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THERMAL SOFTENING EFFECTS IN TYPE 224 CARBON STEEL

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Résumé : Des travaux ont été entrepris sur le comportement en compression d'un acier au carbone 224 (0,18 % ; 1,25 % Mn) dans l'intervalle de température (-110°C, + 300°C) et la gamme de vitesse de déformation $10^{-4}s^{-1}$ à 5000 s^{-1} rendant possible la détermination de la sensibilité thermique de ce matériau. Dans plusieurs essais, un thermocouple a été installé au sein du petit échantillon cylindrique afin d'apprécier une augmentation éventuelle de température lors de la compression. Pour de faibles vitesses de déformation aucune augmentation appréciable de température n'a été observée alors qu'au delà de 4 s^{-1} des accroissements ont été mesurés, conformément aux prévisions fondées sur un comportement adiabatique.
En combinant, pour des essais particuliers, la sensibilité thermique avec l'élévation calculée de température, nous avons pu déterminer la réduction de la contrainte d'écoulement imputable à l'adoucissement adiabatique. Cette réduction peut atteindre 20 % de la contrainte d'écoulement en compression à basse température d'essai, et peut rendre compte de la convergence et du recouvrement des courbes contrainte-déformation à grande vitesse de déformation avec celles obtenues dans des conditions quasi-statiques.

Abstract - An extensive investigation has been carried out on the compressive mechanical behaviour of type 224-carbon steel (0.18 wt % C, 1.21 wt % Mn) over the temperature range -110°C to +300°C and strain-rate 10^{-4} to $5000s^{-1}$, making possible the determination of the thermal sensitivity of this material. In several tests, a thermocouple was mounted inside each small cylindrical specimen to observe any temperature variation during compression. For low strain-rates ($<10^{-2}s^{-1}$) no appreciable temperature rise was observed, while at rates above $4s^{-1}$ temperature rises were measured which agree with predictions based on adiabatic behaviour. Combining the measured thermal sensitivity with the predicted temperature rise for particular tests has allowed the reduction in flow stress ascribable to adiabatic softening to be determined. This reduction can be as high as 20% of the flow stress in low ambient temperature compression, and can account for the convergence and overlapping of the stress/strain curves at high strain rates with those obtained under quasistatic conditions.

1. INTRODUCTION

When carbon steel specimens are compressed nearly all the work of plastic deformation is converted into heat. If the deformation takes place slowly, say at a strain rate of $10^{-2}s^{-1}$ or less, then heat generated within the specimen can be lost at the same rate to the surroundings by means of natural cooling and hence there will be no overall change in temperature of the sample itself. A compression test under these conditions may be considered isothermal.

If, however, the deformation takes place at a high strain rate, as in a split Hopkinson pressure bar (SHPB) test, then there may be insufficient time for the heat to escape and the specimen temperature will rise according to the level of strain. A compression test may be said to be adiabatic if the strain-rate is sufficiently high so that no heat is lost during the test itself.

The critical strain-rate $\dot{\epsilon}_A$ above which a compression test may be considered adiabatic depends not only on the specimen geometry but also the type of test apparatus and its thermal contact with the specimen.

Frost and Ashby /1/ have derived an expression for $\dot{\epsilon}_A$ based on a conventional compression test arrangement in which a cylindrical specimen of radius R is sandwiched between two parallel steel faces. This strain rate is given by

$$\dot{\epsilon}_A = \frac{4\epsilon_C K}{C_p R^2} \qquad (1)$$

where K is the thermal conductivity of the specimen, C_p is the volume specific heat of the specimen at constant pressure, and ϵ_C is the critical strain above which adiabatic shear may occur. This critical state is given by

$$\epsilon_C = \frac{-n\, C_p}{\left|\frac{\partial\sigma}{\partial T}\right|_{\epsilon,\dot{\epsilon}}} \qquad (2)$$

where n is the work hardening exponent, σ is flow stress, ϵ is strain and T is temperature.

In an adiabatic test, assuming there are no heat losses and that all the mechanical work of deformation is converted into heat, then the temperature rise ΔT corresponding to a strain ϵ in the sample is given by

$$\Delta T = \frac{1}{C_p}\int_0^{\epsilon} \sigma(\epsilon)d\epsilon \qquad (3)$$

Measurement of the stress/strain behaviour then enables ΔT to be evaluated.

In general, for carbon steels the rise in temperature during deformation produces a softening of the specimen so that the flow stress is less than if the test had been entirely isothermal.

The subject of adiabatic plastic deformation has been reviewed by Rogers /2/ and more recently by Stelly and Dormeval /3/. In spite of the obvious importance of adiabatic softening, few attempts have been made to evaluate the magnitude of the effect on actual stress/strain behaviour. Follansbee /4/ calculated, using a form of equation (3), that the temperature rise in a specimen of Nitronic 40 stainless steel compressed by 20% in a SHPB test at $5000s^{-1}$ should be 62°C. He estimated that such a temperature rise could account for a reduction in flow stress of 168MPa, i.e. 14% of the observed flow stress, at 20% true strain. Follansbee suggested that this degree of thermal softening could explain an overlap of quasistatic stress/strain curves with dynamic curves at true strain between 20 and 40% for that material.

Holzer and Wright /5/ have applied thermal softening corrections to experimental results from compression tests on AISI 1025 steel and have shown that the effect can account for negative values of strain-rate sensitivity $\partial\sigma/\partial\log\epsilon$ at strain-rates between 0.1 and $20s^{-1}$. Muller /6/ corrected his dynamic test data from iron and nickel specimens, and hence presented effective 'isothermal' curves. Oyane et al /7/ performed a similar exercise for S35C carbon steel (0.33%C, 0.75% Mn) at high ambient temperatures between 650 and 850° C.

It is important to consider this difference between isothermal and adiabatic testing when comparing stress/strain results from low strain-rate tests with those from high strain-rate tests. The present paper describes the measurement of adiabatic heating effects and their implication for plastic stress/strain behaviour.

2. EXPERIMENTAL

2.1 The Specimens

The material investigated was type 224 carbon manganese steel (by weight % 0.18 C and 1.21 Mn, other constituents being 0.34 Si, 0.12 Cr, 0.15 Ni and 0.22 Cu). The steel was tested 'as received' having been normalised by the manufacturers at 880° C.

The compressive specimens were solid cylinders with length by diameter of either 5.0 mm x 10.0 mm or 4.0 mm x 8.0 mm, with a maximum variation of ± 0.1 mm in these dimensions. For both specimen sizes the end faces were parallel to better than 5μm with a surface finish of ± 0.25 μm.

2.2 The Compression Tests

Three types of materials testing apparatus were used: a 50 kN capacity screw driven Instron machine ($10^{-4}s^{-1} \leq \dot{\varepsilon} \leq 10^{-2}s^{-1}$), an hydraulic ESH machine ($10^{-4}s^{-1} \leq \dot{\varepsilon} \leq 4s^{-1}$) and a split Hopkinson pressure bar system ($10^{2}s^{-1} \leq \dot{\varepsilon} \leq 5 \times 10^{3}s^{-1}$). The SHPB apparatus was similar to that described previously /8/. A transient recorder/microcomputer system was used to record and analyse the incident, reflected and transmitted strain-time pulses so that values of true stress, strain and strain-rate were obtained for each test duration /9/.

For all these types of compression systems some tests were carried out at elevated temperatures of 150°C and 300°C by surrounding the specimen with a short ceramic tube furnace. Tests at below room temperature were made possible by placing a lagged copper jacket filled with liquid nitrogen around the specimen. For the Instron and ESH machines it was not possible to achieve test temperatures of lower than -40°C because of the large amount of heat conduction through the specimen support. However, in the SHPB tests temperatures of -110°C were possible. In all tests the initial test temperature was monitored to an accuracy of ± 2°C by a K-type thermocouple placed as close as possible to the surface of the specimen. Preliminary investigations showed that heating or cooling of the pressure bars in the SHPB system had no measurable effect on the shape of the recorded pulses.

For each test condition, defined by the temperature and resulting true strain-rate, up to five tests were undertaken, from which mean true stress/strain curves were established for each test condition. The results were independent of which of the two sizes of specimen had been used.

2.3 Measurement of Temperature Rise

The rise in temperature ΔT within a specimen was measured in several compression tests performed at room temperature. A hole of 0.75 mm diameter was drilled completely through the centre of each specimen in a direction parallel to the two end faces. K-type thermocouple wire was then placed inside the hole and molten soft solder was poured in to ensure good thermal contact between the wire and specimen. The solder should not have inhibited the

temperature measurements since its thermal diffusivity is more than twice that of the 224-steel specimen. K-type thermocouple wire was chosen for its relatively high thermal sensitivity of 40 $\mu V/^{\circ}C$ so that measurable emfs were produced even for small temperature changes. The temperature could be measured to an accuracy of better than $\pm$ 0.5°C.
ΔT measurements were made during compression tests on the ESH hydraulic machine at strain-rates of $3.8 \times 10^{-3}s^{-1}$, $3.8 \times 10^{-2}s^{-1}$, $3.8 \times 10^{-1}s^{-1}$ and $3.8s^{-1}$, the thermocouple leads being connected directly to a sensitive chart recorder. Three separate compression tests at each strain-rate were made so that reliable average figures of ΔT could be established.
The total specimen temperature rise ΔT_F was found in eleven separate adiabatic SHPB tests at the highest possible strain rates for the chosen specimen size. For the short term measurements, the thermocouple emf was amplified and then fed to a transient recorder.

For all the ΔT measurements on the ESH hydraulic machine, 0.2 mm diameter thermocouple wire was employed, but in the SHPB experiments both 0.2 mm and 0.1 mm diameter wires were used. From thermal diffusivity calculations it has been estimated /10/ that even the fine wire would have a response time to a step change in temperature of about 400μs. This is longer than the 100μs duration of an SHPB test. However, heat losses from the SHPB specimens via conduction through the pressure bar end faces were negligible during the response time of the thermocouple. Furthermore, the specimen separated from the bars about 800μs after the first loading pulse, due to wave reflections in the system. This further reduced the heat losses.

3. RESULTS

3.1 Stress-Strain Results

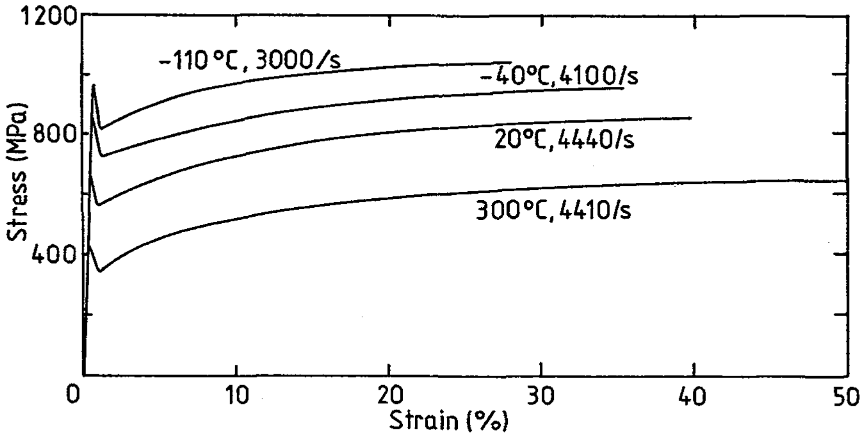

Figure 1 True stress/true strain at high strain rates

Figure 1 shows a selection of mean curves of true stress against true strain for various test temperatures at the highest strain rates used. The variation in flow stress was to be found to be less than $\pm$ 5% about the mean at any strain level. The graphs clearly illustrate the substantial decrease in flow stress with increasing temperature for 224 carbon steel.

The manner in which the flow stress decreases with increasing temperature, at given strain levels, can be more clearly seen by plotting flow stress directly as a function of test temperature. Figure 2 illustrates such behaviour for two different strain rates. For the higher strain-rate of 2000s^{-1}, at which it was possible to undertake tests at -110°C, there is a marked increase in the temperature sensitivity of the flow stress for temperatures below room temperature.

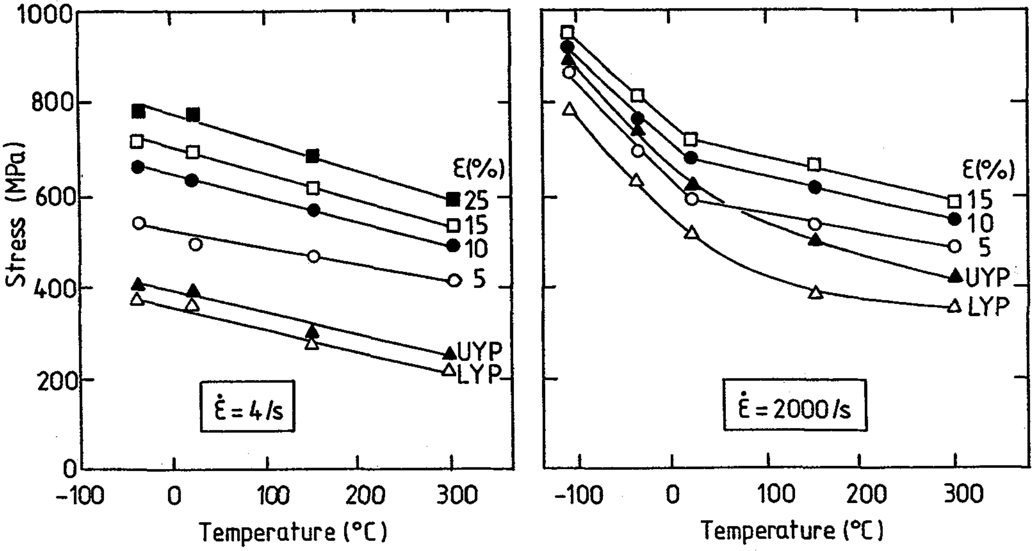

Figure 2. Stress/temperature variation for two strain rates

By using results such as in figure 1, the integral in equation (3) has been evaluated, from which the predicted specimen temperature rise as a function of strain has been obtained for a range of adiabatic test conditions (figure 3). It can be seen that in the higher strain-rate tests appreciable temperature rises of more than 80°C are possible. The effects of such temperature increases will be discussed later.

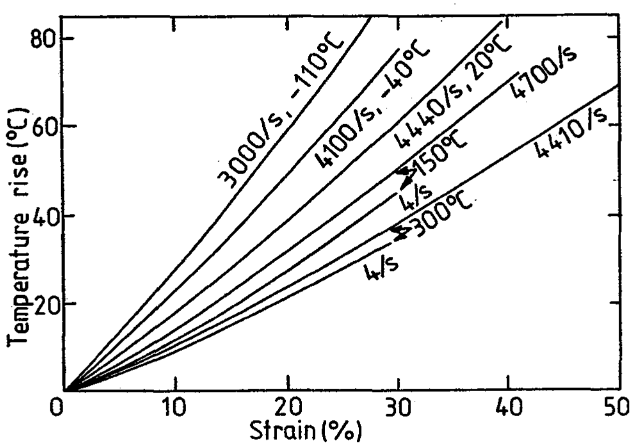

Figure 3. Predicted temperature rise under adiabatic conditions

3.2 Thermocouple Results

Figure 4 is a graph of the recorded final temperature rise ΔT_F against strain-rate for tests carried out using the hydraulic ESH machine in which specimens were compressed to a final true strain of 36%. Below a strain-rate of $10^{-2}s^{-1}$, there is no appreciable temperature rise and therefore conditions may be assumed isothermal. Above this point, the increase in ΔT_F with increasing strain-rate indicates a transition from isothermal to adiabatic test conditions. The horizontal dotted line at $\Delta T_F = 71^\circ C$ marks the expected temperature rise in each specimen according to equation (3), assuming total adiabacity. Thus the graph shows that the compression tests at the highest strain-rate of $3.8s^{-1}$, in which a mean temperature rise of $+66^\circ C$ was recorded, are very nearly adiabatic.

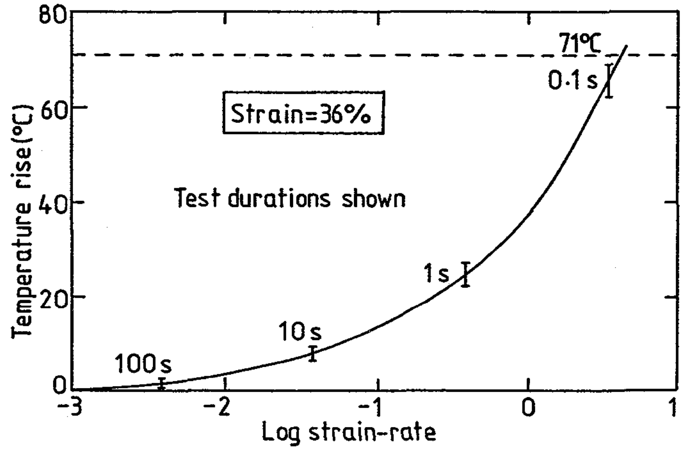

Figure 4. Measured temperature rise at lower strain rates

Extrapolation of the curve beyond the last point to intersect with $\Delta T_F = 71^\circ C$ suggests a critical adiabatic strain rate, ϵ_A of about $4s^{-1}$. This strain rate can be compared with ϵ_A estimated from equations (1) and (2). From /10/ , appropriate parameters for type 224-carbon steel are $n = 0.27$, $C_p = 3.69 \times 10^6 Jm^{-3\circ}C^{-1}$, $K = 48\ Wm^{-1\circ}C^{-1}$. For the specimens of radius $R = 5 \times 10^{-3}m$, with $\partial\sigma/\partial T \sim -350 \times 10^3 Nm^{-2\circ}C^{-1}$ at 5% strain from figure 3a, equations (1) and (2) give $\epsilon_A \sim 6s^{-1}$, this is in close agreement with the present experimental observations.

In the high strain rate SHPB thermocouple measurements, the observed value of the maximum temperature attained by a specimen always agreed, within experimental error, with that predicted from equation 3, indicating clearly the adiabatic nature of the test.

4. ADIABATIC SOFTENING

Having established the manner of the flow stress decreases with temperature at a given strain-rate (as in figure 2), it is possible to calculate the reduction in flow stress $\Delta\sigma$ attributable to adiabatic heating effects. Values of $\Delta\sigma$ due to a temperature rise ΔT in the sample were determined by

$$\Delta\sigma = \left.\frac{\partial\sigma}{\partial T}\right|_{\epsilon = 5\%} \times \Delta T \qquad (4)$$

For a particular test condition, values of ΔT were evaluated according to equation (3) using the area under the stress-strain curve, while $\left.\frac{\partial\sigma}{\partial T}\right|_{\epsilon = 5\%}$ was obtained from appropriate curves such as in figure 2. The gradient at 5% strain was used since 5% true strain is large enough for the flow stress at this point to be undisturbed by yield point effects and yet small enough that no significant temperature rise will yet have taken place during compression.

For the tests at -110°C and $3000s^{-1}$, the predicted temperature rise is 85°C leading to thermal softening which accounts for a total reduction in stress of 208 MPa at a true strain of 28%. This reduction is 20% of the actual observed flow stress. By contrast, at 20°C and above, the total reduction in flow stress ascribable to adiabatic softening at strains of about 30%, amounts to less than 5% at all strain rates from 4 to 4700 s^{-1}.

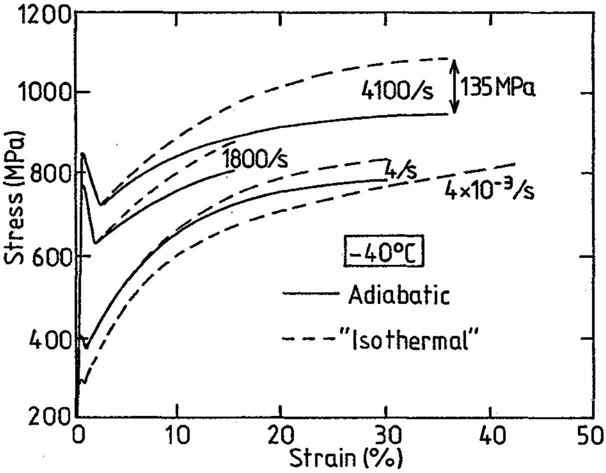

Figure 5. Original and corrected stress/strain at -40°C

Figure 5 shows true stress/strain curves corrected for the affects of adiabatic thermal softening at an initial test temperature of -40°C. This was the lowest temperature at which it was possible to conduct tests from quasistatic to high strain rates. Also shown are the original true stress/strain curves from which the dashed curves were derived by the addition of appropriate values of $\Delta\sigma$. The corrected curves may be referred to as isothermal stress/strain curves, since they represent the stress/strain behaviour which would have resulted had the test conditions been completely isothermal.

At a strain-rate of $4100s^{-1}$ the maximum predicted adiabatic temperature rise of 91°C at 35% strain leads to a corresponding reduction in flow stress of 135 MPa. The plots at $4s^{-1}$ and $1800s^{-1}$ also show that significant correction to the original adiabatic behaviour is necessary. The true stress/strain curve at $4 \times 10^{-3}s^{-1}$ (always isothermal) overlaps the original plot for $4s^{-1}$ at a strain close to 30%. However, this overlap does not occur after correcting the $4s^{-1}$ results.

A similar tendency for overlapping stress/strain curves is observed in figure 6, which shows results obtained at a test temperature of 300°C. The effects of adiabatic softening are much less than in figure 5 since the flow stresses are much reduced, as is the temperature sensitivity of the flow stress. Even so, the adiabatic plot for $4410s^{-1}$ overlaps the quasistatic $4.5 \times 10^{-3}s^{-1}$ (isothermal) results at a strain of 33%. Again, overlapping is removed after correction. Similar considerations apply to the other tests at 20°C and 150°C.

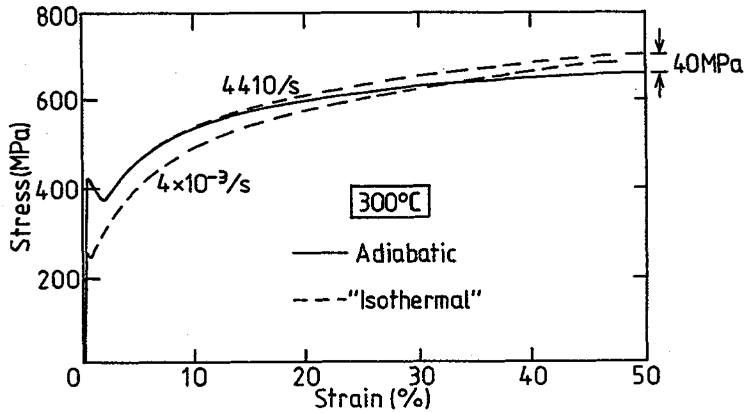

Figure 6. Original and corrected stress/strain at 300°C

5. CONCLUSIONS

Below a strain rate of $10^{-2}s^{-1}$, the compression tests on 224 carbon steel have been shown to be isothermal. For the dynamic testing systems used in the present investigation, when the strain rate exceeds about $4s^{-1}$ the tests have been shown to be adiabatic. By relating these adiabatic temperature rises to reductions in the flow stress it has been possible to deduce the effective isothermal stress/strain behaviour. The differences in flow stress between isothermal and adiabatic conditions have been shown to be quite substantial, especially in low temperature tests.

Adiabatic thermal softening has been shown to account for the converging and overlapping of the stress/strain curves obtained from high strain-rate tests (adiabatic) with those obtained from quasistatic tests (isothermal).

6. ACKNOWLEDGEMENTS

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