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The following main results were completed during the previous grant period.

A photo-elastic technique to measure plastic flow and instability has been developed and measurements for shear band characteristics have been obtained.

An innovative biaxial experimental apparatus for determining the evolution of the yield loci with plate specimens has been designed and manufactured.

Constitutive models incorporating the effects of anisotropy, texture, material rotation, and inhomogeneity have been developed and successfully used to interpret available experimental data such as axial effects in torsion.

Numerical evaluations for shear band and plastic instability problems have been performed resulting in new information about the effects of anisotropy and texture on the stability of plastic deformation.

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THEORETICAL, EXPERIMENTAL AND COMPUTATIONAL STUDIES IN PLASTICITY

(FINAL REPORT)

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OCTOBER 1994

U.S. ARMY RESEARCH OFFICE

DAAL 03-90-G-0151

MICHIGAN TECHNOLOGICAL UNIVERSITY
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1. RESULTS FROM PRIOR ARO SUPPORT

A joint research program between MTU and WSU entitled "Theoretical, Experimental and Computational Studies in Plasticity" was carried out during the last three years with the financial support of ARO under Grant No. DAAL 03-90-G-0151. The program was very successful in terms of expanding our fundamental understanding of the mechanics and physics of plastic flow and related instabilities in the case of large deformations. Several graduate students were partially supported by the grant, three PhD degrees were awarded, and one post-doctoral fellow was involved. The results obtained during the past grant period have encouraged us to seek additional ARO support for continuing and expanding our previous large deformation plasticity and instability studies to consider the peculiarities of fiber- or particle - reinforced composites as outlined in the present proposal. Below, a summary of the main accomplishments and results is provided. It is pointed out, in this connection, that a similar approach and philosophy will also be adopted for the newly proposed project and, therefore analogous research, educational and technology transfer - related results are to be expected.

Objectives Accomplished: The goal of the program was to characterize material behavior at large plastic deformations via theory, experiment and computation as follows:

- Develop sensing methodologies to measure material characteristics and formability (e.g. instabilities, yielding, localization).
- Develop unifying physically based constitutive models to characterize material behavior at a wide range of loading conditions.
- Develop appropriate numerical schemes and enrich existing finite element codes with the new features of the obtained models.
- Cast the main results into an easy-to-use form for applications in critical problems of current technology and of interest to Army (e.g. penetration mechanics).

Experiments: The following techniques/apparatuses were developed and used to measure critical material properties such as anisotropy, yield surfaces, noncoaxiality, and inhomogeneity:

- A photo-elastic technique to characterize plastic flow and instability.
- A biaxial testing apparatus to characterize yield surfaces and noncoaxiality.

Theory: Various classes of physically-based (and mathematically simple) large deformation plasticity models were developed by using the configuration of single slip together with a maximization procedure for the microscopic plastic work and a scale invariance argument to connect micro to macro scales. These models are much simpler to use than corresponding crystal plasticity models. At the same time they do capture important features of crystal plasticity models such as:

- Existing or deformation induced plastic anisotropy and noncoaxiality.
- Distortion of yield surfaces and the onset of localization of deformation.

In particular, directional hardening and axial effects in torsion are modelled quite well by the present approach as discussed below.

Computations: The computational effort of the program involved the following:

- Implementation of the new theoretical models into numerical codes for large scale engineering problems (e.g. penetration manufacturing).
- Solution of specific boundary value problems in order to test the new features of the models and calibrate them according to available experimental data.

Technological Relevance: Among the direct contributions of the completed program to advanced technology, the following are singled out:

- Development of state of the art theoretical/numerical/experimental tools to characterize and optimize material processing and behavior.
- Improvement of basic knowledge of large deformation processes leading to increased productivity and optimum performance of components used in aerospace, manufacturing and nuclear technologies.

Main Results Accomplished: The following main results were completed during the previous grant period.

- A photo-elastic technique to measure plastic flow and instability has been developed and measurements for shear band characteristics have been obtained.
- An innovative biaxial experimental apparatus for determining the evolution of the yield loci with plate specimens has been designed and manufactured (see Figure 1).
- Constitutive models incorporating the effects of anisotropy, texture, material rotation, and inhomogeneity have been developed and successfully used to interpret available experimental data such as axial effects in torsion (see Figure 2).
- Numerical evaluations for shear band and plastic instability problems have been performed resulting in new information about the effects of anisotropy and texture on the stability of plastic deformation.

Personnel: The following graduate students, post-docs and faculty were partially supported during the previous grant period.

Graduate students names	Degree (Graduation)	School
G. Panger	MS (1991)	WSU
C. Cusack	MS (1991)	MTU
T. Webb	Ph.D. (1992)	MTU
H. Zhu	Ph.D. (1993)	WSU
S. Lin	Ph.D. (1994)	WSU
Dr. Ning Jie	Post Doc	MTU

Faculty	School
Professor E.C. Aifantis	MTU
Professor H.M. Zbib	WSU
Professor J.L. Ding	WSU

Publications: The following publications were realized during the previous grant period:

1. Panger, G., Ding, J.L., Zbib, H.M., and Aifantis, E.C., "Measurements of Shear Band Characteristics in Low Carbon Steel Using Photoelasticity, " Scripta Metall. et. Mater., 25, 2103-2108, 1991.

2. Zbib, H.M. and Aifantis, E.C., "On the Structure and Width of Shear Bands in Finite Elastoplastic Deformation," in: Anisotropy and Localization of Plastic Deformation, J.P. Boehler and A.H. Khan, eds., pp. 99-102, Elsevier Appl. Sci., 1991.

3. Zhu, H., Zbib, H.M. and Aifantis, E.C., "On the Effect of Anisotropy and Inertia on Shear Banding: Stability of Biaxial Stretching," Appl. Mech. Reviews, 45, No. 3, Part 2, 1992, 110-117.

4. Zbib, H.M., and Aifantis, E.C., "On the Gradient-Dependent Theory of Plasticity and Shear Banding," Acta Mechanica, 92, 209-225, 1991.

5. Zbib, H.M., "A Model for Elastoplastic Materials with Anisotropic and Vertex effects," in: Microstructural Characterization in Constitutive Modeling of Metals and Soils," G. Voyiadjis, ed., MD-Vol. 32, ASME, 1992, 45-53.

6. Lin, S., Ding, J.L., Zbib, H.M., and Aifantis, E.C., " Characterization of Yield Surfaces Using Balanced Biaxial Tests of Cruciform Specimens", Scripta Metall. et Materialia, 28, 617-622, 1993.

7. Zbib, H.M., and Aifantis, E.C., "On the Stability of Finite Plastic Deformation's (Keynote Lecture), in: Finite Inelastic Deformations (IUTAM Symp. Hannover), D. Besdo and E. Stein, eds. pp. 15-25, Springer-Verlag, 1992.

8. Aifantis, E.C., "On the Role of Gradients in the Localization of Deformation and Fracture", Int. J. Engr. Sci., 30, 1279-1299, 1992.

9. Shi, M.F., Gerdeen, J.D. and Aifantis, E.C., "On Finite Deformation Plasticity with Directional Softening, Acta Mechanica 101, 69-80, 1993.

10. Ning, J. and Aifantis, E.C., "On Anisotropic Finite Deformation Plasticity, Part I: A Two Back Stress Model" Acta Mechanica 106, 55-72, 1994.

11. Ning, J. and Aifantis, E.C., "On Anisotropic Finite Deformation Plasticity, Part II: A Two-Component Model", Acta Mechanica 106, 73-85, 1994.

12. Ning, J. and Aifantis, E.C., "On the Description of Anisotropic Plastic Flow by the Scale Invariance Approach", preprint.

13. Zhu, H.T., Zbib, H.M. and Aifantis, E.C., "On the Role of Strain Gradients in Adiabatic Shear Banding", preprint.

14. Van der Giessen, E. and Aifantis, E.C., "On the Plastic Spin and Texture Description via the Scale Invariance Approach," preprint.

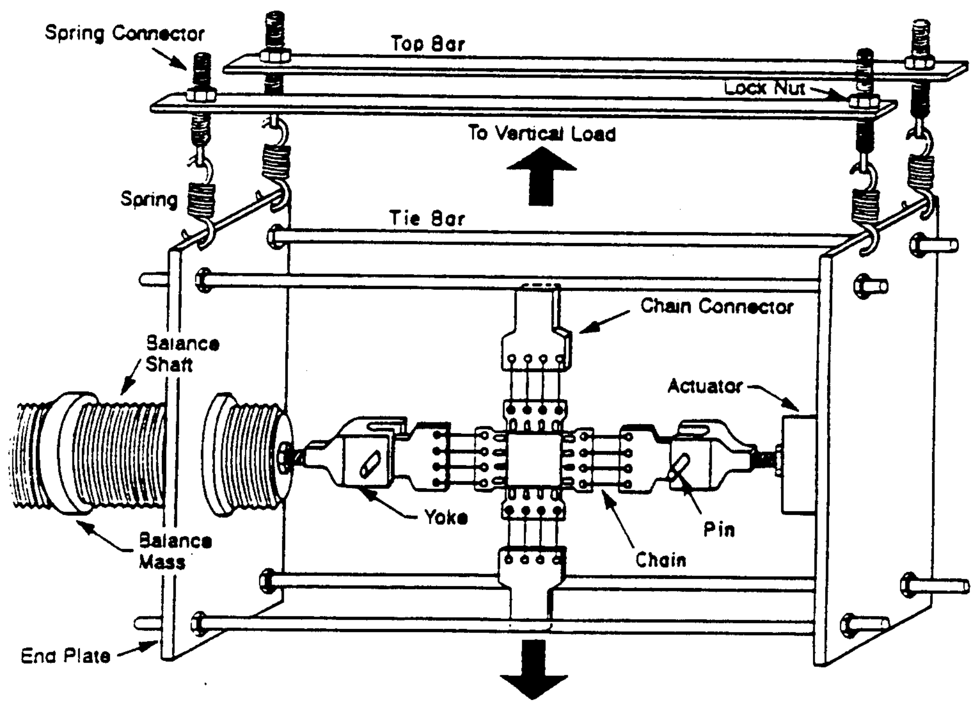

Figure 1. Schematic diagram of the experimental setup

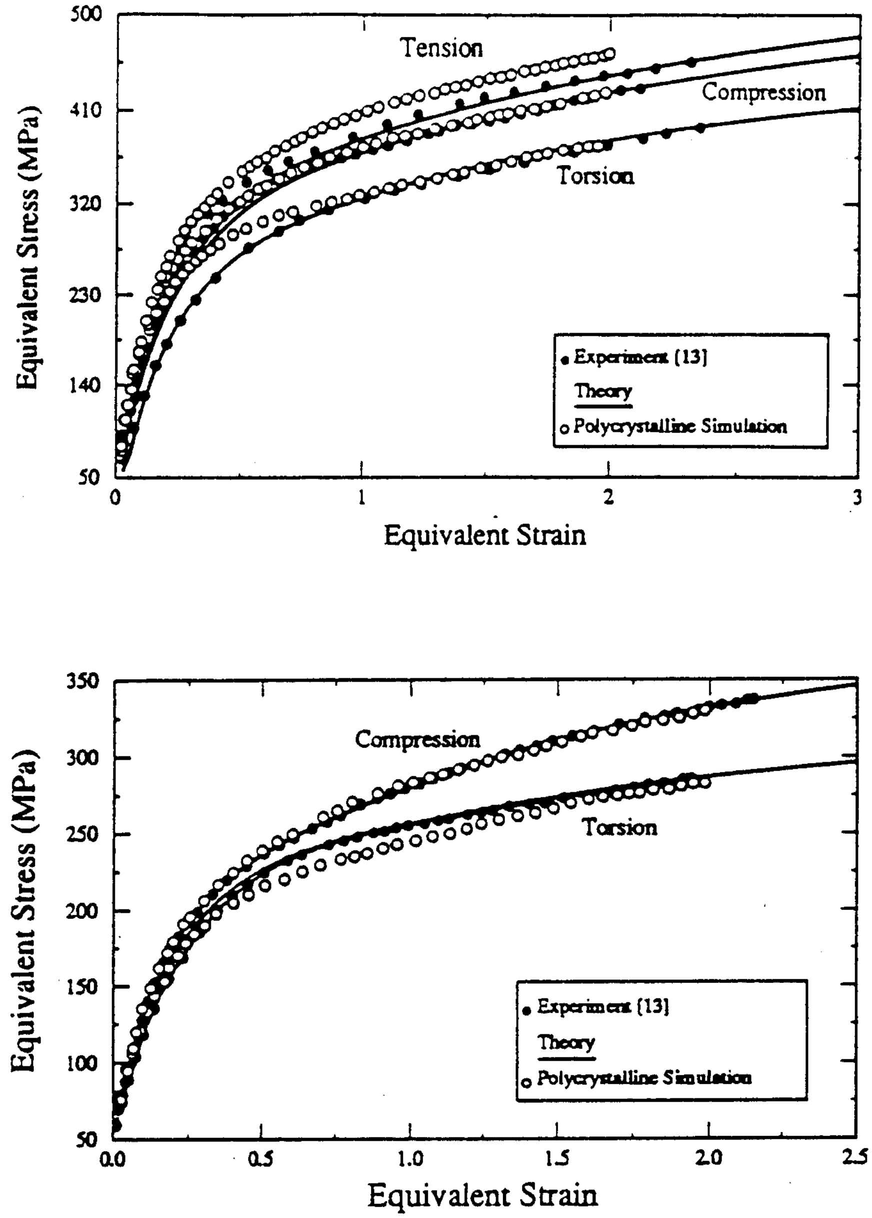

Figure 2. Equivalent stress-strain curves under different loading conditions for a) OFE copper, and b) silver.