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INELASTIC DEFORMATION OF METALS UNDER DYNAMIC LOADING.(U)
SEP 76 J DUFFY, R J CLIFTON DA-ARO-D-31-124-73-G182

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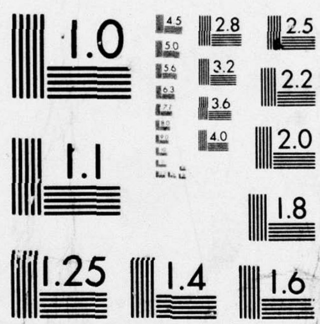

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INELASTIC DEFORMATION OF METALS UNDER DYNAMIC LOADING

FINAL REPORT

J. DUFFY AND R. J. CLIFTON

SEPTEMBER 3, 1976

U. S. ARMY RESEARCH OFFICE

DA-AROD-31-124-73-G132
DAHC04-75-G-0174

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SECURITY CLASSIFICATION OF THIS PAGE (When Data Entered)

REPORT DOCUMENTATION PAGE

READ INSTRUCTIONS BEFORE COMPLETING FORM

1. REPORT NUMBER: DAHC04-75-G-0174/1	2. GOVT ACCESSION NO.
3. RECIPIENT'S CATALOG NUMBER	
4. TITLE (and Subtitle): Inelastic Deformation of Metals Under Dynamic Loading.	5. TYPE OF REPORT & PERIOD COVERED: Final Report. 1 July 1973 — 30 June 1976
	6. PERFORMING ORG. REPORT NUMBER
7. AUTHOR(s): J. Duffy, R. J. Clifton	8. CONTRACT OR GRANT NUMBER(s): DA-ARO-D-31-124-73-G182, DAHC04-75-G-0174
9. PERFORMING ORGANIZATION NAME AND ADDRESS: Division of Engineering, Brown University, Providence, RI 02912	10. PROGRAM ELEMENT, PROJECT, TASK AREA & WORK UNIT NUMBERS
11. CONTROLLING OFFICE NAME AND ADDRESS: U.S. Army Research Office, P.O. Box 12211, Research Triangle Park, NC 27709	12. REPORT DATE: September 3, 1976
	13. NUMBER OF PAGES: 5
14. MONITORING AGENCY NAME & ADDRESS (if different from Controlling Office)	15. SECURITY CLASS. (of this report): Unclassified
	15a. DECLASSIFICATION/DOWNGRADING SCHEDULE: NA

16. DISTRIBUTION STATEMENT (of this Report)

Approved for public release; distribution unlimited

ARO 9288.9-E

17. DISTRIBUTION STATEMENT (of the abstract entered in Block 20, if different from Report)

NA

18. SUPPLEMENTARY NOTES

The findings in this report are not to be construed as an official Department of the Army position, unless so designated by other authorized documents.

19. KEY WORDS (Continue on reverse side if necessary and identify by block number)

dynamic plasticity, split Hopkinson bar, strain rate effects, strain rate history effects, plastic waves, waves in periodic media, self-consistent slip models, plastic waves of combined stress

20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

Torsional split-Hopkinson bar experiments, involving jumps in strain rate from $10^{-4}s^{-1}$ to $10^{3}\ s^{-1}$ have been carried out on four metals (1100-0 aluminum, OFHC copper, zinc, AZ30B magnesium) at temperatures ranging from -200C to 250C. In addition, the effect of annealing temperature on the strain rate sensitivity of the flow stress has been examined for OFHC copper and a tellurium-doped copper alloy, Amtel. Effects of strain rate and strain rate history observed in these experiments have been

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examined within the framework of a theory of thermally activated motion, multiplication and annihilation of dislocations.

Wavefront and late-time asymptotic solutions have been obtained for wave propagation in linear elastic and visco-elastic bilaminates. Plastic waves of combined stress have been analyzed using a self-consistent slip model to characterize the stress-strain behavior of polycrystalline aluminum. Solutions have been obtained for three hardening models in which slip on one slip system increases the yield stress on (i) that system only, (ii) all systems equally, (iii) to a greater degree on nonco-planar systems. Comparison of theory with experiment shows better agreement than when smooth yield surface constitutive models are used.

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FINAL REPORT

"Inelastic Deformation of Metals Under Dynamic Loading"

Under this grant the inelastic behavior of metals subjected to dynamic loading conditions was investigated using two approaches: (a) experiments involving short specimens in which the state of stress is essentially homogeneous and (b) wave propagation studies. The results obtained from these two approaches are summarized in the following sections.

(a) SHORT SPECIMENS

The purpose of these experiments is to contribute to an understanding of the influence of strain rate, temperature and their respective histories on the flow stress of metals.

Description of Experiments

The experiments involving short specimens utilized a split-Hopkinson bar modified for torsional loading. Under previous grants an explosive loading technique was developed which provides a constant amplitude torsional loading pulse that can strain a specimen at a nominal shear strain rate of 1000 s^{-1}, with a final shear strain of 3-6%. The rise time of the loading pulse is about 7 microseconds. In order to investigate the influence of strain rate and strain rate history more precisely our experimental technique was modified to provide a means for loading the specimen first "statically", i.e. at a strain rate of about 10^{-4} s^{-1} to some predetermined shear strain (e.g. 25 percent), and then superposing the torsional loading pulse. The latter is initiated explosively. It causes a jump in strain rate of approximately 10^7 s^{-1} and strains the specimen dynamically by an additional 6 to 12 percent. Since no unloading occur between the "static" and dynamic portions of the experiment, this test provides a measure of the "true" strain rate sensitivity, as deduced from the increment in flow stress resulting from the strain rate increment. Comparison with the flow curve resulting from an experiment on a similar specimen strained entirely at the dynamic strain rate gives a measure of the effect of strain rate history on flow stress. Tests with this apparatus and covering a temperature range were performed and the results, summarized briefly below, were presented in two reports [5,9].

A second split Hopkinson bar apparatus has been constructed in order to improve our capability for evaluating strain rate history effects. This new version, which employs a stored torque--applied hydraulically, is able to provide shear strains of 50 percent at nominal strain rates in the range of 10^3 to 10^4 s^{-1}. The larger strains make possible a more accurate determination of strain rate history effects than was possible using our earlier procedure. On the other hand, the rise time of the loading pulse is significantly longer--about 40 microseconds. This apparatus is now fully functional for constant strain rates and is being modified to allow incremental strain rate experiments.

Summary of Research

Initial work on short specimens under this research project included a study of the effect of annealing temperature on the strain rate sensitivity of two copper alloys - OFHC copper and a tellurium-doped copper alloy, Amtel, which is in common use because of its free-machining properties. The study was motivated by published data which claimed that there is a strong reverse strain rate effect in copper heat treated just enough for stress relief. This finding, if correct, would have been significant since it would have meant that metals would weaken, and weaken appreciably under dynamic loading conditions, whereas engineers believe metals strengthen to some degree under such conditions. Furthermore, it seemed quite conceivable that a result of this sort might have remained unobserved by investigators since nearly all testing in laboratories has involved annealed specimens whereas manufactured equipment seldom utilizes annealed metals. The explanation offered for this reverse strain rate effect postulated the existence of fine adiabatic shear bands within the copper specimens, although they remained unobserved in the tests in question. Such bands would of course provide an unstable effect since the greater strain within a band would result in greater heat production which in turn would decrease flow stress. Our results from tests of the two copper alloys, using specimens of nearly the same shape, size and material as the previous investigators, indicate that the flow stress increases with strain rate regardless of the degree of annelaing or the lack thereof [4]. These results hold for specimens annealed to cover a wide temperature range including temperatures below, above and within the hardness transition temperature zone. We found that the degree of strain rate sensitivity varies with annealing temperature, but the change in flow stress with increasing strain rate is always positive. Actually, the dynamic flow stress of these two copper alloys is more strongly influenced by strain rate in unannealed specimens than in those that have been annealed.

Dr. J. Klepaczko during his 18-month visit at Brown (while on leave from the Polish Academy of Sciences) made use of data obtained from incremental strain rate experiments on 1100-0 aluminum, lead and comercially pure copper to develop a relationship between a simple thermally activated flow mechanism and strain rate effects [2]. This theory relates the observed macroscopic stress-strain behavior to changes in the microstructure in fcc metals. It shows that strain rate history effects play an important role in the plastic deformation of polycrystalline fcc metals. Furthermore it shows that strain rate effects can be attributed to differences in the effective dislocation multiplication rates at different strain rates.

Following on Dr. Klepaczko's work, we performed incremental strain rate experiments covering a substantial range in temperature. Their purpose, in line with his work, was to relate the macroscopic behavior of metals to the underlying dislocation behavior. This work [5], which was the subject of a Ph.D. thesis by P. E. Senseny, involved experiments on four metals with close-packed structures: 1100-0 aluminum, OFHC copper (fcc structure) zinc and AZ30B magnesium (hcp structure). Each metals was tested at selected temperatures ranging from -200C to 250C and covering "static" prestrains of 6 to 18 percent. The results of the incremental strain rate experiments combined with results from constant strain rate experiments at the same dynamic rate provided measures of strain rate effects as well as strain rate history effects over the given temperature range [9].

For all metals tested it was found that the stress increment resulting from an increment in strain rate varies with initial static strain and testing temperature. The influence of strain rate history is generally as great as that of strain rate itself. The possibility of a thermally activated dislocation annihilation process which softens the microstructure of the fcc metals during low strain rate deformation was investigated; it was concluded that if such a process exists, it is not stress independent. It was concluded also that one microstructural parameter is not sufficient to determine exactly the flow stress in the two fcc metals, although it may allow approximations of the material behavior which suffice for certain engineering applications. The results for the hcp metals, magnesium and zinc could not be correlated with the thermally activated process postulated by Klepaczko, perhaps because of the influence of mechanical twinning on the deformation. In the case of zinc, physical evidence of twinning was observed; furthermore, for this metal there is strong evidence that at high strain rates the same mechanism is not dominant at both the low and high temperatures.

(b) WAVE PROPAGATION STUDIES

Initial effort on wave propagation studies was directed towards the development of a late-time asymptotic theory of plastic wave propagation in visco-plastic materials. Specific attention was given to one-dimensional waves in bars for which the dependence of plastic strain-rate on flow stress is given by a hyperbolic sine function, suggested by consideration of thermally activated processes of dislocation motion. Such a constitutive relation models the visco-plastic characteristics of metals quite well; however, the relationships is so strongly non-linear that usual analytical techniques for obtaining asymptotic solutions are inadequate. Attempts to develop new analytical techniques for dealing with the difficulties posed by the strong non-linearity were essentially unsuccessful. An asymptotic solution [3] was obtained only for the case of extremely late times in which the overstresses become small enough that the hyperbolic sine function is approximately linear.

In order to obtain a better understanding of asymptotic methods for late-time solutions in wave propagation problems, attention was directed to the case of waves in linear elastic and visco-elastic bilaminates. In these cases the governing equations are linear so that reasonably complete results could be obtained. Both wavefront and late-time solutions were obtained [6] for step loading which causes wave propagation in the direction perpendicular to the laminates.

Following the investigation of asymptotic solutions our attention turned to an examination of the effects of hardening laws on the predicted features of plastic waves of combined stress. Experiments reported previously had indicated that both isotropic hardening and kinematic hardening models (as well as combinations thereof) were inadequate for predicting some of the features of the observed strain-time profiles for combined longitudinal and torsional plastic wave propagation in thin walled tubes. In particular these models predict, for step loading, an intermediate constant state region which is not observed in the experiments. The intermediate constant state arises because the stress trajectory changes from essentially tangent to the current yield surface in front of the intermediate constant state to essentially perpendicular to the current yield surface behind the intermediate constant state region. For hardening laws based on smooth yield surfaces and normality of the plastic strain rate to the current yield surface, such a change in loading direction results in a marked decrease in the effective stiffness of the material and consequently a marked decrease in wave speed. This abrupt change in wave speed is responsible for the existence of an intermediate constant state region.

In order to understand whether or not prediction of an intermediate constant state region is indicative of the inadequacy of constitutive equations employing smooth yield surfaces, a new analysis of combined longitudinal and torsional plastic was carried out for a constitutive model based on a self-consistent treatment of plastic flow due to slip on slip systems of a large number of randomly oriented single crystals. The first step in this analysis was the development of an efficient algorithm for computing macroscopic stress-strain behavior associated with slip on the various slip systems. The algorithm developed [7] is based on formulation of the problem as a linear programming problem. The algorithm proved to be exceptionally efficient and to allow for the computation of stress-strain behavior along complicated loading paths involving combined stress states.

The algorithm was used to obtain solutions [8] for an aluminum alloy tube subjected to static torque followed by longitudinal impact. Solutions were obtained for three hardening models: (i) isotropic hardening in which slip on one slip system increases the yield stress on all slip systems equally, (ii) independent hardening in which slip on one slip system increases the yield stress on that system only, and (iii) latent hardening in which slip on one slip system increases the yield stress on nonco-planar systems more than on co-planar systems. Comparison of theory and experiment indicate that all hardening models eliminate the undesirable intermediate constant state region and that the best agreement is obtained with the latent hardening model. Discrepancy between theory and experiment still exists at high impact velocities where the predicted wave speed of large strains is too high. This discrepancy may be due in part to determination of the model parameters from the static stress-strain curve for the material instead of a dynamic stress-strain curve obtained at a strain-rate comparable to those existing in the wave propagation experiments. Overall, the improved agreement between theory and experiment is encouraging and suggests that further examination of self-consistent slip models may lead to substantial improvements in the characterization of stress-strain behavior under combined stress states.

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