The Conversion of Plastic Work to Heat Around a Dynamically Propagating Crack in Metals

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Abstract

Investigations of the temperature rise at a dynamically propagating crack tip using an infrared detector array are reported. Also, a measurement of the fraction of plastic work converted to heat using a split hopkinson bar apparatus in conjunction with an infrared detector array is summarized. For 4340 steel it is seen that ≈85% of the plastic work is converted to heat leading to a temperature rise of 300°C at a crack tip propagating 600 m/s in steel. This results is compared to earlier studies that report a 450°C temperature rise at a crack tip propagating 900 m/s in steel.[1] In a titanium alloy the temperature rise is higher than that in steel for equal plastic work rate densities. The conditions at the crack tip are shown to be adiabatic, and, as a result, this effect is due to the difference in density, heat capacity and crack tip speed. Thermal conductivity has no effect.

Introduction

A majority of the plastic work at the tip of a propagating crack is converted to heat while a small percentage (>15%) is actually stored in the material due to dislocation interaction etc.[2] In problems that involve both heat generation due to plastic work and heat conduction it is advantageous to define the converted plastic work fraction, β, as follows:

$$\beta = \frac{\dot{Q}}{\dot{W}^p} \tag{1}$$

where $\dot{Q}$ is the heat production density rate and $\dot{W}^p$ is the plastic work density rate. Using this definition in the heat conduction equation gives a partial differential equation for the temperature rise around a translating plastic zone;

$$k\nabla^2 T + \rho c_p \dot{a}\frac{\partial T}{\partial x_1} = -\beta \dot{W}^p \quad (2)$$

where k is the thermal conductivity, ρ is the density, c_p is the heat capacity and $\dot{a}$ is the velocity of the translating coordinate system in the x_1 direction. The solution to the partial differential equation is given by a convolution[3] ;

$$T(x_1, x_2) = \int_{A_r^\xi} \frac{\beta}{2\pi k} \dot{W}^p(\xi_1, \xi_2) \exp\left[-\kappa(x_1 - \xi_1)\right] K_0(\kappa|\mathbf{r}^x - \mathbf{r}^\xi|) dA_p^\xi \quad (3)$$

where $\kappa = \rho c_p \dot{a}/2k$, K_0 is the modified Bessel's function of zeroth order and the super-scripts, x and ξ, refer to the translating coordinates and dummy integration coordinates, respectively. This solution is difficult to evaluate for a dynamically propagating crack because the plastic work zone, $\dot{W}^p$, is not well known and finding an accurate closed form expression for it using fundamental principles is virtually impossible. Numerical solutions are further complicated by the fact that the temperature measurements are taken on the surface of the specimen where the deformation is not well described by 2-dimensional approximations. Finally, the converted plastic work fraction is expected to depend upon strain[2] and strain rate; although, generally, the converted plastic work fraction is assumed to be a constant in the range .85-1.0.[1,4]

Actually, while considerable work has been directed toward the investigation of the converted plastic work fraction[2], little is known about its dependence upon strain rate and/or temperature. At dynamic crack tips the strain rates are very high and, consequently, due to strain rate hardening, the plastic work rate density can be extremely high as well. As will be shown below, the resulting temperatures are also significant. It is, therefore, important to understand what effects high strain rate, high work rate density and high temperature have upon the converted plastic work fraction in order to properly understand what factors are important in the conversion of plastic work to heat at the tip of a dynamically propagating crack.

Materials and Methods

Infrared detectors have been used successfully to characterize the temperature field in Luder's bands[5] and the temperature field during the formation of an adiabatic shear band.[6] The same methodology is used here to measure the crack tip temperature fields and also to measure the converted plastic work fraction. To measure the crack tip temperature an array of eight detectors is focused on the specimen using reflecting optical elements. As the crack passes through the focussed array a voltage is produced by each detector. The detectors are sensitive to a wide range of temperatures, depending upon the system aperture and specimen material, and they respond quickly to a sudden input. (The rise time is $.75\mu s.$) All that is necessary to measure temperature under dynamic conditions is a proper evaluation of the calibration curve relating the voltage from the detectors to the temperature in the specimen. This calibration curve is evaluated quite easily under static heating conditions.[1,4,7]

Dynamic cracks may be produced by statically overloading a blunt notch until crack initiation occurs and is followed by dynamic crack propagation. The velocity of the crack may be roughly controlled by the notch tip bluntness. Compressive wedge loading is used in this investigation to statically over-load a notch tip in a compact tension specimen producing straight crack growth. The detectors are focussed on the prospective crack path, but, since the detectors focus on closely spaced points on the specimen surface, to provide good spatial resolution, the crack does not always pass through the focussed array, and some luck is required to insure success. Generally, there is a 1/4 success rate with the system. The spatial resolution of the system is $200\mu m$ while the diameter of each observation spot is approximately 160 μm.

Once the temperature is measured the plastic work zone may be estimated using an adiabatic assumption in Eq (2):

$$\rho c_p \dot{a} \frac{\partial T}{\partial x_1} = -\beta \dot{W}^p. \tag{4}$$

Knowing the material parameters, including β, and differentiating the crack tip temperature fields with respect to the x_1 coordinate the left hand side of Eq (4) is evaluated providing an estimate of the plastic work rate and, thus, of the plastic zone. This plastic work zone may then be used in the convolution, Eq (3), to reproduce the entire crack tip temperature field. If the assumptions implicit in Eq (2) are applicable and the estimation of the plastic zone at the crack tip is good, the resulting temperature field should exactly match the measured temperature field. It is noted that the assumption of adiabatic conditions at the crack tip required in the estimation of the plastic zone using Eq (4) may be independently checked by computing both of the terms on the left hand side of Eq (2), $k\nabla^2 T$ and $\rho c_p \dot{a} \partial T/\partial x_1$, and comparing their magnitude.

To investigate β a split hopkinson pressure bar is used in conjunction with the infrared detector array. The split hopkinson pressure bar loads the specimen dynamically with a controllable strain rate.[8] Loading times are very short making adiabatic assumptions more accurate. Since there is no time for conductive, radiative or convective heat loss, it is expected that the dynamic loading apparatus will provide highly accurate measurements of the converted plastic work fraction. A small cylindrical specimen 1/4 inch in length and 1/4 inch in diameter is placed between the two hopkinson bars, the infrared array is then focussed on the center of the specimen. The depth of field of the optical system allows the array to be easily focussed on the cylindrical specimen surface and prevents any loss of focus during the deformation. Finally, the dynamic deformation is induced. Usually only one detector is used since early investigations showed no difference between in the output of two detectors focussed at the largest possible spacing, 1.4 mm.

Once the stress, strain rate and temperature have been evaluated from the results of the split hopkinson experiment, the converted plastic work fraction may be calculated. Assuming adiabatic conditions the heat conduction equation gives

$$\rho c_p \dot{T} = \beta \dot{W}^p. \tag{5}$$

Work density is calculated by integration;

$$W^p = \int_0^t \sigma_{ij} \dot{\epsilon}^p_{ij} d\tau \tag{6}$$

where σ_{ij} and $\dot{\epsilon}^p_{ij}$ are cartesian stress and plastic cartesian strain rate, respectively. Thus, solving Eq (5) for β for a uniaxial deformation gives

$$\beta = \rho c_p \frac{\partial T}{\partial W^p}.$$

By plotting the temperature with respect to the plastic work the converted plastic work fraction, β, may be deduced from the slope. (The slope is evaluated by fitting a polynomial to the results and differentiating the fitted function. This is necessary because the small temperatures involved, $\sim$ 100°C, result in a significant signal to noise ratio.)

The materials studied include 4340 steel in an oil-quenched condition and Ti 10V-2Fe-3Al alloy in a 0%-alpha condition. The titanium has a much lower thermal conductivity and density than the steel while the heat capacity of the two materials is roughly the same. (See Table 1.) Only the converted heat fraction of tempered 4340 steel is reported. Further investigations of β for different materials are reported in Mason et al.[9]

Table 1: Thermal Properties

Material	ρ kg/m^3	c_p J/kg°C	k W/m°C	α^{**} μm^2/s
4340 steel	7834	448	34.6	9.86
Ti 10V-2Fe-3Al	4650	490	8.5	3.73

** $\alpha = k/\rho c_p$

Results

In Fig 1 the results of two investigations of the temperature field around a dynamically propagating crack in oil-quenched 4340 steel are presented. In the first case[1] the crack is propagating at 900 m/s and in the second[4] the crack propagates at 600 m/s. These figures represent a number of experiments, and the results are highly repeatable. Using Eq (5) the active plastic zones ($\dot{W}^p \geq 0$) were estimated in each case, and, using an approximation to the estimate of the plastic zone, a theoretical temperature field was calculated numerically[10] using Eq (3). Coincidentally, both theoretical temperature fields have the same shape as shown in Fig 2, only the size scaling and maximum temperature are different. The predicted maximum temperature is in good agreement with the experimental measurement in both cases indicating the validity of the assumption of adiabatic conditions at crack tip.

The theoretical temperature field is in best agreement with the experimental field when $\dot{a}$=600 m/s. When $\dot{a}$ =900 m/s, agreement is not very good. However, near the crack tip the temperature fields at both velocities are well modeled by the theory. Far from the crack tip both experimentally measured temperature fields are lower in magnitude than expected from Fig 2. These discrepancies between theory and experiment are largely due to the fact that the simple theory used in Eqs (2) and (3) does not account for either heat loss due to radiation and convection or opening of the crack faces. At 900 m/s, for example, it is expected from simple theory and the basic mechanisms of the blunt notch crack generation method that the crack face opening velocities will be much larger than at 600 m/s.[4] This explains the wide contours seen in Fig 1 for 900 m/s. Furthermore, Kuang and Atluri[11] have shown that, not surprisingly, including the effects of convective and radiative cooling results in a more rapid decline in the temperature behind the crack tip than when these effects are neglected. In the theory used here, convection and radiation are neglected, so it is *expected* that the predicted temperatures behind the crack should be higher than experimental temperatures. Near the crack tip convective and radiative cooling are less important because the heating rate is very high and there is no time for significant cooling to occur by these mechanisms; adiabatic conditions prevail.

The results for titanium are shown in Fig 3. It is seen that the maximum temperature when $\dot{a}$ =380 m/s is ~500°C, as high as the maximum steel temperature at 900 m/s. Evaluation of the the plastic work rate density shows that the work rate density in titanium when $\dot{a}$ =380 m/s is approximately the same as the work rate density in steel when $\dot{a}$ =600 m/s. Therefore, using Eq (4) and comparing of the factor $\rho c_p \dot{a}$ for each material, it is seen that the temperature in the titanium alloy should be about twice that in steel when the work rate densities are the same. It is. Also note that the temperature field in titanium when $\dot{a}$ =380 m/s resembles that in steel when $\dot{a}$ = 600 m/s indicating that crack face opening is not significant and adiabatic conditions apply at the crack tip.

For the predictions in Fig 2 a constant converted plastic work fraction was

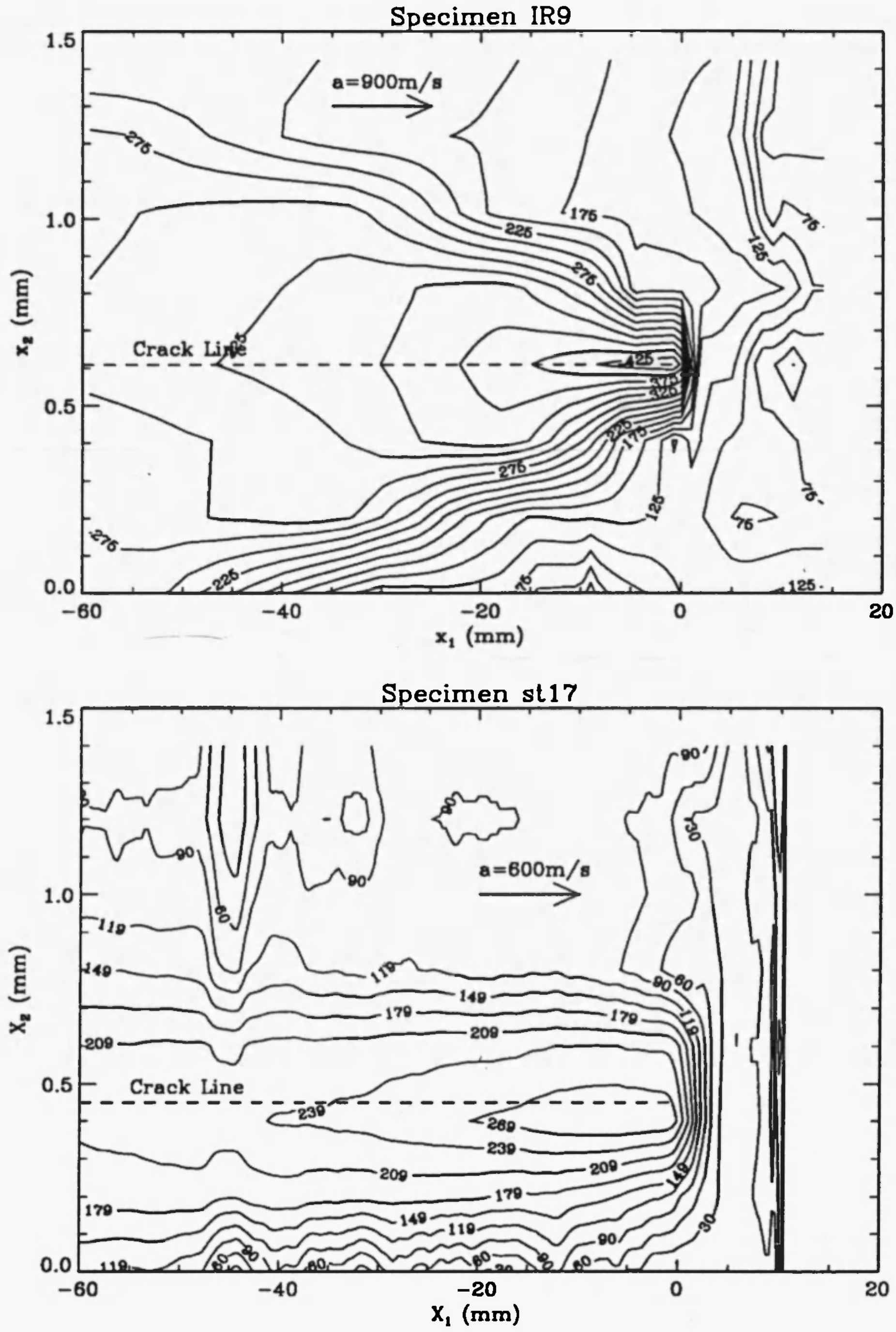

FIGURE 1 Temperature fields around a crack propagating in oil-quenched 4340 steel at two different velocities. The maximum temperature at higher velocities is 450°C[1] while the maximum temperature at 600 m/s is 300°C.

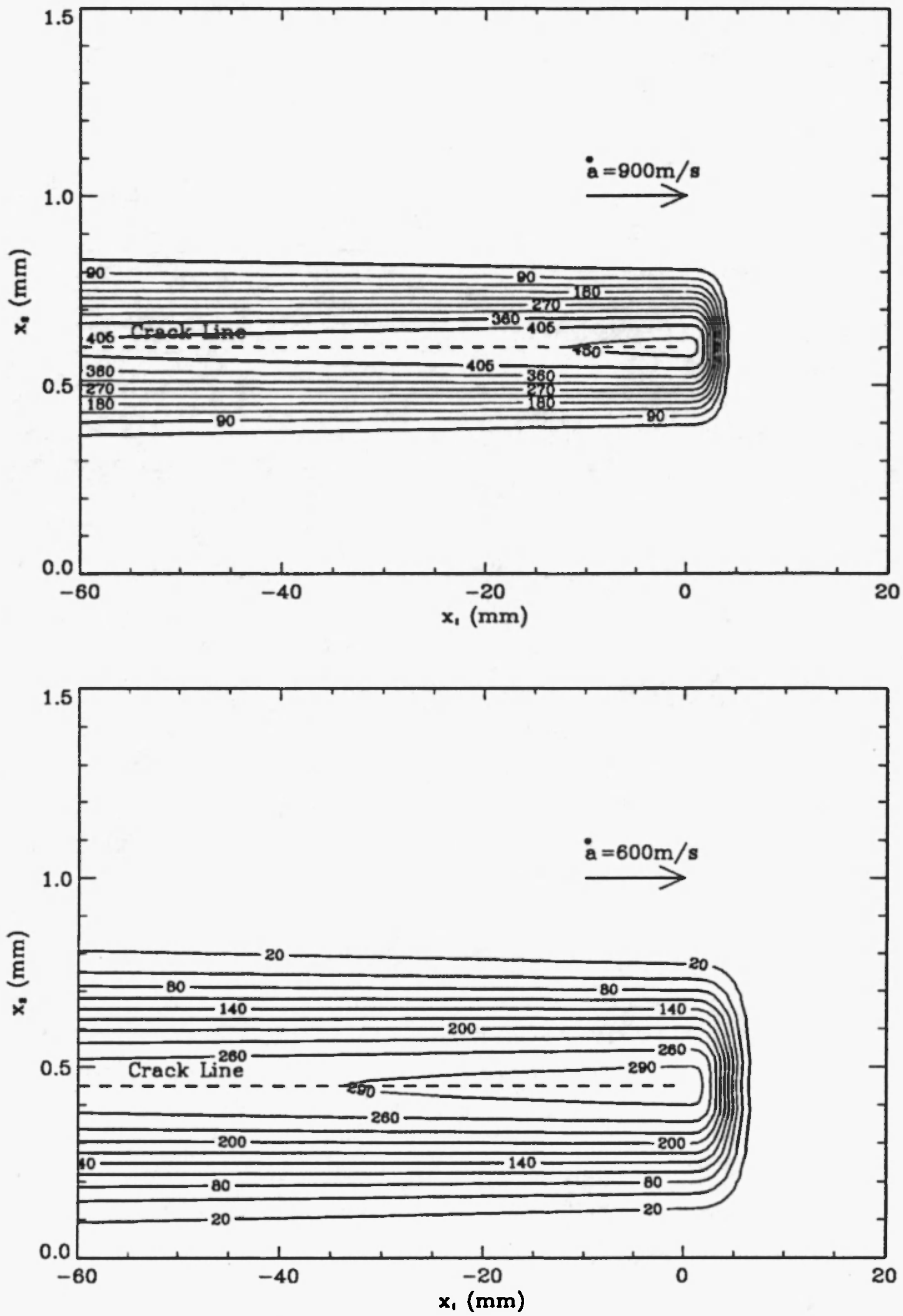

FIGURE 2 The theoretical temperature fields for approximate experimental conditions when $\dot{a}$= 900 m/s and 600 m/s. Good agreement is seen between the predicted maximum temperature at the crack tip and the measured maximum temperature, however some discrepancies are seen in the general shape of the theoretical field when compared to Fig 1.

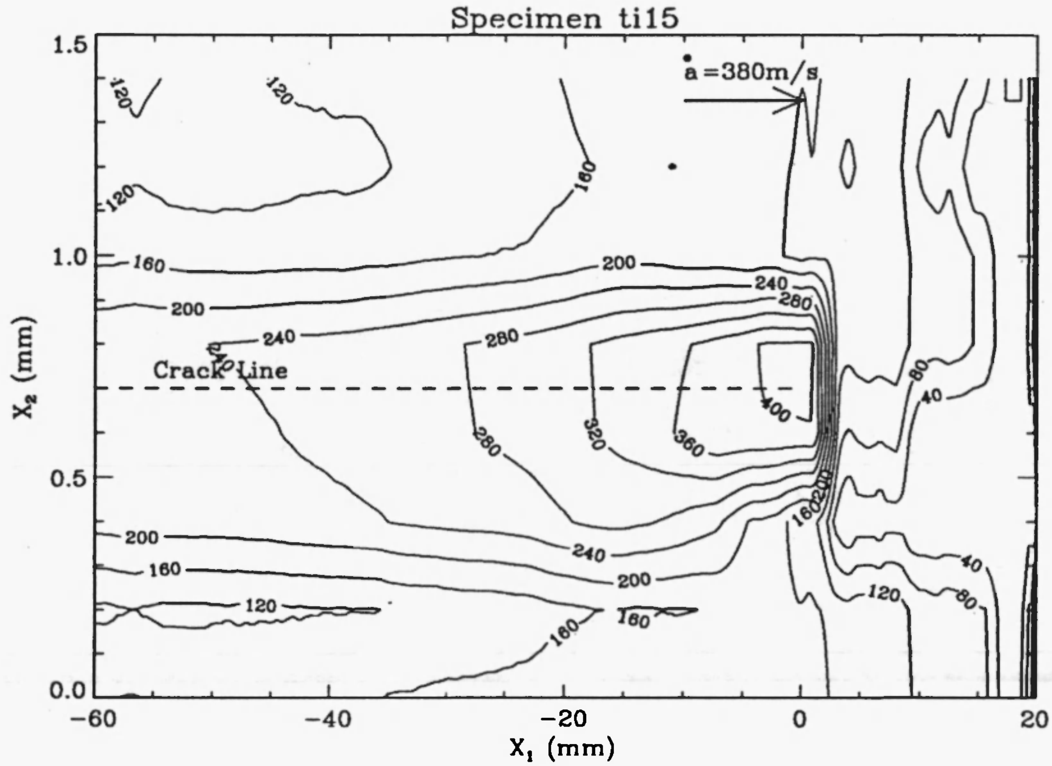

FIGURE 3 The temperature field around a propagating crack tip in Ti-10V-2Fe-3Al alloy. Some of the detectors were saturated, but a maximum temperature of approximately 500°C may be extrapolated from the results.

assumed. When this is the case, the factor β does not appear in Eq (3) because the plastic work rate density has been evaluated using Eq (4) and the measured temperature field. It is necessary to investigate the validity of this assumption. Using the split hopkinson bar a preliminary investigation was performed on 4340 steel. The results of this investigation are seen in Fig 4 for a test performed at a strain rate of 2000 s^{-1} . W^P was calculated using Eq (6), and it was only necessary to fit a linear function to the experimental data resulting in a constant value for the converted plastic work fraction, $\beta = .864$

Discussion

Measurement of temperature fields at the tip of dynamically propagating cracks in metals has lead to the understanding that crack tip temperatures are, in fact, significant and should not be ignored. The temperature fields have also lead to some understanding of the plastic deformation at the tip of the crack by virtue of the adiabatic conditions there and Eq (4). Theoretically, one might predict that crack tip conditions are adiabatic because of the high crack speed and low

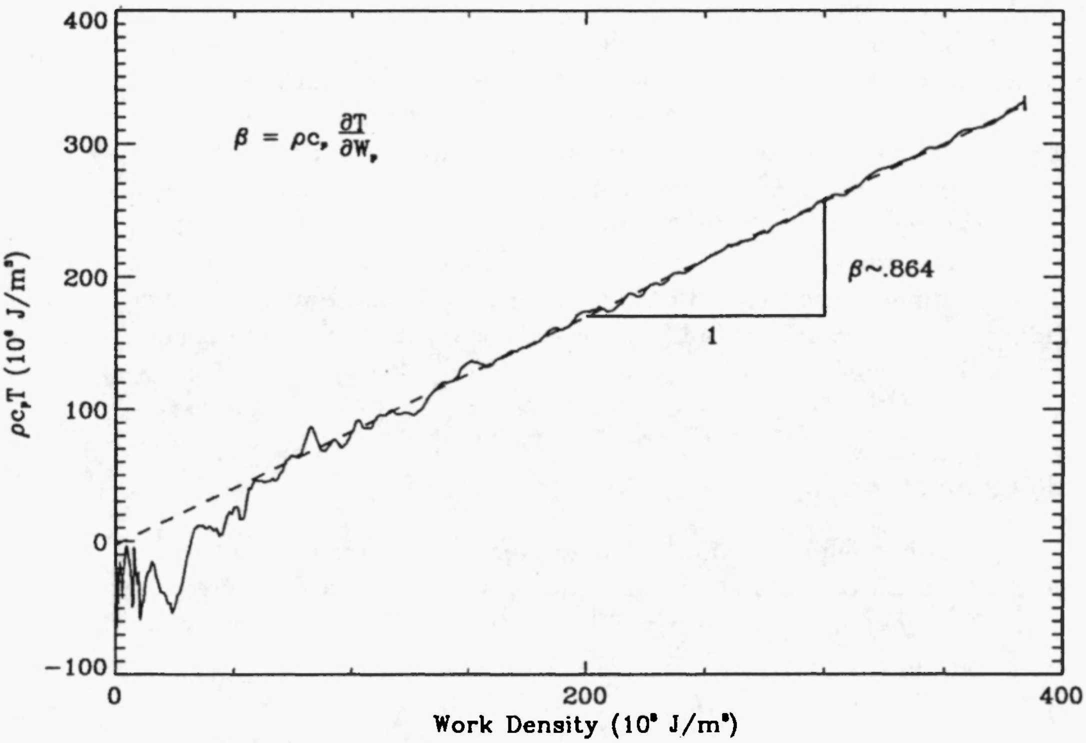

FIGURE 4 Preliminary measurement of the converted plastic work fraction, β, for 4340 steel. A split hopkinson pressure bar was used in conjunction with the infrared detector system.

thermal resistivity, $k/\rho c_p$, of the metals. However, adiabatic conditions are also dependent upon the plastic zone size[10] and, as mentioned before, this parameter is not easy to predict. It is interesting to note that the plastic zones measured in these experiments appear to have the same shape regardless of the material or crack velocity[4] resembling a thin elongated ellipse extending ahead of the crack tip. The crack velocity and material only seem to determine the scaling of the zone spatially and the maximum plastic work rate density.

In steels it is known that the temperature generation leads to shear band formation in the shear lips.[4] This is due to thermal softening and a resultant localization of the deformation to a plane ahead of the crack tip. However, this effect occurs at the surface of the specimen, and not much is known about the effects of the temperature rise within the bulk material as *it* fails. There exist dynamic experimental conditions where shear bands may form in the bulk material, and further investigations of these geometries are planned.

The successful measurement of the converted plastic work fraction using the split hopkinson bar and the infrared detector array is encouraging. It might not have been expected from some simple analysis and the static stress strain curve of the tempered 4340[2] that β is constant with respect to strain and plastic work density because the stress strain curve has a changing slope in the plastic region.

However, the stress strain curve appears to be bi-linear and slope of the plastic deformation region is nearly constant at high strain rates.[9] Thus, β is a constant. Under any circumstances, it has been shown that the method of using infrared detectors in connection with a split-hopkinson bar is an excellent technique for investigating the converted plastic work fraction. The method has significant advantages over other methods[2] in that it does not require calorimetry, thermal isolation of the specimen or any of the complicated post-mortem analyses that have been used in the past. Future numerical investigations of heat generation effects under dynamic loading conditions will be well facilitated by a thorough understanding of the conversion of plastic work to heat under high strain, high strain-rate and high temperatures.

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