JOURNAL OF MATERIALS SCIENCE 26 (1991) 5685–5692

Temperature effect induced by uniaxial tensile loading

H.-T. LEE, J.-C. CHEN
Institute of Mechanical Engineering, National Cheng-Kung University, Tainan, 70101, Taiwan

The coupling effect of thermal and mechanical behaviour of metallic materials was studied by uniaxial tensile test. Heat transfer exists as the specimen is loaded from zero over elastic to plastic region. Cooling occurs in the elastic region and heating in the plastic region. Both theoretical model and experimental results are presented. The theoretically derived model, $\Theta = -(\alpha T_0/\rho C_v)\sigma_{zz}$, which takes exclusively thermoelastic effect into account, explains the cooling phenomenon well. The thermoelastic limit coincides with yield where the temperature drops to its lowest value. This is characterized by the occurrence of an inversion of the trend of temperature against stress. Experimental results on normalized AISI 1045 mild steel reveal a relative maximum temperature drop of about 0.4 K, which is slightly less than as theoretically predicted. Instead of the usual 0.2% offset method, the lowest temperature method introduced here will be preferred in defining the yield stress for its unambiguous and empirical evidence.

1. Introduction

According to elasticity theory, a linear relationship between stress and strain as well as a reversible process between external work and strain energy are traditionally accepted as basic concepts in solid mechanics. In tensile testing, the external work done on loading will be stored totally as strain energy in the specimen; the work done on unloading will reverse the process and the deformed specimen will return back to its original length. However, this is not strictly true when considering the "thermomechanical effect" of material where the temperature of the specimen changes. Heat transfer will occur by deformation. By adiabatic uniaxial tensile testing heat transfer on the material occurs as the specimen loaded from zero over the elastic to plastic regions. Cooling occurs in the elastic region and heating in the plastic region. Such a cooling phenomenon in the linear elastic region was first found and reported by Lord Kelvin in 1851 [1]. Most of the experimental evidence since that time was performed with materials for which the temperature variation is greater than 1 °C and can be easily detected and measured. Polymeric materials such as plastics, rubbers and elastomers, for example, are commonly employed. However, less investigation has been carried out on metallic materials where the maximum temperature change is less than 1 °C. Bottani and Caglioti [2, 3] have used a thermistor as detector and have successfully measured temperature variation in 38NCD4 steel as well as SAFC-40R steel. But, their data and measuring techniques, given by technical patent, were not easily available. After that, however, some reports were published [4–6]. The difficulty of such a study lay in the requirement of a high precision measurement of micro-temperature variation that was needed for experimental evidence. Thus, it is our aim in this paper to study this effect with metallic specimens.

2. Theory

Thermomechanical behaviour deals with the coupling effect of thermal and mechanical behaviour during the deformation process. Thermoelasticity and thermoplasticity are the two major concerns. A theoretical model for the thermoplastic effect is quite complex and still has some open questions which we shall not pretend to derive here. The thermoelastic effect, on the other hand, is well-defined and can be derived directly from thermodynamics and elasticity theory.

From the theory of solid mechanics, when a metallic sample is stretched by ε_z during a non-isothermal tensile test its relative cross-sectional area shrinks by $2\nu\varepsilon_z$ (ν being Poisson's ratio) and the relative volume of the sample increases by

$$\frac{\Delta V}{V} = (1 - 2\nu)\varepsilon_z \qquad (1)$$

The deformation rate is chosen such that: 1. there is no appreciable heat transfer along the sample axis, and 2. any viscous effect is negligible. By using Maxwell's relation, the following equation can be deduced:

$$\frac{\Delta T}{T} = -\gamma(1 - 2\nu)\varepsilon_z \qquad (2)$$

where γ, the Grüneisen parameter, is given by

$$\gamma = \alpha V/K_T C_v \qquad (3)$$

where α is the volume thermal expansion coefficient, K_T is the isothermal compressibility and C_v is the specific heat capacity at constant volume.

From the above equation we know that the sample cools down while it undergoes elastic tensile deformation. The temperature drop is proportional to the deformation and depends on the Grüneisen parameter. At ordinary temperatures, the Grüneisen parameter lies between 1.5 and 2.5 for a wide range of metals [2]. However, an exact value is not easily accessible, unless many investigations have been performed with different materials.

A better way to derive the theoretical model for the thermoelastic effect is introduced here. It can be deduced basically from the generalized thermoelasticity model suggested by Heinz [7]. This generalized model is somewhat complex in its derivation but it is quite useful nevertheless. Its general form can be modified as:

$$\dot{q}_{i,i} = \beta T \dot{e}_{ii} + \rho C_v \dot{\Theta} - \rho \dot{q} \tag{4}$$

where $\dot{q}_i$ is the heat-flux vector within the body, referred to the unit area of the undeformed body, positive inward, and, $\dot{q}_{i,i} \equiv \partial \dot{q}_i / \partial x_i$; β is the isothermal compressibility, $\beta = E\alpha/(1 - 2\nu)$; T is the current temperature of the deformed body; e_{ii} is the first strain invariant, $e_{ii} = \varepsilon_{xx} + \varepsilon_{yy} + \varepsilon_{zz}$ and $\dot{e}_{ii} \equiv \partial e_{ii}/\partial t$; Θ is the temperature deviation from the reference temperature T_0, $\Theta = T - T_0$; ρ is the mass density of the undeformed body; and $\dot{q}$ is the heat produced per unit time and unit mass by heat sources distributed within the body.

For a uniaxial tensile test under adiabatic conditions, that is, no heat input or output, then $\dot{q}_{i,i} = \dot{q} = 0$. Thus, Equation 4 can be simplified:

$$\rho C_v \dot{\Theta} = -\frac{E\alpha}{1 - 2\nu} T \dot{e}_{ii} \tag{5}$$

Integrating Equation 5, with $\Delta T = \Theta$, we get

$$\ln\left(\frac{T_0 + \Delta T}{T_0}\right) = -\left(\frac{\alpha}{\rho C_v}\right)\left(\frac{E}{1 - 2\nu}\right) e_{ii} \tag{6}$$

If $\Delta T \ll T_0$, then $\ln[(T_0 + \Delta T)/T_0]$ may be expanded in an infinite series where the high order terms may be neglected. Thus

$$\Delta T = \Theta = -\left(\frac{\alpha T_0}{\rho C_v}\right)\left(\frac{E\alpha}{1 - 2\nu}\right)(\varepsilon_{xx} + \varepsilon_{yy} + \varepsilon_{zz}) \tag{7}$$

Then, by the stress–strain relation, the simplified final form for temperature variation can be expressed as

$$\Delta T = \Theta = -\left(\frac{\alpha T_0}{\rho C_v}\right)\sigma_{zz} \tag{8}$$

The amount of temperature variation, ΔT, or defined as thermal power, Θ, depends principally on elastic stress, σ_{zz}. Since a metallic material has a positive thermal expansion coefficient, it is clear, from the above equation, that tensile stress causes the temperature to decrease and compressive stress causes the temperature to increase during an adiabatic uniaxial deformation process.

Material parameters such as ρ, C_v, α as well as the ambient temperature T_0, have influence on temperature variation. Fig. 1 is a plot of theoretical temperature variation, ΔT, against elastic stress, σ_{zz}, where the slope $K = -\alpha T_0/\rho C_v$ is defined as coefficient of thermal power and can be treated as constant when the ambient temperature remains constant.

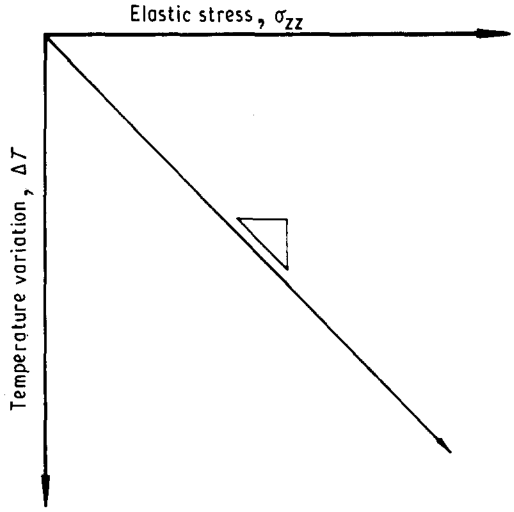

Figure 1 A plot of theoretical temperature variation, ΔT, against elastic stress, σ_{zz}; where the slope $K = -\alpha T_0/\rho C_v$ is defined as coefficient of thermal power.

3. Experimental procedure

In order to ascertain the temperature effect, different materials such as AISI 1045 mild carbon steel, AISI 4140 alloy steel and ASTM W1-8 tool steel were used in the experiment. The materials were first heat-treated and then machined and polished to the desired dimension according to the ASTM-E8 specification. Both round and flat specimens were used: 10 mm dia. and 40 mm gauge length for the round specimen and 12.5 mm width and 80 mm length for the flat specimen. Detailed specimen dimensions are shown in Fig. 2.

The experiments were performed on an MTS 810 hydraulic pulsator with a maximum capacity of 25 tons. The schematic configuration of the system arrangement including pulsator, AT computer and self-installed interfaces, in addition to detecting system, is illustrated in Fig. 3. Temperature measurement with conventional instruments, such as thermometers or thermocouple, were not satisfactory due to the small amount of temperature variation. A self-designed temperature detecting system consisting of highly sensitive semiconductor thermistors as temperature detector was employed [8]. With the aid of a digital multimeter and IEEE-488, this was linked with the AT computer. The detector head had an area of 2.0 mm × 2.3 mm. With this arrangement and the well-designed program a high "temperature resolution" of about 0.0027 K was attained [8, 9]. This has permitted the measurement of micro-temperature variation on the metallic specimens. The operation as well as data acquisition and processing of testing parameters such as load, strain, stroke and temperature variation were executed automatically by computer. The data can be stored and recalled for analysis after a test run. The range for the strain rate variation in our experiment is between 5×10^{-5} and 1×10^{-3} s^{-1}.

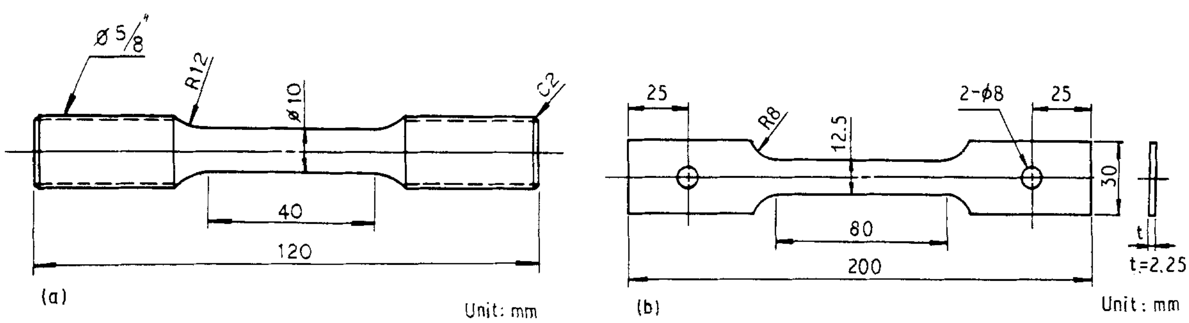

Figure 2 Dimensions of (a) round and (b) flat specimens (in mm).

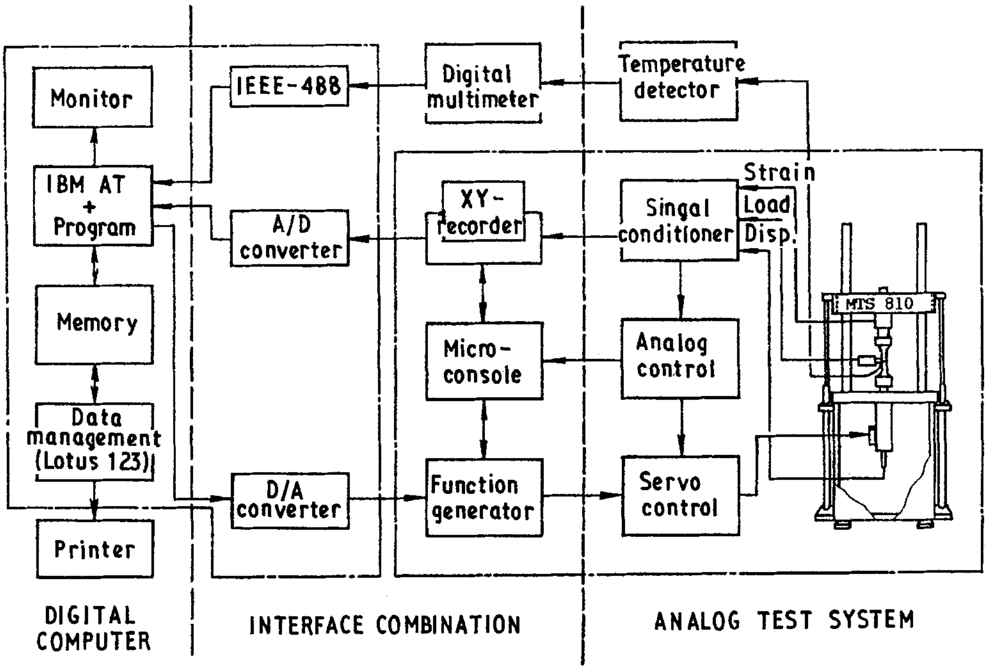

Figure 3 Schematic configuration of MTS 810 hydraulic pulsator combined with computer system and temperature detecting system.

4. Experimental results

4.1. Material with apparent yielding point

Normalized AISI 1045 mild carbon steel has an obvious yield point during a tensile test. During the test, the temperature changes on the specimen surface at the middle point were measured. The results show that the temperature drops quasi-linearly by increasing the load in elastic region. Fig. 4 shows the temperature variation corresponding to the stress. This may be divided into three stages or regions, labelled I, II and III. Stage I, the thermoelastic region, shows the cooling effect. The temperature decreases linearly with increasing deformation and the temperature drop is proportional to the deformation. The relative lowest temperature lies on the right margin of stage I and has a value of $\Delta T = -0.35$ K, that is the limit of thermoelasticity. Experimental results depicted from the curve as well as the testing data show that the point of temperature reversing coincide precisely with that of upper yielding ($\sigma_{\mathrm{lt}} = \sigma_y = 437.6$ MPa). Following this quasi-reversible temperature decrease, a sudden inversion of the trend on the temperature curve has occurred (stages II and III) and the sample heats up violently due to the plastic deformation.

In stages II and III, the plastic region, a thermal emission phenomenon can be observed. This is obviously due to the frictional effect of thermoplastic behaviour. A great deal of initially sessile dislocations inside sample begin to move on the slip plane which causes frictional heat emission. This causes the temperature to increase rapidly at the beginning of stage II, but slowing down as the yielding comes to the end. This is due to the movement of dislocations which are encumbered and material gradually becomes harder. On stage III, the work hardening region, the temperature begins to rise again by a further increase of deformation. However, heat dissipation from the specimen due to an increasing temperature gradient between specimen and surroundings gradually slows down the heating rate.

4.2. Material without apparent yielding point

With material such as ASTM W1-8 tool steel, there appears to be no apparent yield point in the tensile test. Fig. 5 shows the induced temperature change corresponding to stress during tensile loading. Instead of three divisions as in the former case, there are only

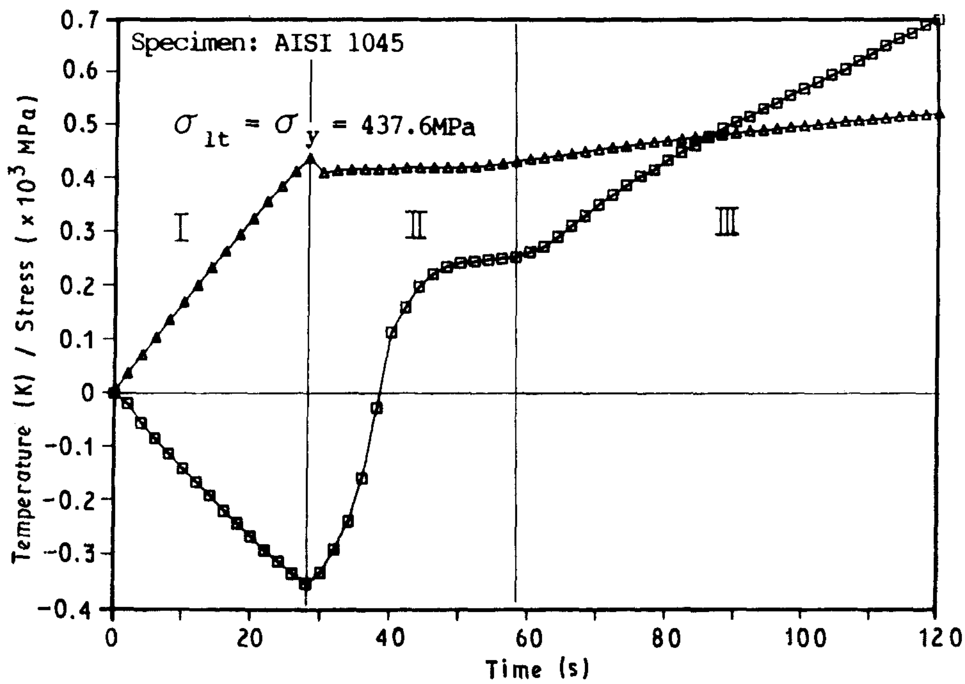

Figure 4 Variation of temperature (□) and stress (△) as a function of time for an AISI 1045 round specimen under uniaxial tensile loading (strain rate = $1.0 \times 10^{-4}\ s^{-1}$).

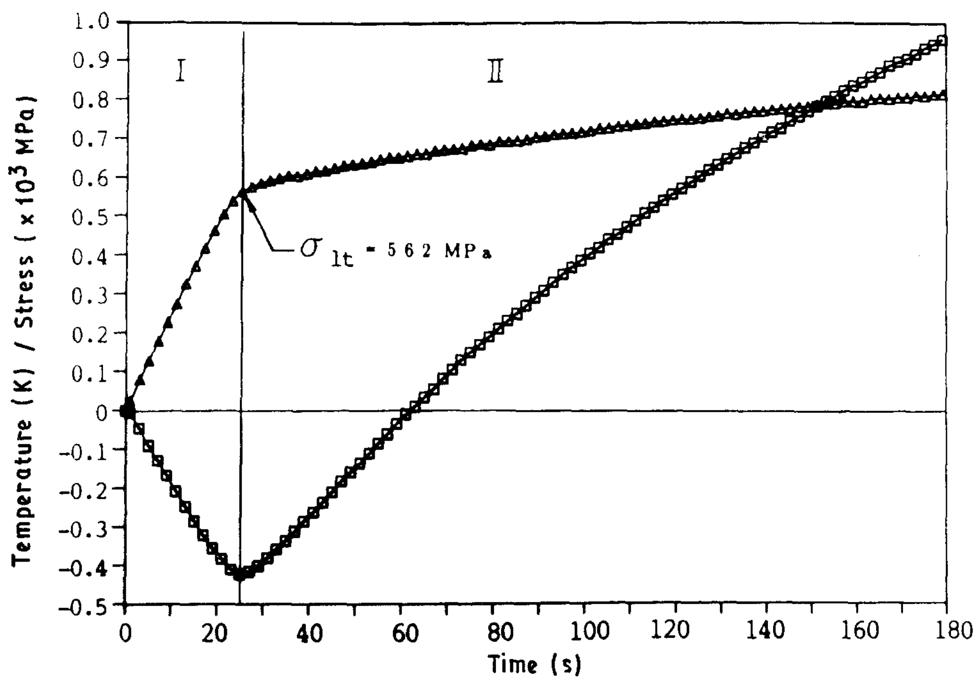

Figure 5 Variation of temperature (□) and stress (△) as a function of time for an ASTM W1-8 plate specimen under uniaxial tensile loading (plate thickness = 2.5 mm and strain rate = $1.3 \times 10^{-4}\ s^{-1}$).

two regions to be distinguished: the thermoelastic region with cooling and the thermoplastic region with heating phenomenon. Lack of yielding causes no extra heating as shown in Fig. 4. Thus, stage II cannot be distinguished from stage III. The lowest temperature reaches a value of $\Delta T = -0.42$ K after loading for 25 s under testing condition. The strain rate used was $1.3 \times 10^{-4}\ s^{-1}$. The stress, σ_{lt}, corresponding to this minimum temperature is 562 MPa (Fig. 5). By use of the 0.2% offset method, a yielding stress, $\sigma_{y0.2}$, with a value of 602 MPa is obtained (Fig. 6). It is different from that of σ_{lt} by 40 MPa (6.6%). By contrast, the permanent deformation corresponding to the lowest temperature stress is only 0.03%, which is far below the engineering value of 0.2%.

4.3. Effect of strain rate

The results of tensile test of AISI 4140 alloy steel at three different strain rates are shown in Fig. 7. The strain rate varied from 5×10^{-5} to $1 \times 10^{-3}\ s^{-1}$. It was found that by decreasing the strain rate not only

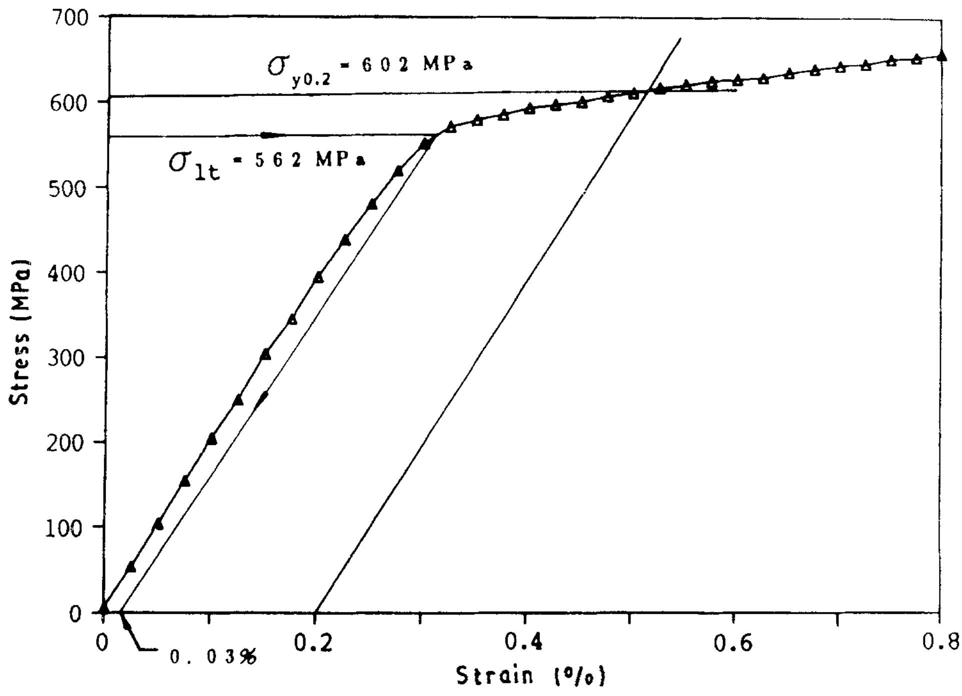

Figure 6 Stress–strain diagram of an ASTM W1-8 plate specimen (as Fig. 5).

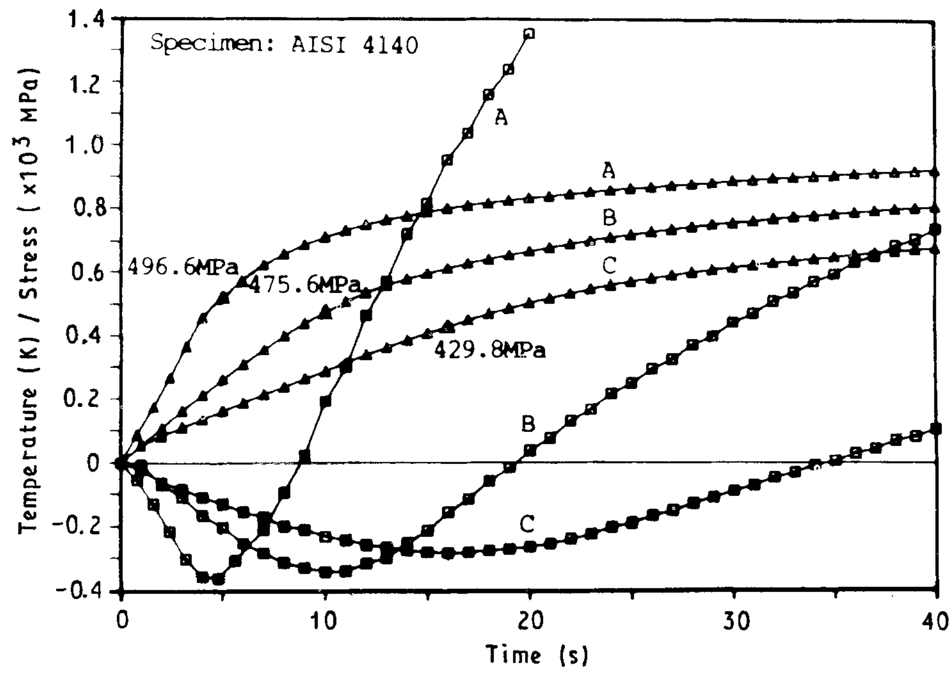

Figure 7 The influence of strain rate on microtemperature variation (AISI 4140): (A) 7.0×10^{-4}, (B) 2.5×10^{-4}, and (C) $1.0 \times 10^{-4}\,s^{-1}$. (△) stress, (□) Temperature.

does the appearance of the lowest temperature seems to delay, but also the amount of maximum temperature drop tends to decrease. This is obviously due to the lower stress level caused by a decrease of strain rate. Besides, the influence of time must also be taken into account. The time interval needed to ascertain the corresponding minimum temperature is longer when the strain rate is low. This causes a much more abundant heat transfer between specimen and surrounding environment. The specimen absorbs heat from its surrounding and in turn decreases the maximum temperature drop. By investigating the discrepancy between σ_{lt} and $\sigma_{y0.2}$ we have found that the difference between them tends to decrease by increasing the strain rate. Fig. 8 shows the results.

5. Discussion

Temperature is a parameter which acts as a response to mechanically induced changes of state. They are mutually coupled. For metallic specimens, although the temperature change due to the thermoelastic effect is relatively small, it is, nevertheless, in evidence even in the elastic regime before the onset of plasticity. The

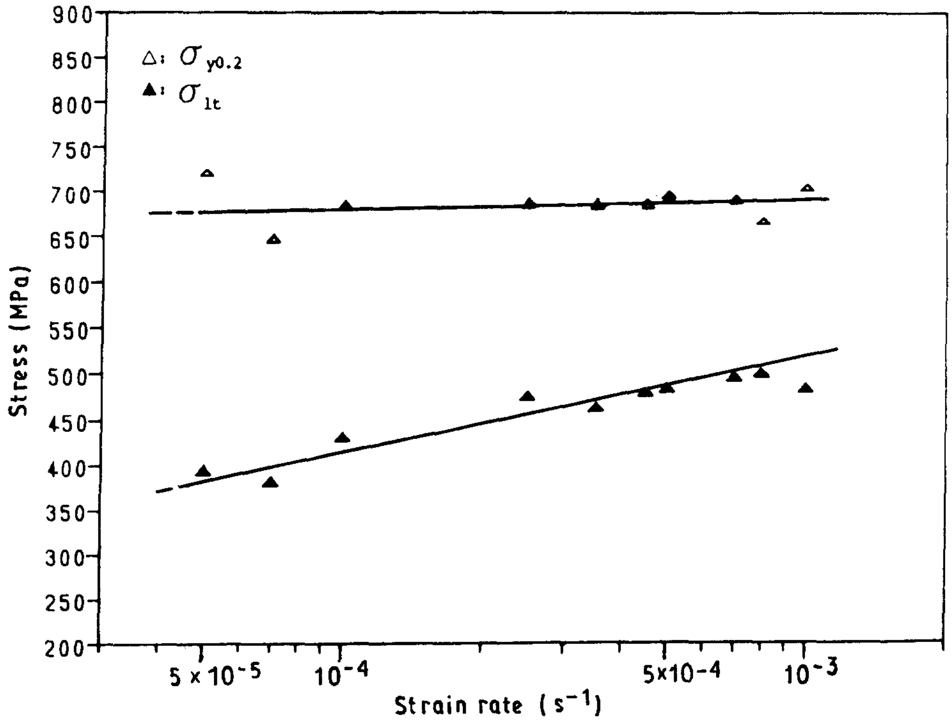

Figure 8 The relationship between σ_{lt} and $\sigma_{y0.2}$ for various strain rates (AISI 4140).

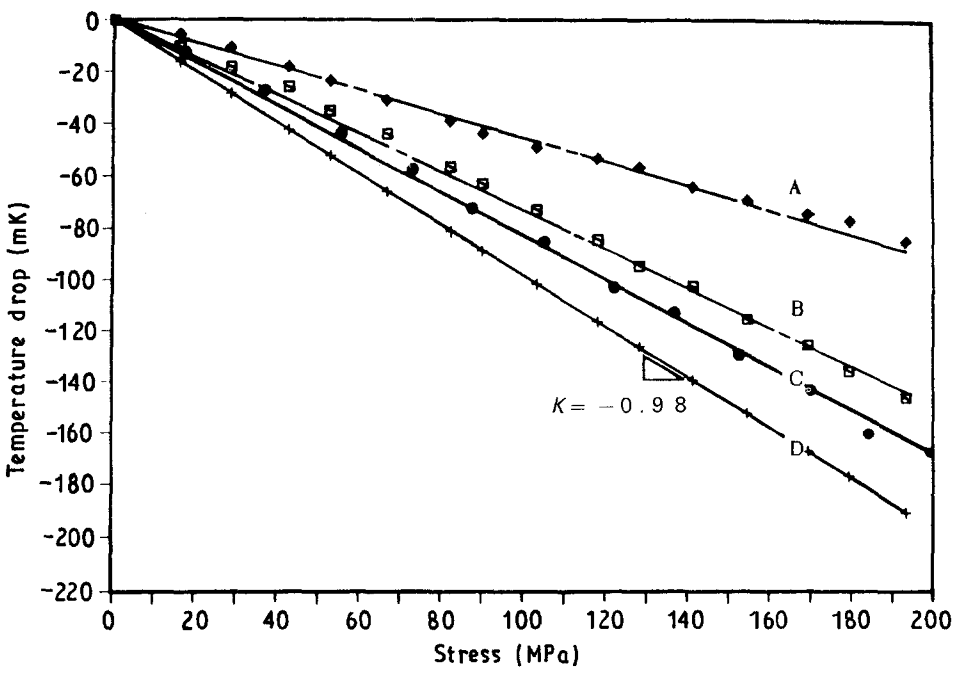

Figure 9 Comparison of theoretical temperature drop and experimental results for different strain rates (AISI 1045): (A) 2.8×10^{-5}, (B) 5.6×10^{-5}, and (C) $1.0 \times 10^{-4}\,\mathrm{s}^{-1}$. (D) Theoretical curve with $K = -0.98\,\mathrm{mK\,MPa}^{-1}$.

cooling phenomenon and the trend of temperature decrease obtained from experiments coincide quite well with that predicted by the theoretical model. Only the amount of relative maximum temperature drop is somewhat smaller (-0.35 K against -0.43 K for σ_y by 437.6 MPa, for AISI 1045 mild steel). This discrepancy comes from the fact that the heat transfer happens between the sample and its surroundings. It is particularly evident by the low deformation rate or quasi-static loading condition: sufficient time being offered for heat to transfer during the process and hence the degree of thermoelastic cooling being thus influenced. Experimental results show that the discrepancy is minimized by increasing of the strain rate. Fig. 9, plotted with theoretical and experimental curves, shows such a trend. Curves A, B and C are performed with strain rates of 2.8×10^{-5}, 5.6×10^{-5} and $1.0 \times 10^{-4}\,\mathrm{s}^{-1}$ individually, and curve D is calculated according to the theoretical model. For normalized AISI 1045 mild steel, the coefficient of thermal power, K, is -0.98 (theoretically). However, it should be also noted that the cooling phenomenon and the argument discussed above may not be valid here if the strain rate is further raised beyond a certain value ($10^{-3}\,s^{-1}$, for example) [9]. For processes with higher strain rates, the viscous heat dissipation effect becomes significant and cannot now be neglected. The heat generated by viscous dissipation is proportional to the square of strain rate. It is independent of the loading direction and heats the sample steadily. Thus, the cooling phenomenon caused by the thermoelastic effect may be compensated by heating caused by viscous dissipation and so a steady temperature increase from the beginning of loading can be observed if a higher strain rate is employed [9].

The temperature rise in the thermoplastic region is the result of more and more movement of dislocations within the specimen which, in turn, generate a large amount of heat transfer. Quantitatively it is beyond the cooling effect. The result shown in the temperature measurement is a dramatic inversion from cooling to heating when the applied stress increases to change the state of material from elastic to plastic. At the point of lowest temperature, the abrupt change of the trend on the temperature curve acts as a response to the sudden moving of initially sessile dislocations inside sample which causes frictional heat to be emitted. The stress corresponding to this thermoelastic limit, or lowest temperature, σ_{lt}, coincides with the stress of physically defined yielding, where the irreversible dynamic instability occurs and the true macroscopical material flow happens. For materials with an apparent yielding point, there is no obvious discrepancy between σ_{lt} and the upper yielding stress. However, materials without an apparent yielding demonstrate a difference between σ_{lt} and $\sigma_{y0.2}$: σ_{lt} is slightly smaller than $\sigma_{y0.2}$. Clearly, it is beyond dispute that some empirical safety factors have been taken into consideration in defining $\sigma_{y0.2}$ for structural design which makes $\sigma_{y0.2}$ conservative. In comparison with the usual 0.2% offset method and relying on the test results we prefer to adopt σ_{lt} as yield strength because of its unambiguous and precise definition. We shall call it "the lowest temperature method".

Besides, it is theoretically clear that the yielding stress of the material increases as the strain rate increases. At a low strain rate, a relative large rate of change is required to effect noticeable changes in the yielding. From the experimental test results with a strain rate variation in range of 5×10^{-5} to $1\times10^{-3}\,s^{-1}$, there is no appreciable change in $\sigma_{y0.2}$. However, a recognizable increase of σ_{lt} with the increasing strain rate is ascertained. Compared to the 0.2% proof stress, $\sigma_{y0.2}$, σ_{lt} is a much more state-sensitive term. It is even capable of reflecting the microscopical state change. On the contrary, the commonly used $\sigma_{y0.2}$ obtained via stress–strain characteristic using the 0.2% offset method is relatively insensitive to rate-change by such a low strain rate level. Fig. 8 shows the difference.

In comparison with Fig. 5, the yielding behaviour of the specimen, as shown in Fig. 4, causes extra heating effect. This effect is significant and can be proven when we neglect the curved part in region II and instead use the extrapolation method to extend the curve of region III smoothly backward. One can easily draw back to the point of the lowest temperature without any mismatch. Now, we have the same type of curve as indicated in Fig. 5. The physical meaning of this extra thermal energy formed can be understood from the microstructural behaviour of metallic material under deformation. Plastic flow starts when dislocations begin to slip on the slip planes. By yielding, no further increase of external force is required, however, deformation continues. Dislocations change from immobile to mobile by stressing over yielding and then the frictional resistance is dramatically lowered. An extra large amount of thermal frictional energy will thus be generated. This situation remains until all the mobile dislocations are seized and stopped by obstacles.

6. Conclusion

From the experimental results and above discussions on the thermomechanical effect, the following points may now be stated:

1. By uniaxial tensile testing, there exists heat transfer on materials as the specimen is loaded from elastic to plastic. Cooling occurs in the elastic region and heating occurs in the plastic region. Experimental results for AISI 1045 mild carbon steel reveal a maximum temperature drop of 0.35 K, where ASTM W1-8 has a value of 0.42 K.
2. Tensile stress causes the temperature to decrease quasi-linearly with increasing deformation in the thermoelastic region. The point of temperature inversing, from thermoelastic to plastic, coincides with that of upper yielding by materials with apparent yielding. Physically it is the point at which the stress–strain curve departs from linearity.
3. Thermal emission by internal friction due to movement of dislocations causes the temperature to rise in the thermoplastic region. For materials with apparent yielding there is an extra thermal emission recognizable. This is due to the motion of mobile dislocations on slip planes.
4. Variation of strain rate has an influence on the thermomechanical effect. By decreasing the strain rate, not only will the appearance of the lowest temperature be delayed, but also the amount of maximum temperature drop obtained will decrease.
5. σ_{lt} is smaller than the engineering yield strength $\sigma_{y0.2}$ for materials without apparent yield. Empirical results support the standpoint of adopting σ_{lt} as yield strength due to its unambiguous and precise definition compared with that by 0.2% offset method.

Reference

1. A. SWALIN, "Thermodynamics of Solids" (John Wiley & Sons, New York, 1961) Ch. 2.
2. C. E. BOTTANI and G. CAGLIOTI, *J. Metall. Sci. Technol.* **2** (1984) 3–7.

3. *Idem, Mater. Lett.* **1** (1982) 119–21.
4. G. C. SIH and D. Y. TZOU, in Report of Institution of Fracture and Solid Mechanics, Lehigh University, October (1985).
5. H. T. LEE and J. C. CHEN, in Proceedings of the Annual Conference on Chinese Material Science, May (1988) pp. 328–31.
6. S. MATSUOKA and H. E. BAIR, *J. Appl. Phys.* **48** (1977) 4058–62.
7. P. HEINZ, "Thermoelasticity" (Waltham Blaisdell, 1968).
8. J. C. CHEN, M. S. Thesis, Cheng-Kung University, June (1988).
9. H. T. LEE and C. H. CHUE, "Studies of thermomechanical effect of materials", in Research Report of the Chinese National Science Council (NSC79-0405-E006-16), October (1990).

Received 8 August 1989
and accepted 31 January 1991