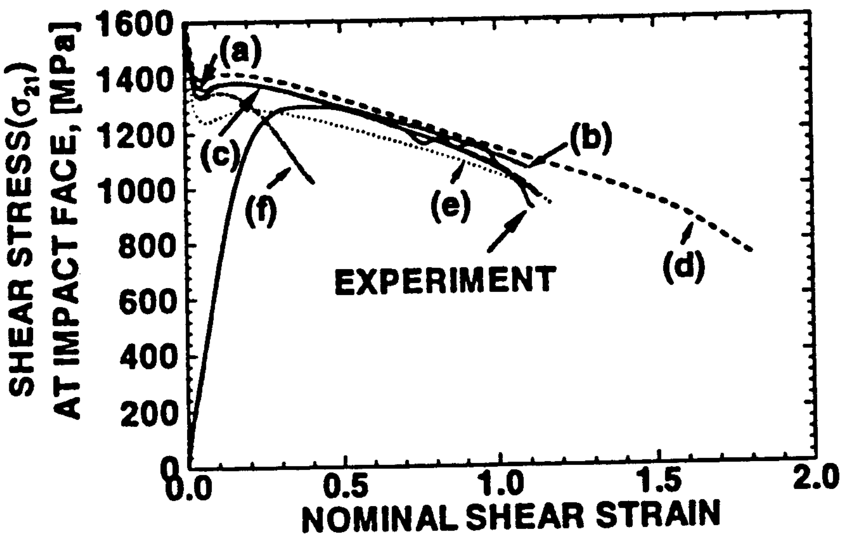


Figure 2: Experimental stress-strain curve for WHA alloy (93-W, 4.9Ni,2.1Fe) in pressure shear at $\dot{\gamma} = 5.4\times10^5 s^{-1}$ and $\sigma_{11} = 9.6GPa$. Curves (a)-(e) are computed curves for the grain-matrix microstructures shown in Figure 4. Curve (f) corresponds to the digitized microstructure (c), but with adiabatic conditions assumed.

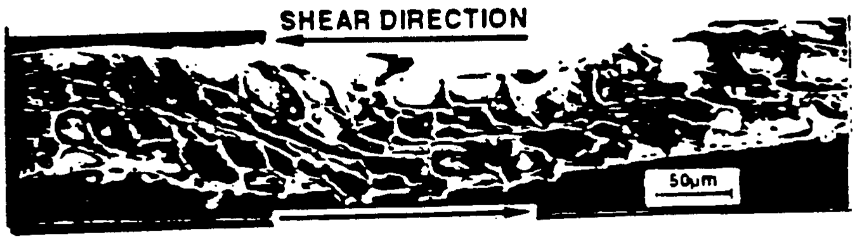


Figure 3: Deformed microstructure of a WHA specimen after pressure-shear plate impact, showing a shear band at the midplane. (The slight bending of the specimen occurred when it was arrested inside a catcher tank filled with soft lead plates.)

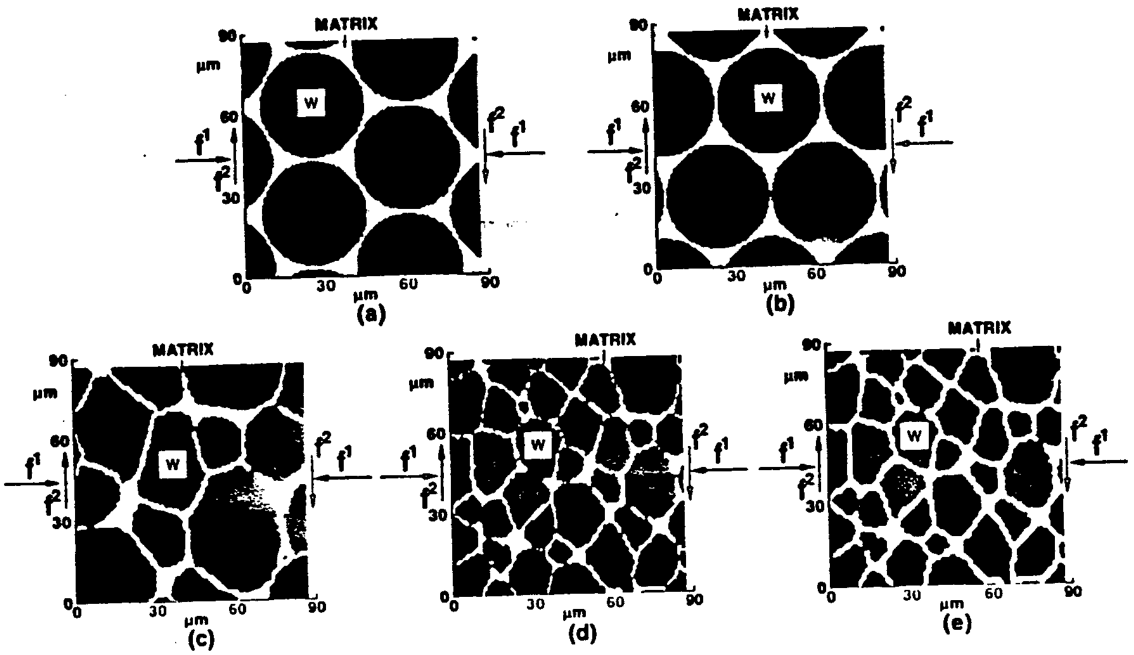


Figure 4: Grain-matrix distributions used in the plane strain numerical analyses; (a) circular grains embedded in a soft matrix; (b) circular grains embedded in a soft matrix, obtained by rotating (a) by 90° counter-clockwise; (c) digitized microstructure from the micrograph of the actual alloy; (d) digitized microstructure with the grain size reduced by a factor of 1.75; (e) the same grain-matrix distribution as in (d) with the grain volume fraction reduced to 76.8%. Distributions (a)-(d) have the same grain volume fraction of 87.7%.

Finite element simulations of the impact experiments have been performed considering the effects of finite deformations, inertia, material thermal softening, rate sensitivity, elasticity, strain hardening and heat conduction. The effect of microscopic material inhomogeneity is considered by modeling the material as a composite of an array of cylindrical tungsten grains connected by a matrix binder phase. (See Fig. 4) The tungsten grains have high density, high flow stress, high melting temperature, low rate of strain hardening and low specific heat while the matrix has lower density, lower flow stress, lower melting temperature, higher rate of strain hardening and higher specific heat. In order to obtain the mechanical behavior of the constituent grains and matrix, pressure-shear plate impact experiments are conducted on both pure tungsten and a custom-made matrix alloy. The matrix alloy, having a composition of $25wt\%W$, $50wt\%Ni$ and $25wt\%Fe$, which is similar

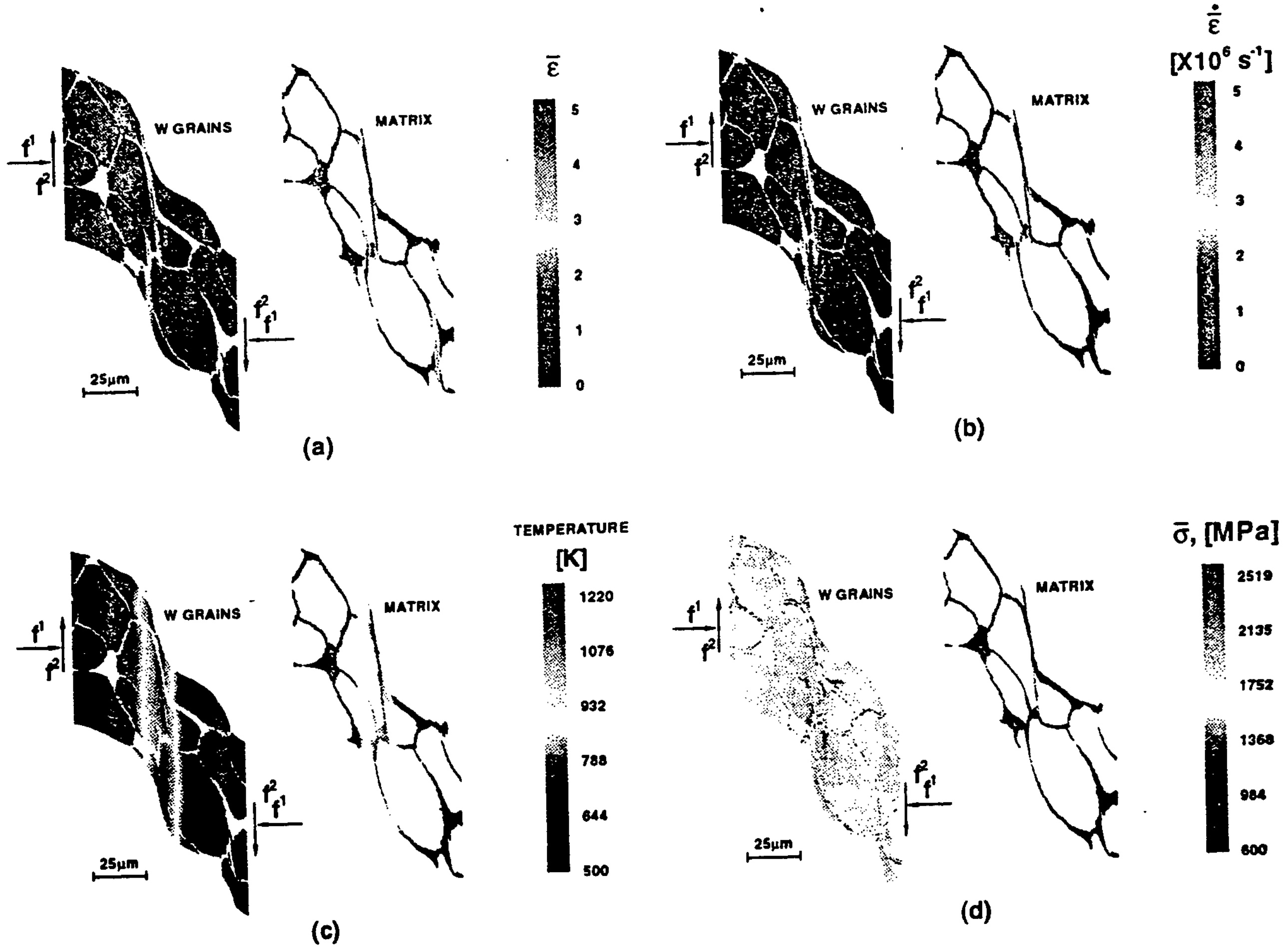


Figure 5: Distributions of (a) equivalent plastic strain rate $\dot{\bar{\epsilon}}$, (b) equivalent plastic strain $\bar{\epsilon}$, (c) temperature, and (d) equivalent stress $\overline{\sigma}$ at 2 μs after impact for the digitized microstructure shown in Figure 4(c).

to the reported compositions of the matrix phase in tungsten heavy alloys, is believed to have similar response to that of the matrix phase in the heavy alloy. Simulation of the experiments demonstrates that conduction of heat into the anvil and flyer plates plays an important role in determining the location of the shear band relative to the impact face. The plane strain simulations demonstrate clearly the development of a shear band, as observed in the experiments. (See Fig. 5) The calculated equivalent plastic strains inside the band are of the order of 12. The relatively lower strength of the matrix gives it a higher rate of plastic straining initially. Subsequently its strength increases substantially because of its relatively high rate of strain hardening. The hardening of the matrix causes the tungsten grains to begin to account for a greater proportion of the plastic deformation. As the two phases are softened by the heat generated from plastic dissipation, the deformation localizes into a band involving both the matrix and the grains, thus exhausting the stress carrying capacity of the composite. The width of the band agrees well with that observed in experiments. From varying the thermal conductivity in the computer simulations, and from theoretical analyses, the width of the band has been shown to be governed by thermal conductivity.

Shear Bands in 4340 Steel

Experiments have been conducted to investigate the process by which adiabatic shear bands are formed in an AISI 4340 VAR steel (425 °C temper). To produce the shear bands, short, thin-walled tubular specimens were deformed in torsion at a nominal shear strain rate of about 10^3 s^{-1} in a torsional Kolsky bar apparatus (split-Hopkinson bar). Strains of a few hundred percent and local strain rates of 10^5 s^{-1} were reached in the region of localization. The temperature rise in the band, recorded using an array of infrared detectors, was approximately 460 °C. Observations of deformed samples by means of transmission electron microscopy (TEM) revealed that the microstructure of the material within the shear band is characterized by highly elongated subgrains and by dislocation cells as shown in Figure 6. Selective area diffraction showed a variation from a ring pattern at the center of the shear band to a spot pattern at the edge of the band. The rings index as α-Fe (bcc); no ring has a radius corresponding to the calculated radius for the bct martensite phase corresponding to the carbon content of the steel. From this evidence it is concluded that the shear band development did not involve a phase transformation to austenite and a subsequent quenching to martensite since no martensitic phase is present in the shear bands.

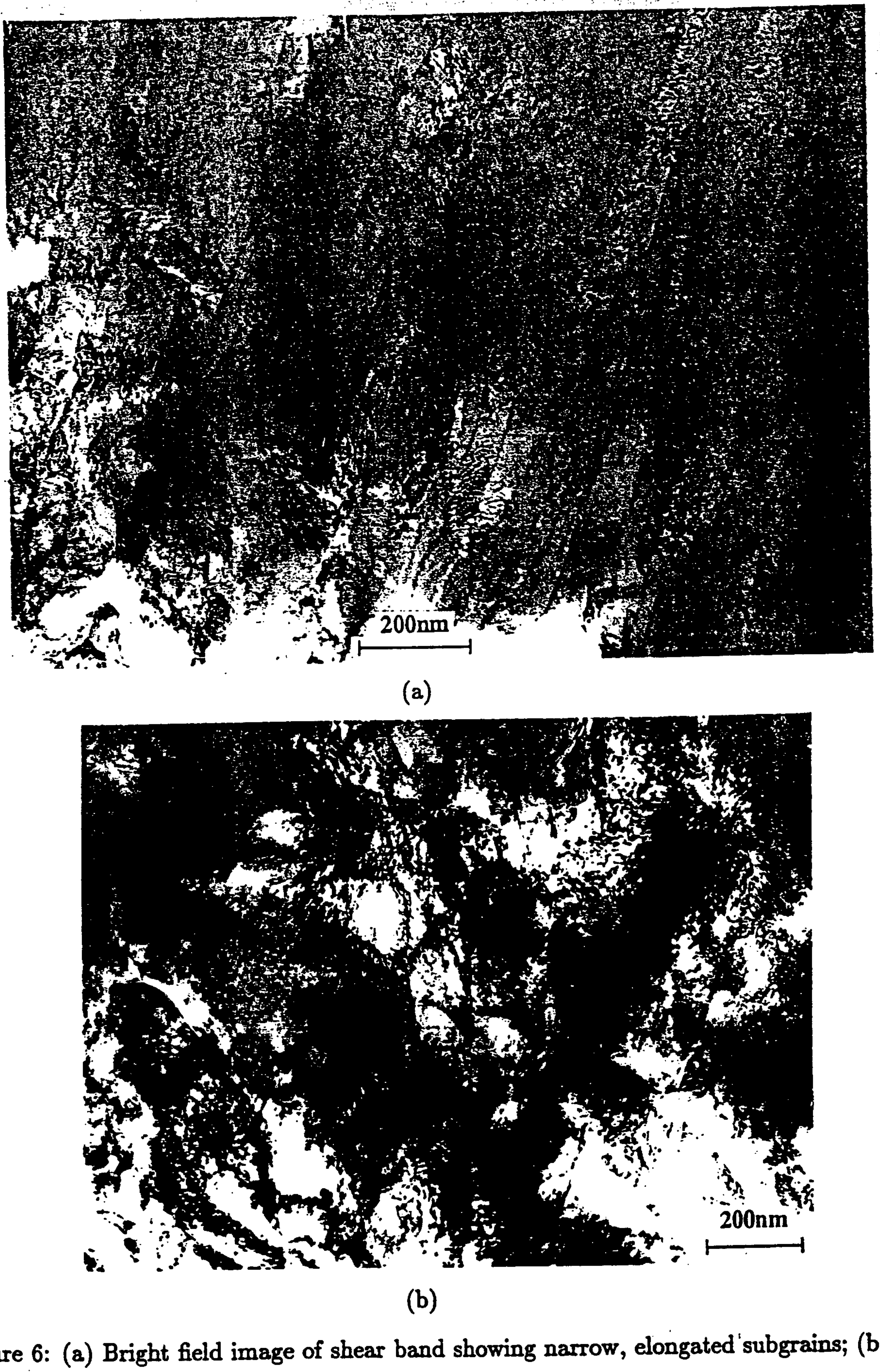


Figure 6: (a) Bright field image of shear band showing narrow, elongated subgrains; (b) dislocation cell structure at the edge of the shear band. (The shearing direction is shown by the double arrow in (a) and is vertical in (b).)

Papers Published under ARO Support

Andrews, E.W., Bower, A.F. and Duffy, J. "Shear Band Formation in a Tungsten Heavy Alloy" (to appear in Mechanics of Materials)

Duffy, J. "Experimental Studies of Shear Band Formation Through Temperature Measurements and High Speed Photography," Proc. DYMAT Conference, Strasbourg, France, October, 1991. *J. de Physique IV*, Colloque C3, pp. 645-652.

Mello, M.C., Prakash, V. and Clifton, R.J., "Multi-Point Interferometer for Monitoring Two-Dimensional Wave Motions," Ibid.. pp. 763-766.

Mgbokwere, C.O., Nutt, S.R. and Duffy, J., "Adiabatic Shear Bands in AISI 4340 Steel: Microstructural Observations," Proceedings of Army Symposium on Solid Mechanics, Plymouth, MA, November, 1991.

Mgbokwere, C.O., Nutt, S.R. and Duffy, J., "Microstructural Observations of Adiabatic Shear Bands in an AISI 4340 VAR Steel", (to appear in Mechanics of Materials).

Prakash, V., Freund, L.B. and Clifton, R.J., "Plane Strain Fracture in Plate Impact," Shock Waves in Condensed Matter–1991, Edited by S.C. Schmidt, R.D. Dick, J.W. Forbes, and D.G. Tasker, pp. 515-518.

Prakash, V., Freund, L.B. and Clifton, R.J., "Stress Wave Radiation From a Crack Tip During Dynamic Initiation," *J. Appl. Mechs.* **59**, 1992, pp. 356-365.

Zhou, M. and Clifton, R.J., "Dynamic Ductile Rupture in a Spheroidized 1045 Steel," Proceedings of Army Symposium on Solid Mechanics, Plymouth, MA, November, 1991.

Zhou, M., Clifton, R.J. and Needleman, "Shear Band Formation in a W-Ni-Fe Alloy under Plate Impact," *Tungsten and Tungsten Alloys - 1992*, Metal Powder Industries Federation, Princeton, NJ, pp. 343-356.

Zhou, M., Clifton, R.J. and Needleman, A. "Shear Bands in Pressure-Shear Plate Impact," Proceedings of Army Symposium on Solid Mechanics, Plymouth, MA, 1993.

Zhou, M., Needleman, A. and Clifton, R.J., "Finite Element Simulation of Dynamic Shear Strain Localization," (to appear in *J. Mechs. Phys. Solids*).

Scientific Personnel Supported by this Project and Degrees Awarded during this Reporting Period

E. Andrews
J. Blume
R. J. Clifton (P.I.)
J. Duffy
L. B. Freund
G. LaBonte
H. C. Lei
M. Mello
C. Mgbokwere
S. R. Nutt
S. Y. Shen
M. Zhou

Report of Inventions (by Title Only)

NONE