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## Determination of temperature rise during high strain rate deformation

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### Abstract

The energy converted to heat during high strain rate plastic deformation is measured directly using an infra-red method for Ta–2.5% W alloy and, indirectly, using UCSD's recovery Hopkinson bar technique for the same alloy, as well as for commercially pure Ti, 1018 steel, 6061 Al and OFHC Cu. The infra-red measurement yields a 70% conversion of work to heat for Ta–2.5% W and generally underestimates this factor for all tested materials. The final temperature at a given strain can be determined indirectly, based on the calculated plastic work. For this, three separate measurements are made: First, a sample is deformed at a high strain rate to a total strain of, say, 60%; this is essentially an adiabatic test. Then a second sample is deformed at the same strain rate to about 30% strain; this should reproduce the first half of the previous adiabatic stress–strain curve and in our test it does. This sample is then allowed to cool down to the initial room temperature. This sample may then be heated to the temperature as was measured by the infra-red detectors and then deformed at the same strain rate to check if the adiabatic curve is traced. It is observed that only when the sample temperature is increased based on 100% conversion of the plastic work to heat, that the original adiabatic stress–strain curve is traced. It is thus concluded that the infra-red detection system records a lower (surface) temperature than the actual temperature of the sample. © 1998 Elsevier Science Ltd.

*Keywords:* Thermomechanical processes; Infra-red signal; Impact testing; Kolsky bar; Metallic materials

### 1. Introduction

Plastic deformations generate heat. The plastic work per unit volume in a uniaxial deformation equals the area under the true stress–strain curve. Internal energy of the material changes with the creation of internal defects such as vacancies, interstitials, and dislocations. This stored internal energy

depends on the amount of defects and also of their arrangement within the material. Thus randomly distributed dislocations have different energy than dislocations which are piled up against barriers. Stroh (1953) and Moore and Kuhlmann-Wilsdorf (1970) calculated the internal energy of a metal sample assuming dislocations are locked in pileups. Zehnder (1991) calculated internal energy as a function of strain, assuming randomly distributed dislocations. The heat generated in the material is either dissipated to the surrounding or is used to increase the temperature of the material. When the rate of heat generation

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is greater than the rate of heat loss, the temperature of the material increases.

For materials whose flow stress is temperature dependent, continuous rise of temperature during deformation results in simultaneous lowering of the flow stress. Thus if the deformation was carried out with complete heat loss to the surroundings (isothermal), the flow stress would be higher than when there is no heat loss (adiabatic). It is thus important to determine the fraction of work which goes to increasing the temperature of the material.

An indirect means to determine the temperature rise during deformation is to measure the stored energy using calorimetric measurements after the test. A review of such experimental studies is given by Bever et al. (1973). It is reported that, in general, not more than 5% of work done is stored in metals as the elastic energy of defects. The surface temperature can be measured during deformation by attaching thin thermocouple wires to the surface of the sample. How thin the surface wire is depends on the response time of the wires. No study has been reported on such a thermocouple based temperature measuring technique<sup>1</sup>. Using infra-red radiation given off by a body is another technique of measuring the surface temperature. Moss and Pond (1975) used this technique to measure surface temperature of deforming Cu samples. Deformation was carried out at about 100/s using pneumatic loading devices. For a strain of 0.2, a temperature change of 20 to 30°C was observed. Hartley et al. (1986) and Marchand and Duffy (1987) have carried out Hopkinson bar tests on steel and observed a 500°C temperature rise within shearbands. Noble and Harding (1994) carried out high strain rate tensile tests on iron. Description of the setup, calibration and working of the infra-red system is given by Craig et al. (1994) and Noble and Harding (1994). Mason et al. (1994) measured the surface temperature of materials deformed uniaxially and uniformly in the Hopkinson bar. They report that for Al and steel, the fraction of

work converted to heat varies from 80 to 90%. In the case of Ti–6Al–4V, this fraction is reported to decrease to as low as 60% at a strain of about 0.2. No explanation for the balance of energy was provided. This suggests that 40% of the work done is stored within Ti–6Al–4V as elastic energy of the defects, which is difficult to justify. Recently Nemat-Nasser and Isaacs (1996), used an indirect temperature measurement technique, to conclude that essentially all of the plastic work gets converted to heat, for the case of Ta–10% W alloy.

The objective of the present research is to experimentally determine the temperature rise of cylindrical samples of Ta–2.5% W alloy during high strain rate deformation. Indirect temperature measurements were also carried out on commercially pure Ti, 1018 steel, 6061 Al and OFHC Cu.

## 2. Experiments

As mentioned above, the aim of this research was to determine the fraction of work converted to heat as the alloy is adiabatically deformed (justification that deformation carried out at 3000/s to 0.3 strain is adiabatic, is provided in Appendix A). In order to achieve this, two different experiments were carried out:

(1) Direct measurement of the sample temperature through infra-red radiation as the sample is being deformed.

(2) Load the sample to a strain of about 0.3, unload the sample and calculate the work done. Assume that all of the work has been converted to heat and, hence, calculate the temperature of the sample before unloading (strain of 0.3). Heat the sample to that temperature, deform it at the same strain rate by another 30% strain and compare the yield stress of the sample to that of another sample which has been deformed adiabatically at the same strain rate to 60% strain.

The first experiment is a direct measurement of the surface temperature, whereas the second experiment is an indirect measurement of the temperature through the measurement of the corresponding flow stress. Nemat-Nasser and Isaacs (1996) were the first to use this indirect technique to determine the frac-

<sup>1</sup> Some preliminary experiments of this kind were carried out by Mr. Jon Isaacs at CEAM of UCSD, showing that such surface temperature measurements seem to underestimate the actual temperature rise by at least 10%.

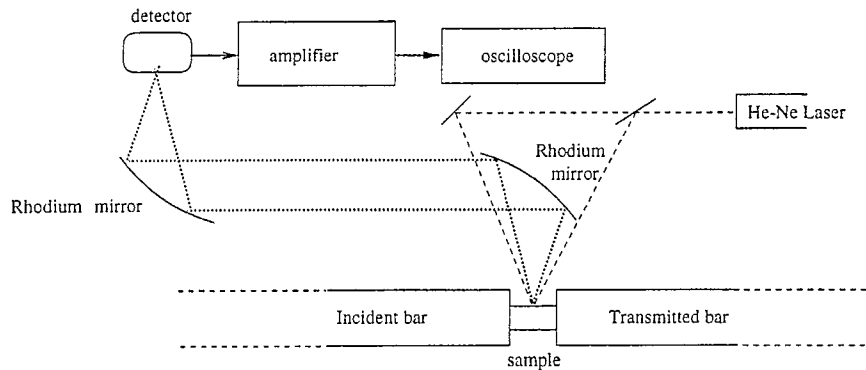


Fig. 1. Experimental setup: infra-red detection system.

tion of work converted to heat in Ta–10% W alloy <sup>2</sup>. From this study it was concluded that essentially all the work was converted to heat.

### 3. Experimental setup

High strain rates of 3000/s are achieved using a split Hopkinson pressure bar (SHPB). The classical Hopkinson bar setup has an incident bar, a transmission bar and a striker bar. The sample is placed between the incident and the transmission bars. The striker bar impacts the incident bar and generates in it an elastic stress pulse whose width is twice the length of the striker bar. Strain gauges are placed at equal distances from the sample ends of the bars. The incident pulse on reaching the sample is partly reflected back in the incident bar as tension and is partly transmitted through the sample into the transmission bar. From a one dimensional theory of elastic wave propagation, the strain rate and the stress in the sample are calculated as explained by Davies (1948), Kolsky (1949) and Folansbee (1985). The reflected tensile pulse, reflects off the free end of the incident bar as compression and reloads the sample if it is not ‘trapped’. This trapping is achieved by the addition of a flange to the end of the incident bar, and a sleeve with the same impedance as the incident

bar (for details see Nemat-Nasser et al., 1991). For high temperature tests, a small cylindrical tube furnace is placed around the sample and ends of the bars. The sample is placed between chromel and alumel wires, thus creating a thermocouple junction by which the temperature of the sample can be measured. The temperature of the furnace is controlled manually using a variac connected to the furnace.

Infra-red signals are measured using a 4-channel, EG&G Judson, Indium Antimonide, photovoltaic detector. The InSb photodiodes provide excellent performance in the 1 to 5.5  $\mu\text{m}$  wavelength region. The detector is mounted in a liquid nitrogen cooled dewar with a sapphire window. Since the detector is at 77 K, the noise is significantly reduced. The detector area is a 2 mm diameter InSb semiconductor etched with a cross to yield four quadrants. The signals pass through 1 MHz amplifiers and are recorded on a Nicolet 4094 oscilloscope. Fig. 1 is a schematic diagram of the infra-red imaging system. The imaging system consists of two, 7.6 mm diameter, off axis paraboloid rhodium mirrors. The first mirror is positioned so that the sample is located at the focus of the paraboloid mirror. This results in a 7.6 mm diameter collimated infra-red beam from radiation emitted by 1 mm of sample surface. The second mirror positioned approximately a meter away, reflects and focuses the radiation into the infra-red detector. The infra-red detector is positioned at the focal point of this second mirror. An aperture is installed both in front of the sample and in front of the detector. The aperture in front of the sample

<sup>2</sup> The results of this experiment were first reported at the 29th Annual Technical Meeting of the Society of Engineering Sciences, held at UCSD, in September 1992.

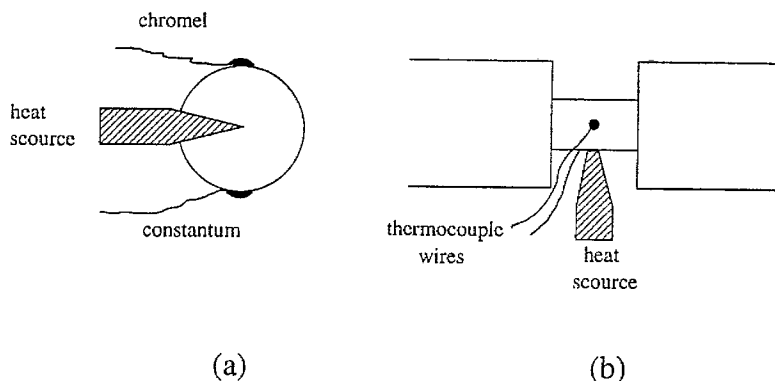


Fig. 2. Configuration of sample with heat source and thermocouples.

ensures that radiation emitted from bars does not interfere with radiation emitted from the sample. The whole experimental setup is covered by a black cloth to prevent external light from affecting the detector signal. Alignment of this system was performed by illuminating the sample with He–Ne laser and imaging the spot into the detector. Use of mirrors, instead of lenses, allows visible light for alignment of infra-

red optics. This optical system is mounted on a sturdy, movable and adjustable optical bench.

#### 4. Infra-red detector calibration

Cylindrical samples of Ta–2.5% W were used for calibrating the infra-red (IR) detector signal. The

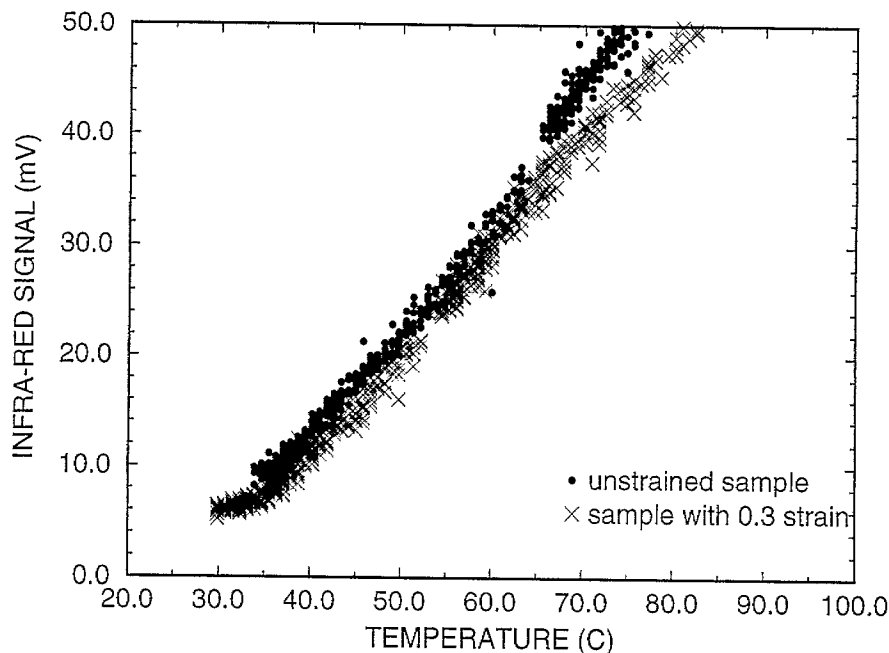


Fig. 3. Comparison of the infra-red detector signals for different surface. The different surface conditions were due to different strains of the sample.

approach was to internally heat the sample and then record the IR signal as a function of temperature as measured by thermocouple. A hole was drilled on the lateral surface of the calibration sample such that the sample could be heated internally using a soldering iron. One wire each of constantan and chromel were spot welded on either side of the sample. Constantan and chromel produce a thermocouple junction with a sensitivity of about  $6.3 \text{ mV}/100^\circ\text{C}$ . Fig. 2(a) and (b) schematically depict the sample in between the bars with thermocouple and soldering iron. As shown in Fig. 2(b), the sample is placed in between the incident and the transmitted bars with the infra-red detection system aligned. The sample is heated with a soldering rod placed in its hole. After reaching a stable temperature of about  $150^\circ\text{C}$ , the heat source is withdrawn. The signal, as measured by the IR detector and the thermocouple are recorded simultaneously. A comparison between the two, results in the calibration of the IR detector signal. A similar calibration was carried out using a sample deformed to 0.3 strain. This was done in order to check if the detector signal changes because of a change in surface condition (as a result of straining).

Fig. 3 is a comparison of the calibration between samples at different strains. No appreciable change in calibration is detected.

## 5. Results and discussion

Fig. 4 shows the raw data of the compression test on Ta–2.5% W at a starting temperature of  $22^\circ\text{C}$  and a strain rate of  $3000/\text{s}$ . Shown here is the incident pulse, reflected pulse, transmitted pulse and two signals from detectors. Conversion of the detector signals to temperature were done using an empirical equation. Noble and Harding (1994) suggested the following empirical relation between the detector signal ( $I$ ) and the absolute temperature ( $T$ ) of the body, where  $R$ ,  $B$  and  $F$  are empirical constants,

$$I = \frac{R}{\exp(B/T) - F} \quad (1)$$

Since at  $T = 295 \text{ K}$  (room temperature),  $I = 0$ , a modified relationship is,

$$I = \frac{R}{\exp(B/T) - F} - I' \quad (2)$$

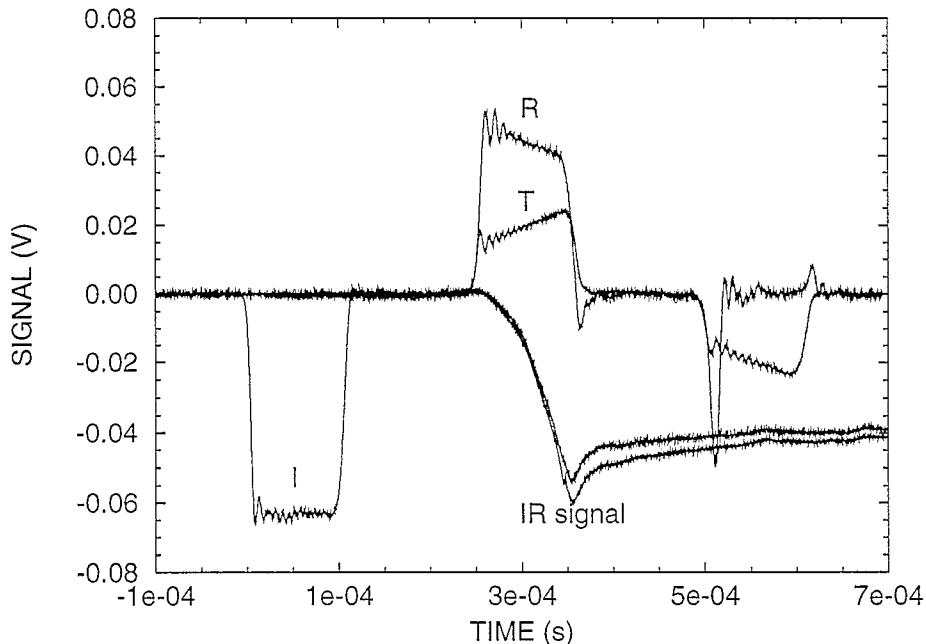


Fig. 4. Raw data of Ta–2.5% W tested at  $22^\circ\text{C}$  and at  $3000/\text{s}$  strain rate; shown here is the incident pulse (I), reflected pulse (R), transmitted pulse (T) and two infra-red detector signals, as functions of time.

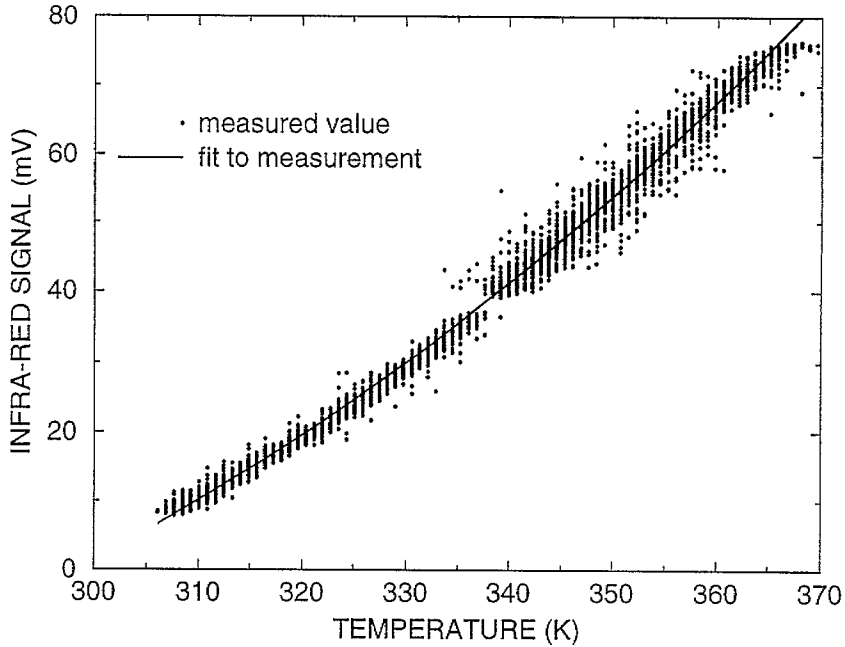


Fig. 5. Calibration signal as a function of absolute temperature, showing experimental points and an empirical fit.

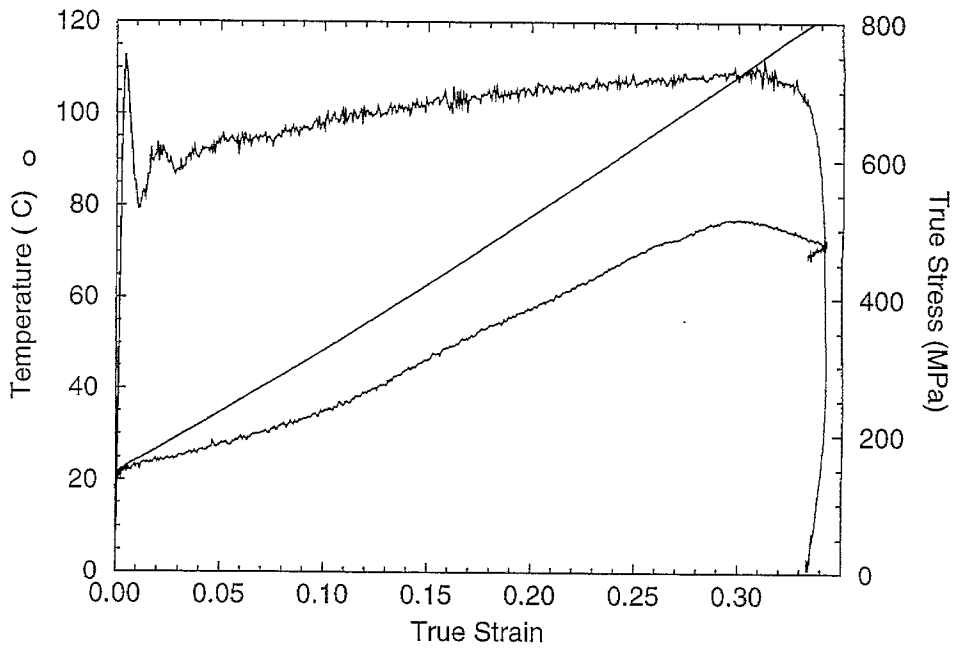


Fig. 6. Double Y-axis plot: the left Y-axis represents temperature and the right Y-axis represents true stress; shown here is the calculated as well as measured temperatures as functions of strain, for Ta-2.5% W alloy.

which results in,

$$T = \frac{B}{\ln(R/(I + I')) + F} \quad (3)$$

Using non-linear regression, the values of  $B$ ,  $R$ ,  $I'$  and  $F$  are obtained. Fig. 5 is a plot of the calibration signal versus the absolute temperature, showing both experimental points as well as the fit of Eq. (2). The parameters thus obtained are used in Eq. (3) to determine temperature,  $T$  (K), given a signal,  $I$  (mV). In this way the detector signal in mV can be converted to temperature in kelvin.

From the true stress–true strain curve of Ta–2.5% W deformed at 3000/s and 22°C (initial temperature), the total work done on the sample is calculated. The temperature of the sample is then calculated as a function of strain, assuming that the  $\eta$ -fraction of the work goes to heating the sample,

$$\eta \Delta W \approx \Delta Q \quad (4)$$

$$\eta \int_0^\epsilon \sigma \, d\epsilon = \rho C_v \Delta T \quad (5)$$

$$\Delta T(\epsilon) = \frac{\eta}{\rho C_v} \int_0^\epsilon \sigma \, d\epsilon \quad (6)$$

here  $\Delta W$  is the work done,  $\Delta Q$  is the heat generated,  $\sigma$  is the true stress,  $\epsilon$  is the true strain,  $\rho$  is the material density,  $C_v$  is the specific heat capacity at constant volume (plastic flow is essentially isochoric) and  $\Delta T$  is the rise in temperature.  $\eta = 1$  when all the work is used to heat the sample without any heat loss.

Fig. 6 is a double Y-axis plot. On the left Y-axis the temperature of the sample is a function of strain, whereas on the right Y-axis the true stress is a function of strain. There are two curves showing the temperature. The lower one is that recorded by the IR detectors, while the upper curve is as calculated from Eq. (6) (with  $\eta = 1$ ). The IR detectors show a temperature increase of 63°C (85–22°C), while the calculated curve shows a temperature increase of 93°C (115–22°C). The results from the IR detector suggest that about 68% of the input energy is converted to heat. A 68% conversion of work to heat implies a 32% storage of work as internal energy in

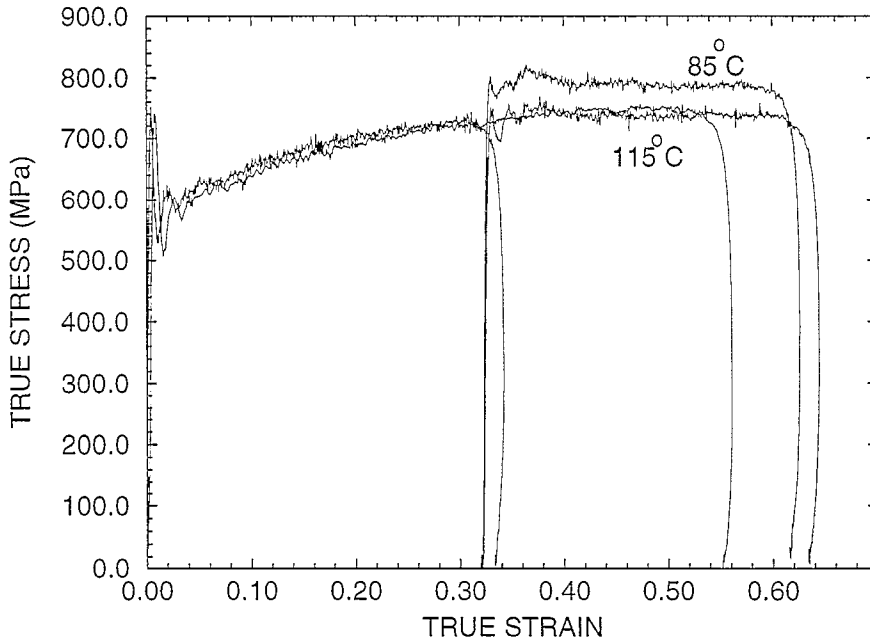


Fig. 7. True stress–true strain plot of Ta–2.5% W alloy, loaded at 3000/s strain rate and 22°C initial temperature; the samples are then unloaded after a strain of 0.32 and then reloaded at 85 and 115°C.

the form of defects (with assumption of no heat loss, which is justified as shown in Appendix A).

In order to verify the actual temperature, two samples were deformed under the same conditions up to a true strain of 0.32. They were allowed to cool to room temperature and were then heated to different temperatures before reloading. One sample was heated to 85°C and reloaded, whereas the other sample was heated to 115°C and reloaded. Another undeformed sample was strained (starting at room temperature) up to a strain of 0.54. Fig. 7 is the stress-strain plot showing the results of these three experiments. It is observed that reloading the sample at 115°C ( $\approx 100\%$  conversion of work to heat) results in a flow stress which is essentially the same as that just before unloading. Further, the flow stress of this sample is essentially identical to the flow stress of the sample deformed to a strain of 0.54. Reloading the sample at 85°C (infra-red detector measurement) results in a flow stress higher than that before unloading. This clearly suggests that, within the experimental error, all of the work done in deformation goes into generation of heat in the sample, i.e.  $\eta \approx 1$ , in Eq. (6) and that the infra-red measurement underestimates the actual temperature of the sample.

The question which now arises is that, for how many other materials (during adiabatic deformation) essentially all of the work gets converted to heat. To answer this, similar tests (loading-unloading-reloading at a calculated temperature) were carried out on commercially pure Ti, OFHC Cu, 6061 Al in T6 condition and 1018 Steel. Mason et al. (1994) suggested that in Ti-6Al-4V, only 60% of the work done converts to heat. Further it was suggested that the conversion of work to heat was 80% for 4340 steel and 85% for 2024 Al. These values were used as guidelines in performing the following tests. Two samples of each material were tested under the same conditions up to a given strain. They were allowed to cool to room temperature. The work done during deformation was calculated (area under the stress-strain curve). Assuming 100% of the work is transformed to heat, the temperature just before unloading was estimated. One out of the two samples was reheated to that temperature, and then reloaded. The second sample was reloaded at a temperature which corresponds to only a fraction of work being con-

Table 1

Deformation-induced temperature change, assuming 100% conversion and  $x\%$  conversion of work to heat

Material	Strain increment at unloading	$\Delta T$ (°C) (100%)	$\Delta T$ (°C) ( $x\%$ )
Ti	0.2	73	50 (60)
1018	0.32	91	73 (80)
6061 Al	0.4	71	60 (85)
Cu	0.45	60	48 (80)

verted to heat. Apart from these two samples, a third sample was adiabatically deformed to a larger strain. Table 1 shows the strain at which the sample is first unloaded, the rise in temperature at that strain assuming 100% conversion of work to heat and the rise in temperature assuming a fraction,  $x\%$  (as indicated), of work being converted to heat. 22°C (room temperature) was added to these temperatures.

Fig. 8(a), (b), (c) and (d) show the results for Ti, 1018 steel, 6061 Al and Cu, respectively. In the case of Ti, the assumption that 60% of work gets converted to heat results in a flow stress higher than that before unloading and does not continue along the adiabatic stress-strain curve. Similarly, the assumption of 80% conversion of work to heat results in a higher flow stress for 1018 steel. In both cases, the assumption of 100% work to heat results in the overlap of the flow stress with that of the sample continuously deformed to a larger strain. For the case of 6061-Al and Cu, the temperature sensitivity of the flow stress is very low. Thus the change in the sample temperature does not result in a significant change in the flow stress. If it is assumed that 100% work is converted to heat, for each of the materials, the reload flow stress follows the flow stress of the sample deformed to a larger strain. From this, it can be concluded that a good estimate of the flow stress can be made with the assumption of full conversion of work to heat during adiabatic deformation.

The elastic stored energy within a metal can be calculated to within an order of magnitude by calculating the energy of the dislocations. The energy of a dislocation per unit length ( $E'$ ) is written as

$$E' = \frac{\mu b^2}{4\pi} \ln \frac{R}{r_0} \quad (7)$$

where  $\mu$  is the shear modulus,  $b$  is the burgers vector,  $R$  is the upper cut off radius and  $r_0$  is the



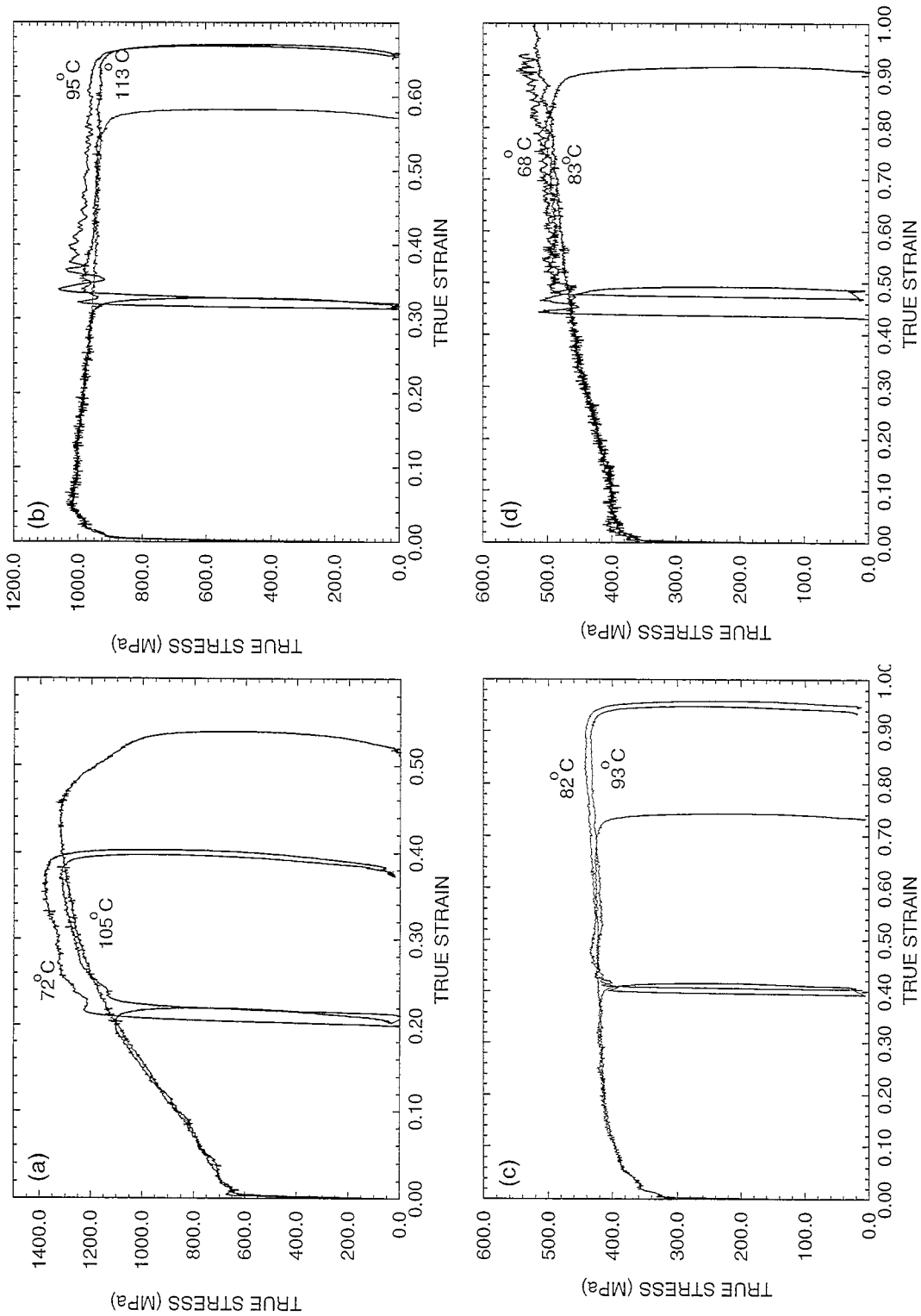


Fig. 8. (a) True stress–true strain plot of Ti, loaded at 3000/s strain rate and 22°C initial temperature; the samples are unloaded at 0.2 strain, and then reloaded at 95 and 72°C. (b) True stress–true strain plot of 1018 mild steel, loaded at 3000/s strain rate and 22°C initial temperature; the samples are unloaded at 0.32 strain and then reloaded at 113 and 95°C. (c) True stress–true strain plot of 6061 Al, loaded at 3000/s strain rate and 22°C initial temperature; the samples are unloaded at 0.4 strain and then reloaded at 93 and 82°C. (d) True stress–true strain plot of Cu, loaded at 3000/s strain rate and 22°C initial temperature; the samples are unloaded at 0.45 strain and then reloaded at 83 and 68°C.

lower cut off radius. For the case of randomly distributed dislocations,  $R \approx 2/\sqrt{\rho}$ , where  $\rho$  is the dislocation density;  $r_0$  is the lower cut off radius and is taken as  $b$ . The total energy per unit volume is

$$E = \rho E' = \rho \frac{\mu b^2}{4\pi} \ln \frac{2}{b\sqrt{\rho}} \quad (8)$$

For a very high dislocation density of  $10^{15}/\text{m}^2$ , the energy per unit volume is calculated to be  $0.6 \times 10^6 \text{ J/m}^3$ . The interaction energy of dislocation is of the order of  $\rho\mu b^2$ . Thus, the total energy per unit volume due to dislocations is of the order of  $10^6 \text{ J/m}^3$ . Energy input in the system is approximately the area under the stress–strain curve, which is about  $200 \times 10^6 \text{ J/m}^3$ . Thus, the fraction of energy stored as dislocations is about 0.5%.

Stroh (1953) calculated the stored energy in single crystal Cu due to dislocation pileups, as 4.5%. Moore and Kuhlmann-Wilsdorf (1970) also calculated the energy due to dislocation pileups. For an average pileup of 50 dislocations and a dislocation density of  $10^{14}/\text{m}^2$ , the interaction energy for Ta–2.5% W is,

$$E = 100\rho \frac{Gb^2}{4\pi} = 0.9 \times 10^6 \text{ J/m}^3$$

This gives the fraction of stored energy as 1%.

Zehnder (1991) attempted to relate work-hardening to the fraction of stored energy assuming a random distribution of dislocations. He calculated the fraction of stored energy to be related to the work-hardening as

$$\frac{1}{E} \frac{\partial \sigma}{\partial \epsilon} \quad (9)$$

where  $E$  is the elastic modulus and  $\partial\sigma/\partial\epsilon$  is the slope of the stress strain curve during plastic deformation. In the present case, the relation between stress and strain can be written as

$$\sigma = A\epsilon^{0.3} + B \quad (10)$$

$$\frac{\partial \sigma}{\partial \epsilon} = \frac{A\epsilon^{0.3} \cdot 0.3}{\epsilon} = \frac{0.3\sigma}{\epsilon} \quad (11)$$

From this, the fraction of stored energy is calculated as 4%.

From the above approximate calculations, it is observed that only a few percent of the work can be

stored within the material as the elastic energy of defects. Most of the applied energy produces heat within the sample. From the results obtained in the present research, it appears that infra-red measurement system underestimates the sample temperature, which in turn results in higher estimation of stored energy within the material. A possible error could be in the method of calibration of the infra-red detector signal. During calibration the sample is heated at a slow rate, allowing the atmosphere around the sample to heat up as well. This surrounding atmosphere will itself add to infra-red radiation during the calibration procedure. In the case of the actual test, which lasts only about 100  $\mu\text{s}$ , the surrounding atmosphere is not affected. This results in a lower infra-red signal received by the detector which in turn results in a lower apparent temperature. Previous studies (Moss and Pond, 1975; Hartley et al., 1986; Marchand and Duffy, 1987; Mason et al., 1994) have used a similar method for the calibration of the infra-red detector system. The calibration is carried out at near steady state, whereas the actual testing is done under adiabatic conditions.

If the purpose of obtaining a temperature increase within a deforming specimen is to predict its flow stress, the assumption that, at strains less than 0.6, about 100% of work done goes to heating the sample is valid, as is observed in Figs. 7 and 8.

## 6. Conclusions

Within experimental error, close to 100% of the work done during high strain rate deformation is converted to heat. Experiments on Ta–2.5% W, commercially pure Ti, 1018 steel, 6061 Al and OFHC Cu confirmed this result. Infra-red detectors underestimate the rise in temperature of the sample, probably due to the difference in the conditions during calibration and during testing, calibration being done at a slower heating rate as compared to the test. For the purpose of predicting the flow stress as a function of strain during adiabatic deformation, the assumption that all of the work done is converted into heat generation, is valid.

### Acknowledgements

The authors wish to thank David Lischer for his technical assistance in the detailed setup and calibration of the infra-red detection system. This research was supported by the Army Research Office under contract ARO DAAL03-92-G-0108 to the University of California, San Diego.

### Appendix A

This is a calculation of heat loss assuming one dimensional heat transfer between specimen and bars. The thermal diffusivity ( $k = K/\rho C$ ,  $K$  is thermal conductivity,  $\rho$  is density,  $C$  is specific heat capacity) of Ta is  $25 \times 10^{-6} \text{ m}^2/\text{s}$ , whereas that of steel is  $23 \times 10^{-6} \text{ m}^2/\text{s}$ . As a first approximation, it is assumed that a bar of Ta is infinitely long with a region from  $-L$  to  $+L$  having an initial temperature of  $90^\circ\text{C}$ , whereas the remaining region has a temperature of  $0^\circ\text{C}$ ;  $90^\circ\text{C}$  is the approximate rise in temperature of the sample if it is assumed that 100% of the plastic work is converted to heat. With this, the problem to solve is

$$\frac{\partial T}{\partial t} = k \frac{\partial^2 T}{\partial x^2} \quad (\text{A.1})$$

for  $-\infty < x < +\infty$  and  $t \geq 0$ , with the initial condition that  $T(x, 0) = f(x)$ . The solution of this problem is given by

$$T(x, t) = \int_{-\infty}^{\infty} f(\bar{x}) \frac{1}{\sqrt{4\pi kt}} \exp\left(-\frac{(x-\bar{x})^2}{4kt}\right) d\bar{x} \quad (\text{A.2})$$

For the initial condition

$$\begin{aligned} T(x, 0) &= 90 & \text{if } -L < x < L \\ &= 0 & \text{if } |x| > L \end{aligned} \quad (\text{A.3})$$

the solution reduces to

$$T(x, t) = \int_{-\infty}^{\infty} 90 \frac{1}{\sqrt{4\pi kt}} \exp\left(-\frac{(x-\bar{x})^2}{4kt}\right) d\bar{x} \quad (\text{A.4})$$

This can be solved numerically for a sample 4 mm in length, since the sample is defined from  $-L$  to  $L$ ,

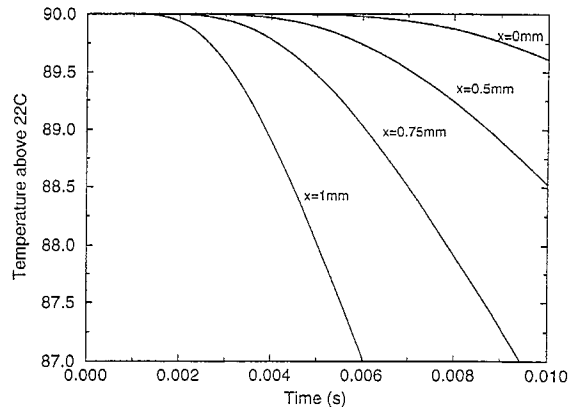


Fig. 9. Plot of temperature above  $22^\circ\text{C}$  as function of time for different positions on the specimen; the sample is from  $x = -2$  mm to  $x = 2$  mm.

$L = 2$  mm. A plot of the temperature change from  $22^\circ\text{C}$  versus time, for different positions on the sample, is given in Fig. 9. At  $x = 0$  the temperature drops by about  $0.4^\circ\text{C}$  in 10 ms. For  $x = 1$  mm, the temperature drops by about  $1^\circ\text{C}$  in 4 ms. Clearly the rate of heat transfer is insignificant for the actual test durations of the order of  $100 \mu\text{s}$ .

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