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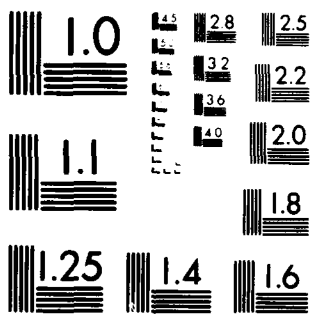

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Plastic Deformation and Fracture of Steel
Under Dynamic Loading
Final Report

R. J. Clifton
J. Duffy

May, 1980

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

→ The authors summarize their research effort during the grant period. Included is a comprehensive study relating dynamic plasticity and fracture initiation through experiments on 1020 hot rolled steel and 1018 cold rolled steel. A comparison of values of K_{Ic} obtained using the method developed by Brown University and the instrumented precracked Charpy test is given as well as a finite element analysis of the specimen configuration used in the dynamic plasticity experiments utilizing a torsional Kolsky bar. An experimental investigation into

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the formation of shear bands in low carbon steel including the measurement of the temperature rise during the formation of the shear band as well as the derivation of a criterion for predicting shear band formation is reported. Further, the details of the development of a plate impact experiment designed to attain strain rates of 10^5 s^{-1} up to strains of 10% and pressures of more than 10k bar are also reported.

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Final Report

Plastic Deformation and Fracture of Steel Under Dynamic Loading

A number of studies was completed during the grant period December 15, 1976, through January 31, 1980. These include:

I) Dynamic plasticity and dynamic fracture experiments involving two structural steels.
II) A study of shear bands in the same two steels.
III) Derivation of a criterion for predicting shear band formation.
IV) Development of plate impact experiments to attain strain rates of $10^5 s^{-1}$.
V) Research on plastic waves.

These studies can be described in more detail as follows:

I) The dynamic plasticity tests on steel involve specimens of two low carbon steels, 1018 cold-rolled steel (CRS) and 1020 hot-rolled steel (HRS). The specimens were machined into thin-walled tubes and loaded in torsion. Plastic shear strains of 30% were attained at strain rates ranging from 10^{-5} s^{-1} to 800 s^{-1} and at temperatures from -150C to 120C. The results show that the flow stress is quite sensitive to strain rate, particularly for HRS in which flow stress increases by a factor of two when strain rate is changed from 10^{-5} to 800 s^{-1}. In addition, incremental strain rate experiments were conducted with these steels in the torsional Kolsky bar over the same temperature range as above. The purpose of the incremental tests was to determine the effect of strain rate history on flow stress. The results show that the dynamic portion of the stress-strain curve obtained in incremental strain rate experiments nearly coincides with the flow curve resulting from loading entirely at the dynamic strain rate. Our conclusion is that strain rate history is of little importance in determining the flow stress of these two steels, in spite of their relatively high sensitivity to strain rate. A report of the results of room temperature incremental strain rate experiments on these steels was issued in 1979 [1].

In related work, notched round bars of the same materials were tested in tension to determine the plane strain fracture toughness K_{Ic} over the same range of temperatures. These tests were performed using a fracture initiation experiment developed at Brown University and based on the principle of the Kolsky bar (split-Hopkinson bar) [2-4]. Using this technique, we are able to attain stress intensity rates $\dot{K}_I \approx 2 \cdot 10^9$ psi$\sqrt{in}$/s, or about 1000 times faster than can be attained by means of a hydraulic testing machine.

On the basis of the dynamic plasticity and dynamic fracture experiments, the following conclusions can be drawn:

1) AISI 1020 hot-rolled steel has plastic flow properties that are significantly different from those of a cold-rolled steel of similar composition and grain size. The hot-rolled steel has a lower initial yield stress, a much greater strain hardening rate and a somewhat greater strain rate sensitivity.

2) The fracture initiation tests show that the fracture toughness of hot-rolled steel is not strongly dependent on the loading rate; i.e., on

the value of. $\dot{K}_I$. This is in contrast to the behavior of cold-rolled steel which shows a strong loading rate sensitivity when fracture occurs by cleavage.

3) A microstructural examination of the fracture surface shows that the mechanisms of fracture initiation are quite similar for these two steels. Cleavage fracture in either steel occurs when a critical tensile stress is attained and is believed to initiate at small cracks which form in the thin plates of iron carbide that are present along the ferrite grain boundaries. However, calculations as to the value of this stress for hot-rolled steel are more difficult to make because of its greater work-hardening rate. Ductile fracture in both steels proceeds by void nucleation and growth. The greater percentage of voids in hot-rolled steel makes this occur at a somewhat lower stress than in cold-rolled steel.

In addition to the above, a collaborative investigation has been completed with W. L. Server, Vice President of Fracture Control Corp., Goleta, California. In this study [5], we compare fracture toughness as determined in the instrumented precracked Charpy test with that resulting from the dynamic fracture initiation experiment developed at Brown University. The comparative tests involved specimens of 4340 steel and a mild steel (1018). The results obtained from the two dynamic fracture test methods were in good agreement for tests conducted on the nominally brittle material (4340 steel) and for tests on the mild steel on the lower shelf and in the transition region. However, for mild steel tests on the upper shelf, the instrumented precracked Charpy impact test gave higher toughness values than did the Brown University method. It was concluded that this difference is due in part to the difference in methods used to define the initiation point at which J_{Ic} is determined. However, other factors such as the differences in magnitude of the triaxial stresses present in the near crack tip region in the two specimen shapes also contribute to the difference in J_{Ic} values observed in the fully plastic tests.

Further, a finite element analysis was made of the elastic-plastic deformation process in the dynamic plasticity specimens. These specimens consist of thin-walled tubes machined with heavy flanges. It is evident that the stress concentration at the specimen-flange interface could conceivably lead to non-homogeneous deformation and hence to large errors in the analysis of the experimental results. For the metals tested thus far, with one exception (see below), the deformation has been homogeneous. Experimentally, this is established by scribing a fine line axially along the inside surface of the tube. We found that after testing this scribe line is inclined at the shear angle but remains straight, indicating homogeneous strain. Recently, however, we employed a finite element scheme to study growth of the plastic zones within our specimens [6]. This study showed that, although initially severe straining does occur at the flange-specimen interface, rapid growth of the highly strained zone toward the internal boundary of the specimen is not observed; instead, a rather smooth and homogeneous shear deformation takes place across the entire gage length of the specimen. It was shown that in materials exhibiting lower strain hardening rates, the initial degree of strain concentration at the specimen-flange interface would be somewhat greater.

Additionally, a technical report reviewing testing techniques at high strain rates was prepared and presented as the J. D. Campbell Memorial Lecture at the Conference on the Mechanical Properties of Materials at High Rates of Strain held at Oxford, England, in March, 1979 [7].

II) The dynamic plasticity experiments involving CRS led to a study of the development of shear bands in this material. We found that CRS specimens loaded dynamically in torsion develop an instability after about 10 or 12 percent shear strain has accumulated. This phenomenon did not occur in the HRS, except at the lowest test temperature, -157C, in spite of its very similar chemical composition. Our investigation included the measurement of temperature over the shear band area during deformation; this was effected by means of an infrared radiation detector. We conclude that the shear bands were formed adiabatically as a result of a low work hardening rate coupled with a temperature sensitivity of the flow stress sufficient to cause thermal softening during plastic work at the high deformation rates [8].

III) The stability of homogeneous shearing deformations in elastic/visco-plastic materials has been analyzed. The characteristic equation governing the rate of growth or decay of an initial fluctuation is found to be

$$\eta^4 - B\eta^3 + C\eta^2 - D\eta + E = 0 \qquad (1)$$

in which

$$B = \frac{\partial\phi}{\partial\bar{\gamma}^p} - \mu\frac{\partial\phi}{\partial\bar{\tau}} + \beta\frac{\tau^o}{\rho c}\frac{\partial\phi}{\partial\theta}$$

$$C = \frac{\mu}{\rho}\xi^2 - \kappa\frac{\partial\phi}{\partial\bar{\gamma}^p}\xi^2 + \beta\frac{\mu\phi^o}{\rho c}\frac{\partial\phi}{\partial\theta} + \kappa\mu\frac{\partial\phi}{\partial\bar{\tau}}\xi^2$$

$$D = \frac{\mu}{\rho}\frac{\partial\phi}{\partial\bar{\gamma}^p}\xi^2 - \kappa\frac{\mu}{\rho}\xi^4 + \beta\frac{\mu\tau^o}{\rho^2 c}\frac{\partial\phi}{\partial\theta}\xi^2$$

$$E = \kappa\frac{\mu}{\rho}\frac{\partial\phi}{\partial\bar{\gamma}^p}\xi^4$$

where $\phi = \phi(\bar{\tau}, \bar{\gamma}^p, \theta)$ is the plastic shear strain-rate as a function of the effective shear stress $\bar{\tau}$ (i.e., octahedral shear stress), the corresponding plastic shear strain $\bar{\gamma}^p$ and the temperature θ; μ is the elastic shear modulus ρ is the mass density, c is the specific heat, κ is the thermal diffusivity and β is a dimensionless parameter representing the fraction of the plastic work that is dissipated as heat. The quantities τ^o and ϕ^o are, respectively, the shear stress and plastic shear strain-rate in the homogeneous deformation from which fluctuations are being considered. The fluctuations have wave number ξ; their time variation is given by a factor $e^{\eta t}$. Thus, given initial fluctuations either grow or decay depending on the signs of the real parts of the roots η of (1).

Roots η of (1) can be obtained numerically for values of the coefficients that are characteristics of materials and homogeneous deformations of interest. Explicit results can be obtained in a few special cases. For example, in the long wavelength limit (i.e., $\xi \to 0$) the fluctuations grow exponentially if the inequality

$$\frac{\partial\phi}{\partial\bar{\gamma}^p} - \mu\frac{\partial\phi}{\partial\bar{\tau}} + \beta\frac{\tau^o}{\rho c}\frac{\partial\phi}{\partial\theta} > 0 \qquad (2)$$

is satified. For most metals the first two terms are negative and the last term is positive. Thus, instability of long wavelength fluctuations is predicted when the thermal softening represented by the last term dominates the strain hardening and viscosity effects represented by the first two terms, respectively.

Another case for which explicit results can be obtained is the quasistatic case in which inertia effects are negligible. The characteristic equation for this case can be derived independently, or obtained from (1) by taking the limit as $\rho \to 0$ with ρc held fixed. The result is the characteristic equation

$$\eta^2 + \left[\kappa\xi^2 - \frac{\partial\phi}{\partial\bar{\gamma}^p} - \beta\,\frac{\tau^o}{\rho c}\,\frac{\partial\phi}{\partial\theta}\right]\eta - \kappa\,\frac{\partial\phi}{\partial\bar{\gamma}^p}\,\xi^2 = 0 \tag{3}$$

Exponential growth of initial fluctuations with wave number ξ occurs when the inequality

$$\frac{\partial\phi}{\partial\bar{\gamma}^p} + \beta\,\frac{\tau^o}{\rho c}\,\frac{\partial\phi}{\partial\theta} - \kappa\xi^2 > 0 \tag{4}$$

is satisfied. This is the stability condition reported in [9]. The stability limits given by (4) appear to be consistent with the experimental results on shear bands in the dynamic torsion experiments.

Further work following the termination of the grant indicates that for the special case of viscous materials (without elasticity or strain hardening) Equation (1) reduces to a quadratic equation that can be solved explicitly. For expected signs of the coefficients the roots η are real. There exists a range of values of the parameters for which η is positive and a maximum value for a finite, non-zero, value of the wave number ξ. Thus, Equation (1) admits instabilities with characteristic lengths that are determined by material properties. Detailed examination of the consequences of (1) are being investigated.

IV) Development of a plate impact analogue of the split-Hopkinson bar experiment was undertaken in order to try to study plastic response at strain rates up to $10^5\ s^{-1}$. If these strain rates could be attained under controlled, well characterized conditions, then the strain-rate regime for which constitutive models of dynamic plasticity can be verified by experiments would be extended by 1-2 orders of magnitude. Not surprisingly, development of an experiment which involves such a pronounced increase in plastic strain rates leads to numerous difficulties. Nevertheless, progress has been made and we expect that satisfactory procedures will be developed for at least some metals.

One difficulty is the preparation of thin specimens to be sandwiched between two hard elastic plates. In order to generate high strain-rates and low time intervals for reaching nominally homogeneous deformation through the thickness, the specimens should be as thin as possible. On the other hand, finite grain size, specimen handling considerations, and surface damage effects provide lower limits on acceptable specimen thicknesses. Experience suggests that satisfactory specimens with thicknesses as small as 0.25mm can be prepared from bulk samples.

Another difficulty is that of maintaining high plastic stain rates, comparable to those induced at impact. Since unloading waves from an interface with a material with lower acoustic impedance reduce substantially the plastic strain rates in the specimen it follows that the hard elastic plates on each side of the specimen must have acoustic impedances which are greater than that of the specimen. Realization of this restriction caused us to switch from steel to aluminum specimens in order to obtain sufficient impedance mismatch with readily available materials that remain elastic under the loading conditions imposed. Furthermore, the prospect of generating unwanted unloading waves makes it necessary to give careful attention to the interfaces between the specimen and the adjoining hard elastic plates. A thin layer of epoxy, because of its low impedance and low sound velocity, can cause unloading waves of sufficient duration (say 20 nsec) to introduce significant spurrious effects in the transmitted wave profiles. Detailed comparisons between theory and experiment are then less informative because the quantitative effects of the epoxy layer are not well known. Even if low interference coupling between impedance mismatched specimen and bounding plates is realized, plastic strain rates in the specimen decrease as the state of stress becomes more nearly hydrostatic.

Results of exploratory experiments on 3003 aluminum alloy specimens [10] reveal several of the difficulties mentioned previously. Plastic strain rates decrease substantially before a significant number of reverberations occurs for the stress state to be regarded as uniform through the specimen thickness. Thus, numerical solutions, based on assumed constitutive equations, are required to relate observed wave profiles to models of the dynamic plastic response of the specimen. Such comparisons indicate that satisfactory agreement would not be obtained if the stress versus log strain-rate curve showed a pronounced increase in strain-rate sensitivity in the strain-rate interval 10^3 s^{-1} to 10^5 s^{-1}. This preliminary indication if borne out by further experiments, has significant scientific and technological implications. Previous attempts by others to reach strain rates up to approximately 10^4 s^{-1} in aluminum have been inconclusive since some investigations show a marked increase in strain-rate sensitivity in this interval whereas at least one investigation did not show such an increase.

The experiments [10] from which the preliminary indications of strain rate sensitivity of aluminum in the 10^3 s^{-1} to 10^5 s^{-1} range are obtained are not viewed as definitive since they include artifacts due to an epoxy layer between the specimen and the elastic flyer plate. Computed and measured velocity-time profiles do not agree well after the wavefront reflects from the epoxy layer. However, there is no ambiguity in the conclusion that after a few nanoseconds the stress at the impact face is relaxed to values comparable to quasi-static values. The level of the wave profile behind the wavefront was establish by monitoring the motion of the rear surface of the elastic target plate with a velocity interferometer and a displacement interferometer to avoid possible confusion in the number of fringes missed at the wavefront using the velocity interferometer. The rapid relaxation of the stress at the impact face is not predicted by constitutive models that show a marked increase in strain-rate sensitivity (say a change from logarithmic to linear dependence on strain-rate) for strain rates greater than, say, 10^4 s^{-1}. Unless the rapid stress relaxation at the impact face can be attributed to exceptionally high strain rates due to surface roughness or surface damage it appears correct to interpret the experiments as indicating that the flow stress does not increase markedly with strain-rate over the range of strain-rates investigated. The steepness of the profiles of the reflected waves, although reduced by the interaction with the epoxy layer, supports the interpretation that new deformation processes with greater strain-rate sensitivity are not activated in the experiments.

In order to preclude the reduction of plastic strain rates by stress relaxation towards a hydrostatic state of stress the impact configuration has been changed to impose both normal and shear tractions (i.e. pressure-shear loading) at the impact face. This loading condition is obtained by impacting parallel plates that are inclined relative to the axis of the launch tube. At the end of the grant period the modifications necessary to implementing this impact configuration had been made. Subsequently, the experimental program was begun. Preliminary results suggest that such experiments are feasible although there is concern about slip at the interfaces between the specimen and the adjoining elastic plates. Reduced ratios of shear to normal tractions, and increased surface roughness will be tried as means for preventing interfacial sliding. If sliding is prevented, then it should be possible to sustain plastic shear strain rates of 10^5 s^{-1} for time intervals of 10^{-6} sec. Such experiments would provide stress-strain curves up to strains of 10% at strain rates of 10^5 s^{-1} and pressures of more than 10 kbar.

V) Research on plastic waves based on self consistent slip models that was carried out mostly under the previous ARO grant has been completed and accepted for publication.

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