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Workshop on Shear Bands
March 23-25, 1992
(Abstracts)

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March 1992

Carnegie Mellon

Carnegie Mellon University
Center for Nonlinear Analysis
Workshop on Shear Bands
March 23-25, 1992

FINAL PROGRAM
Location: Software Engineering Institute Auditorium, Carnegie Mellon University

ORGANIZERS
Morton E. Gurtin, Department of Mathematics, Carnegie Mellon University
John Walter, U.S. Army Ballistic Research Laboratory

Monday, March 23, 1992

9:15 **M. Gurtin**, Department of Mathematics, Carnegie Mellon University

Introduction

9:30 **R. Clifton**, Division of Engineering, Brown University

"An Update on Experimental Investigations of Shear-Strain Localization at High Strain Rates"

10:30 Break

11:00 **T. Wright**, U.S. Army Ballistic Research Laboratory

"Asymptotic Analysis of Adiabatic Shear Band Formation"

12:00 Lunch

1:30 **J. Walter**, U.S. Army Ballistic Research Laboratory

"Numerical Experiments on Adiabatic Shear Band Formation in One Dimension"

2:30 **C. Dafermos**, Division of Applied Mathematics, Brown University

"Thermal Softening in Shear Bands"

3:30 Break

4:00 **M. Myers**, Department of Applied Mathematics and Engineering Science, University of California, San Diego

"Microstructural Evolution in Shear Localization"

Tuesday, March 24, 1992

9:30 **R. Armstrong**, Department of Mechanical Engineering, University of Maryland

"Microstructural/Dislocation Mechanics Aspects of Shear Banding in Polycrystals"

10:30 Break

11:00 **W. Edward Olmstead**, Department of Engineering Sciences, Northwestern University

"Shear Bands as Discontinuities"

12:00 Lunch

2:30 **J. F. Kalthoff**, Experimental Mechanics, Ruhr Universität Bochum

"Analysis of the Formation of Adiabatic Shear Bands by the Shadow Optical Method of Caustics"

3:30 Break

4:00 **R. Malek-Madani**, Department of Mathematics, U.S. Naval Academy

"Some Examples of Shear Localization in Continuum Mechanics"

5:30 **Reception**, Carnegie Mellon College Club

Wednesday, March 25, 1992

9:30 **A. Tzavaras**, Department of Mathematics, University of Wisconsin, Madison

"Analysis of Models Describing Adiabatic Shear Bands"

10:30 **M. Berstch**, Dipartmento di Matematica, Università di Roma 2

"A Mathematical Model of Heat Transfer in Stably Stratified Turbulent Shear Flow"

11:30 Lunch

1:00 **T. Burns**, Applied and Computational Mathematics Division, National Institute of Standards and Technology

"Some Connections Between Localized Behavior in Plasticity and in Combustion"

To register for this workshop, please contact Deborah Hardy, Department of Mathematics, Carnegie Mellon University, (412) 268-2545, or cn0s@andrew.cmu.edu.

MICROSTRUCTURAL/DISLOCATION MECHANICS ASPECTS OF SHEAR BANDING IN POLYCRYSTALS

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ABSTRACT

At increased tensile strain rates or decreased test temperatures, face-centered-cubic (fcc) metals show an increased uniform strain to the maximum load point, in contrast to the decreased uniform strain behavior exhibited by body-centered-cubic (bcc) metals under the same conditions (1). The opposite tensile plastic instability behaviors of the two structure-types are explained on a thermal activation/strain rate analysis (TASRA) basis in terms of strain-dependent dislocation "forest" intersections controlling the fcc thermal component of stress as compared with a strain-independent intrinsic Peierls stress for individual dislocations being responsible for the relatively larger bcc thermal component of stress (2). Bcc metals are differentiated from fcc metals, also, by showing an initial discontinuous yield point behavior that is increasingly pronounced as the polycrystal grain size is smaller (3). The yield point behavior is explained by the breakthroughs at grain boundaries of blocked dislocation pile-ups in slip bands. The behavior is gauged by the microstructural stress intensity value determined from the dependence of yield stress on the reciprocal square root of the average polycrystal grain diameter (3,4). Substantial temperature rises are calculated on a dislocation pile-up avalanche basis for this instability behavior in metallic, ionic, and energetic (explosive) materials (5,6).

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Shear Instability Testing of High-Strength Steels

Morris Azrin
John H. Beatty
Brian Pothier
U.S. Army Materials Technology Laboratory
Watertown, MA

Abstract

The U.S. Army Materials Technology Laboratory has an ongoing study to determine the effect of second phase dispersions on shear instability. This presentation will report the results of experiments performed on 4340 steel for different normalizing conditions, and present the outline of study to be used for future work in this area. Shear instability has been found to vary with the carbide dispersion in 4340 steel at both low and high shear strain-rates. Shear instability testing included quasi-static and dynamic thin-wall torsion, quasi-static and dynamic double linear-shear (with and without an applied normal stress), and a unique hat-shaped shear specimen for use with a split-Hopkinson bar. Using this spectrum of tests on different microstructures and alloys should serve to elucidate the underlying mechanisms of destabilization of plastic flow in these materials.

A Mathematical Model of Heat Transfer in Stably Stratified Turbulent Shear Flow

Michiel Bertsch
Università Degli Study Di Roma II

A degenerate pseudo-parabolic PDE is derived from the balance law for the turbulent energy. The imposed shear field is supposed to be statistically homogeneous in horizontal direction. The equation is not connected with a special model of turbulence. The mathematical problem is shown to be well-posed, and the peculiar behaviour of its solutions (in particular the occurence of discontinuities) is studied in detail.

The results presented in this lecture are obtained in collaboration with G. I. Barenblatt (Moscow), R. Dal Passo (Rome) and M. Ughi (Trieste).

SOME CONNECTIONS BETWEEN LOCALIZED BEHAVIOR IN PLASTICITY AND IN COMBUSTION

Timothy J. Burns
Computing and Applied Mathematics Laboratory
National Institute of Standards and Technology
Gaithersburg, Maryland 20899

There are some interesting similarities between the localization of plastic strain into *adiabatic shear bands* during rapid plastic shearing of metals and chemical explosions during rapid combustion processes. In particular, both processes are thermally activated, and the dependence on temperature can be modeled in both cases by an Arrhenius rate law, with large thermal activation energy. Furthermore, both processes are characterized by thin internal layers where most of the interesting phenomena occur. During shear band formation, most of the plastic deformation is confined to the narrow region of the shear band; during an explosive chemical combustion process, the chemical reaction is confined to a thin reaction zone. A mathematical model will be presented of adiabatic shear strain localization in plasticity, which will then be compared with a well-known mathematical model of explosive reaction in chemical combustion. Some open problems will also be discussed.

An Update on Experimental Investigations of Shear-Strain Localization at High Strain Rates

Rodney J. Clifton
Professor of Engineering
Rush C. Hawkins University Professor
Brown University

Abstract

Shear band formation is reviewed with emphasis on results obtained from torsional Kolsky bar experiments and transmission electron microscopy (TEM). The torsional Kolsky bar is presented as an attractive configuration for shear band investigations because it provides a simple shearing deformation for which one can record (in real time) the applied shear stress, the nominal shear rate, and the variation of strain and temperature across the band. Recent results of Duffy and co-workers are presented for martensitic steels (especially 4340), a tungsten heavy alloy (WHA), Ti-6Al-4V, and OFHC copper. TEM observations of the shear bands in 4340 steel (425°C temper) reveal dislocation cells outside the band and lamellar structures, aligned with the shearing direction, inside the band. The width of the lamella ($\approx 0.1\mu m$) is comparable to the diameter of dislocation cells at the edge of the band and an order of magnitude smaller than the widths of the laths in the pre-test microstructure of tempered martensite. These observations are interpreted as suggesting that the transition from the dislocation cell structure to the lamellar structure is closely connected with the formation of shear bands in martensitic steels. Selected area diffraction analysis allows the structure of the material within the band to be identified as primarily α-iron with weak concentrations of unidentified carbides.

Torsional Kolsky bar experiments and pressure-shear plate impact experiments on WHA and OFHC copper are reported which show that shear bands are formed in the torsion tests but not in the plate impact tests even though the shear strains are larger in the plate impact tests. These observations may indicate that hydrostatic pressure tends to inhibit the formation of shear bands in these materials; however, there are alternative explanations, including the stabilizing effect of inertia at the higher strain rates of the plate impact tests. The shear bands in copper are relatively wide and form at relatively large shear strains ($\approx$90%). TEM studies of the copper reveal dislocation cells which develop lamellar structures as the angular misorientation from cell-to-cell, along the shearing direction, becomes much less than the misorientation perpendicular to the shearing direction. Shear bands in WHA form after the tungsten grains become highly elongated and rotated toward alignment with the shearing direction. Shear bands obtained in WHA in a plane strain, symmetric punch indentation test in plate impact are especially narrow, with widths of approximately $1\mu m$.

Shear band formation in Ti-6Al-4V is shown to lead to narrow bands (≈10μm). Strain hardening is especially small in this material and the critical strains at strong localization are highly sensitive to variations in the wall thickness of the tubular specimens.

Future research is suggested in further utilization of the torsional Kolsky Bar configuration for both experiments and detailed mathematical modeling. Greater utilization of TEM is recommended as important for improved understanding of the mechanisms of shear band formation. Special emphasis should be placed on the formation of sub-micron lamellar textures. Pressure effects and the role of the Ni-Fe-W binder in WHA should also be examined.

Thermal Softening in Shear Bands

C. M. Dafermos
Division of Applied Mathematics
Brown University

The lecture outlines an analytical investigation of the equations that govern the plastic shearing of a slab. The objective is to determine whether thermal softening may initiate instability of the uniform shearing motion that may lead to the formation of shear bands.

Some Examples of Shear Localization in Continuum Mechanics

Reza Malek Madani
U.S. Naval Academy

I will describe the formulation of localized shear solutions in three models: a) simple shearing of a plastic material, b) motion of a lubricant in elasto-hydro-dynamics, and c) formation of wing-cracks in ice. I will also describe an abstract stability theorem and its connnection to the steady-state solutions of the above models.

Microstructural Evolution in Shear Band Formation

Marc André Meyers
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University of California, San Diego

Abstract

Work conducted by author and co-workers over the past ten years on shear-band formation is reviewed [1-9] with emphasis on microstructural aspects. Shear-band configurations in low-carbon (AISI 1018 and 8620) steels, medium-carbon (VAR 4340) steel, high carbon (AISI 1090) steel, titanium and titanium alloys, and copper are described. Two basic experimental approaches have been used: (a) impact experiments [1-6], in which no control of the formation of shear bands can be obtained, but which display a wide range of phenomenology; and (b) controlled shear experiments using a compressional Hopkinson (Kolsky) bar [7-9]. Observations by optical microscopy (up to a magnification of 1,000) do not reveal any significant textures inside the bands, and transmission electron microscopy is an essential tool to develop an understanding of the microstructure within the shear band. These observations reveal a very fine grain size (0.02 to 0.2 μm), and a relatively low dislocation density. For copper [7,8], the regions adjoining the shear band consist of elongated subgrains which gradually break down at the shear band core. These major microstructural changes are suggestive of dynamic recovery and/or recrystallization processes within a shear band. A detailed knowledge of the evolution of the microstructure during high strain, high strain rate, deformation under adiabatic or quasi-adiabatic conditions is a very important component of the modeling of shear-band formation.

A second aspect of shear-band formation that is of utmost importance and has been virtually ignored by researchers is the propagation of the band tip. One can envisage the shear band as a Mode II or III crack and should study its advance [3]. A preliminary treatment using the finite element method has been developed by Kuriyama and Meyers [3].

The propagation of shear bands is also complicated by factors such as bifurcation; this aspect has herefore not been investigated.

The initiation of shear-band formation within the material is triggered by microstructural or thermal fluctuations, and a few examples are:

*Rotation (texture) softening
*Microbands
*Dislocation pile-up avalanches
*Second-phase particles
*Ludens band-yield drop
*Dislocation (substructural) softening

The last stages in shear-band formation are coalescence with other shear bands, and cooling and fracture by a ductile or brittle mode along the bands. This leads to the fragmentation of the material.

In summary, the four stages of formation of shear bands that should be investigated are:

1. Initiation
2. Propagation
3. Bifurcation and coalescence
4. "Freeze-up" and fracture

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Analysis of the Formation of Adiabatic Shear Bands by the Shadow Optical Method of Caustics

J. F. Kalthoff
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Abstract

A technique is described for generating failure by either fracture processes or adiabatic shear bands from shear impacted cracks or notches by varying the loading rate. The technique allows for generating macroscopic adiabatic shear bands in the laboratory by applying modest impact velocities in the range of 30 m/s to 100 m/s only. The shadow optical method of caustics in combination with high speed photography is used to quantify the stress strain concentration rates that are obtained in experiments with specimens made from an epoxy resin and high strength steels. The physical principles of the caustic technique and in particular its application for analyzing dynamic failure phenomena are presented. The damage behavior observed in series of experiments with systematic variation of the local loading rate are presented and discussed with respect to the size of the damage, damage orientation, damage appearance, and the energy absorption associated with the varying failure mechanisms. An outline of a simple continuum mechanics concept for quantitatively describing failure by adiabatic shear bands is given.

SHEAR BANDS AS DISCONTINUITIES

W. Edward Olmstead
Northwestern University

Shear bands which are observed in high-strength metals are typically only about ten micros in thickness. This relative smallness compared to the size of the material sample suggests treating the shear band as a surface of discontinuity. A consistent approach utilizing this concept is developed for the basic one-dimensional theory.

Representing the shear band as a surface of discontinuity implies a jump in both the velocity and temperature gradient across this surface. The continuity of stress and temperature across the shear band are maintained, as well as the inherent symmetry of the problem. This description appears to be entirely compatible with experimental results.

Describing the shear band as a surface of discontinuity allows for a significant simplification of the mathematical problem which is analogous to the treatment of flame fronts in combustion. Using this approach, equations for the temporal evolution of temperature and stress in the shear band are derived.

Analysis of models describing adiabatic shear bands

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Abstract

One of the most striking manifestations of instability in solid mechanics is the localization of shear strain into narrow bands during high speed, plastic deformations of metals. According to one theory, the formation of shear bands is attributed to effective strain-softening response, which results at high strain rates as the combined outcome of the influence of thermal softening on the, normally, strain-hardening response of metals. Our objective is to review some of the insight offered by nonlinear analysis techniques on simple models of nonlinear partial differential equations simulating this scenario for instability. First, we take up a simple system, intended as a paradigm, that describes isothermal shear deformations of a material exhibiting strain softening and strain-rate sensitivity. As it turns out, for moderate amounts of strain softening, strain-rate sensitivity exerts a dissipative effect and stabilizes the motion. However, once a threshold is exceeded, the response becomes unstable and shear strain localization can occur. Next, we present extensions of these results to situations where explicit thermal effects, through the energy equation, are taken into account.

Numerical Experiments
on
Adiabatic Shear Band Formation
in
One Dimension

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Adiabatic shear band formation in an elastic, thermo-visco-plastic, simple material is studied in the context of unidirectional shearing of an infinite slab. The effect of varying the thermal softening behavior of the material on localization strain and post-localization morphology is studied for a rigid, perfectly-plastic material; the material parameters are appropriate for a high-strength steel. In this case it is demonstrated that localization of the strain rate can be *transient*. A coupling between linear-elastic response and the basic thermo-visco-plastic localization mechanism is explored in the absence of strain hardening. Lastly, the flow law is modified to include strain hardening in order to simulate a high-rate torsion test on OFHC copper. In this case localization is initiated by thermal boundary layer diffusion. When a flow law of simple "over-stress" type (specifically that of Johnson and Cook [1]) is employed the solution takes on a complex, apparently nonperiodic, post-localization morphology quite different from that in the perfectly-plastic cases. This may be due, in part, to the fact that this sort of flow law does not account for dynamic recovery processes which occur due to the very large strains and high temperatures experienced during shear band formation. Consequently, the same problem is simulated using the MTS flow law [2], which does account for dynamic recovery, and substantially different post-localization behavior is observed.

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Asymptotic Analysis of Adiabatic Shear Bands

Thomas W. Wright
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Abstract

Over the last ten or twelve years, there has been renewed interest in developing the mathematical theory of adiabatic shear bands. One major theme has been to make a clear distinction between instability and localization. The former refers to incipient growth of inhomogeneities; the latter refers to a dramatic narrowing of the deformation zone, accompanied by a sharp loss of shear strength and an increase of strain rate and temperature in the band. Localization can occur significantly later than instability due to heat conduction and strain rate effects. The rapid transients at localization are then followed by a final phase associated with a fully formed band.

A second major theme has been to elucidate the role of various nondimensional groups of physical parameters. Inertia can often be ignored in problems with finite domain, but not in those with infinite domain. Thermal conductivity tends to stabilize the material, or to retard localization if the stability threshold is exceeded, and plays a major role in determining the post localization morphology. Strain rate sensitivity retards the formation of shear bands, but does not prevent singularities in the solution (i.e., regularize the equations) in the absence of thermal conductivity. Elasticity is relatively unimportant before localization. Thermal softening is the essential ingredient for localization, and often only the initial rate of softening plays a major role before localization. Throughout, work hardening is a major complication in the analysis since it introduces an extra degree of freedom into problem.

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