JOURNAL OF MATERIALS SCIENCE 28 (1993) 5500–5507

Thermomechanical behaviour of metals in cyclic loading

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Temperature variation induced by repeated mechanical cyclic loading on AISI 1045 mild steel was studied. The experimental results of cyclic loading at low stress levels elucidate the coupling phenomena of thermal/mechanical behaviour which causes cooling and/or heating corresponding to the stressed state. The governing factors are thermoelastic effect and viscous dissipation. The thermoelastic effect causes the specimen temperature to go down and/or up which corresponds to the loading and/or unloading in cycling, where the viscous dissipation effect causes heat to generate inside the sample which steadily heats the specimen. As a result, a trend of increasing specimen mean temperature with periodical local fluctuation on temperature history can be observed. The heating rate, due to viscous dissipation, is increased with increasing strain rate. Cyclic loading at high stress levels results in large amounts of heat generation where thermoplasticity predominates. An abrupt temperature rise in the first few cycles, followed by a slow-down in later cycling, is to be seen. The phenomena and results were discussed. In addition, the effect of heat transfer between the specimen and its surroundings should be considered for both cases if the time is sufficiently long or the temperature gradient evolved is of significance.

1. Introduction

When a metallic sample is stressed under mechanical cyclic loading, energy transfer may occur as heat accompanying the deformation [1–3]. Thermomechanical behaviour concerning the coupling of thermal and mechanical effects is evolved. On deformation at low stress levels, the elastic strain is dominant. A basic assumption that a reversible process between external work and elastic strain energy is often accepted and referred to. Thus, the heat generated during the process is neglected. The work done by external work is assumed to be totally stored as elastic strain energy in the specimen, which completely releases it by unloading, thereby returning the deformed specimen to its original length [4]. The related problems are thus simplified and can be easily solved theoretically from the basis of stress and strain analysis. Therefore, the mutual coupling of thermal and mechanical effects are traditionally neglected in thermal stress analysis and solid mechanics. The temperature field and deformation resulted by changes of mechanical loading and thermal state are usually solved separately. However, these conceptual assumptions of neglecting the heat generated in the deformation process encounter difficulty in interpreting failure [5, 6]. There are sufficient examples implying that it could become significant, particularly under high stress-loading conditions or as the material is loaded beyond its elastic limit. A large amount of mechanical energy obtained from external work is considered to be transformed into heat [7–9]. Therefore, any observable temperature rise in the specimen is equivalent to a large amount of mechanical energy. Problem solving without consideration of such coupling effects is inadequate. Relevant examples include stability analysis of metal forming, catastrophic shearing during machining, metal fatigue by high- or low-cycle loading, fault analysis of nuclear reactors, damping of stress-wave propagation, deformation localization after bifurcation, strength softening or hardening behaviour of materials, and many other factors of fracture analysis [9, 10].

In the coupling of thermal and mechanical effects, known as thermomechanical behaviour of materials, it is known that any mechanical disturbance of a solid sample will cause the temperature to change even though it is elastically stressed. Therefore, a thermodynamically irreversible process is developed. Furthermore, deformation under mechanical cyclic loading is always performed at a finite loading rate or, in most cases, even with a high strain rate. Rapid fatigue loading, for example, is often encountered in dynamic mechanical parts. The viscous dissipative heat generated due to the internal friction becomes noticeable.

In this paper we present the phenomena and summarized experimental data of temperature variation on a stressed metallic sample during repeated cyclic loading. Numerous experiments were performed. The temperature history was measured and traced as a physical parameter in addition to stress and strain. It is not intended here to give a thorough theoretical

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derivation and interpretation. However, a theoretical model based on thermoelasticity and thermodynamics is suggested and discussed, in order to give a more comprehensive elucidation of the relationship between the coupled mechanical cyclic loading or fatigue behaviour and temperature variation. The demonstration and the discussion of the phenomena and the data results may help us better to understand materials under deformation to fracture.

2. Theory

The thermoelastic energy equation derived from thermodynamics and elasticity is based on the assumptions that the deforming process is elastically reversible and continuous. It is achieved when the deformation rate is infinitesimal. However, mechanical deformation, such as that by repeated cyclic loading, is always with a finite strain rate so that kinetics of defects cause the generation of dissipative heat.

To simplify the problem, the energy equation for mechanical cyclic loading by uniaxial tensile and/or compressive testing can be obtained from the generalized energy equation [7]. It is a direct derivation from the Heinz's [11] energy equation with consideration of the strain-rate effect. Therefore, a modified equation is derived with the addition of dissipative friction energy and heat-transfer effect between the specimen and its surroundings for the uniaxial tensile/compressive deformation process, which has the form

$$\rho C_v \dot{\Theta} = - E\alpha T \dot{\varepsilon}_{zz} + \eta \dot{\varepsilon}_{zz}^2 + \dot{q}_{i,i} \qquad (1)$$

where ρ is the mass density of the undeformed body, C_v specific heat at constant volume per unit volume, $\dot{\Theta}$ the rate of temperature variation or thermal power, $\dot{\Theta} \equiv \partial T/\partial t$, E Young's modulus, α the thermal expansion coefficient, $\dot{\varepsilon}_{zz}$ the uniaxial strain rate, T the current absolute temperature of the deformed body, η the viscosity coefficient, and $\dot{q}_{i,i}$ the heat transfer rate tensor per unit volume within the body, positive inwards. The first term on the right-hand side of Equation 1 represents the thermoelastic effect and the negative sign implies cooling. Because the thermal expansion coefficient, α, is always positive for most metallic specimens, the cooling phenomenon will occur by tension, and the heating phenomenon will occur by compression. In the case of cyclic loading in the elastic range, cooling occurs on loading and heating occurs on unloading. The second term represents the viscous dissipative heating effect due to kinetics of defects. The viscosity coefficient is temperature dependent. The dissipative term is negligible as the employed strain rate is still low or under a static loading condition. However, it becomes significant as a high loading strain rate is employed. The cases of fatigue failure are typical. The last term represents heat transfer between the specimen and the environment, and depends largely on the temperature gradient and the duration of the deformation process. Of particular significance is the deformation at high stress levels where an enlarged temperature gradient is easily formed, or by deformation with a sufficiently prolonged time where thermal balance would be met.

The term $\dot{\Theta}$, defined as thermal power, depends on the preceding terms. In high cyclic fatigue of metallic samples, the first term causes the temperature to fluctuate corresponding to the loading/unloading cycle. Tension causes cooling to occur, while compression, causes heating to occur. There is a linear relationship between temperature variation, and stress and/or strain. The second term of dissipative heat is always positive, regardless of the direction of loading. It heats the specimen steadily from the beginning of the test. The result is a steady increase of specimen mean temperature. The final term of heat flux has a retardation effect as long as any temperature gradient exists between the specimen and its surroundings. It always reacts in a negative direction.

3. Experimental procedure

The material used in this experiment was AISI 1045 mild steel in round-bar form. The specimens were normalized and then fabricated to have sizes and dimensions shown in Fig. 1. The tests were performed in a MTS 810 hydraulic pulsator with a maximum capacity of 25 tons. Fig. 2 shows the test arrangement [12, 13]. Temperature measurement with conventional instruments such as thermometers and thermocouples failed due to the small amount of temperature variation. A temperature measuring system was developed which consists of high sensitive semiconductor thermistors as temperature detector, and a digital multimeter. It is then connected to a computer

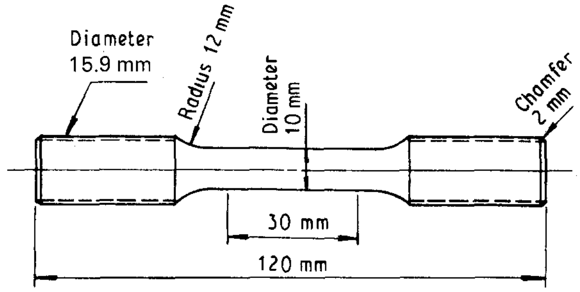

Figure 1 The detailed dimensions of the experimental specimen.

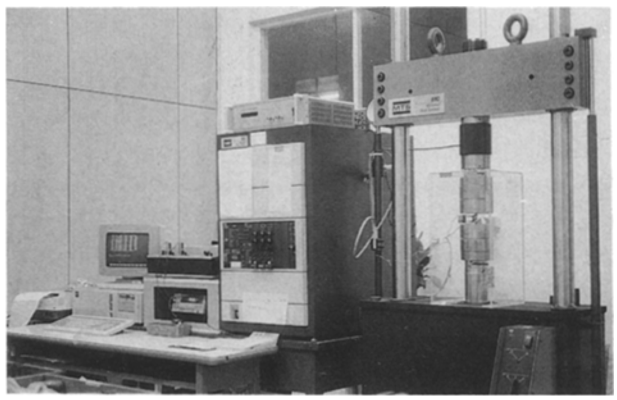

Figure 2 Configuration of the testing system employed for the experiments. The testing specimen is enclosed in a protective box during the tests.

(PC/AT) via an IEEE–488 interface. The detector head has an area of 2.0×2.3 mm^2. Through this design, a high "temperature resolution" of about 2.6 mK is obtained. Fig. 3 shows the stability of temperature recording in a plot of temperature versus time in the first 60 s after set-up, but before the start of the experiment. This successfully permitted the measurement of micro-temperature variations. Data acquisition and the processing of testing parameters such as load, displacement, strain and temperature variation were automatically performed in the computer. The sampling rate is adjustable between 0.01 and 100 Hz according to the employed strain rate. However, compromise should be made between the high sampling rate and the high-temperature resolution. The temperature resolution is sacrificed from 2.6–12 mK as the sampling rate is promoted to 100 Hz. In addition, for the purpose of tracing the history of the specimen mean temperature in high cyclic fatigue, the temperature-measuring program was modified in such a manner that only the average value of the acquired data in every 10 s was taken and stored in the memory. All other data were discounted. The overflow of data that typically occupies large amounts of memory space in the computer can then be avoided. The nominal strength of normalized AISI 1045 mild steel measured at room temperature is as follows: yielding stress $\sigma_y = 424.5$ MPa and tensile strength $\sigma_u = 643.5$ MPa.

4. Results

4.1. Thermoelastic effect in cyclic loading

The thermoelastic effect is particularly significant as the low loading rate is employed. The test is performed first under the following testing conditions: stress ratio $R = -1$; stress amplitude $S_a = 280$ MPa $\cong 0.7\sigma_y$ (load vibrations between 22 and -22 kN, i.e. amplitude = 22 kN); triangular waveform by load control; and loading rate = 0.88 kN s^{-1} (or cyclic frequency $f = 0.01$ Hz). The relationship between temperature variation and stress in the first two cycles is shown in Fig. 4. Significant temperature fluctuation can be seen in the figure. Because the specimen is exclusively elastically loaded, the thermoelastic effect predominates. Elastic tensile loading causes cooling, and compression causes heating to occur in the specimen. A linear relationship exists between the applied stress and the induced temperature variation. The peaks of the temperature history (lowest and highest temperatures) correspond to the maximum or minimum loading stress. According to the theoretical model, thermoelastic effect-induced temperature change in an elastically stressed body is linearly proportionally correlated to stress or strain when the influence of heat transfer between the specimen and the surrounding environment is not taken into account [7, 14]. Thus, an ideal temperature curve corresponding to load variations can be predicted and is shown by the dotted line in Fig. 4. The calculated temperature history, according to the theoretical prediction, should vary between $\pm$ 0.252 K. However, considering the internal defects of the material and the heat convection effect between the specimen and the environment, the change in the specimen temperature does not linearly proportionally correspond faithfully to the load variation. Empirical study results reveal that the temperature drops linearly to its relatively lowest value of -0.19 K as the specimen is loaded from zero to its first peak of maximum stress (280 MPa). A discrepancy of -0.06 K exists. The following process of unloading, however, results in the heating effect. A drastic sudden inversion of the trend on the temperature curve has occurred. The specimen begins to heat up. In addition, the specimen temperature at this moment is lower than the surrounding environment's temperature. The heat convection effect causes the specimen to absorb heat from the environment and therefore enhance the heating rate. The actual curve deviated from the ideal one in a positive direction. The relative zero value of temperature is attained earlier than the point of zero loading. The specimen maintains a tensile stress of 112 MPa as the temperature reaches zero. As unloading proceeds the specimen temperature rises further. However, a heat flux from the specimen to the environment becomes gradually evident as the specimen temperature is higher than the environment temperature. This causes the temperature curve to incline gradually to the ideal curve. At

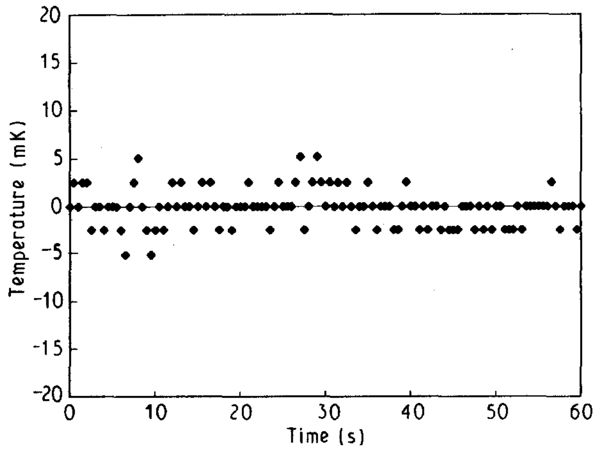

Figure 3 The stability of temperature recordings in a plot of temperature versus time in the first 60 s after set-up.

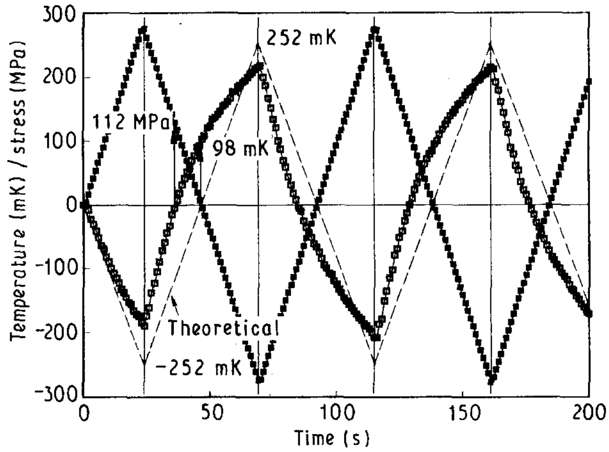

Figure 4 The relationship between (□) temperature variation and (■) stress in the first two cycles of a low-stress cyclic-loading test (loading rate = 0.88 kN s^{-1}; 0.01 Hz).

the point of zero loading, the relative specimen temperature has increased to a value of + 0.098 K. After that, the compressive loading in the later half of the cycle continues the heating. A maximum temperature of + 0.22 K is obtained as the maximum compressive stress of − 280 MPa is reached. Cyclic loading causes a cyclic temperature variation. Fig. 5 provides the measured temperature history in the first 11 cycles. A steadily stable increase in the specimen mean temperature is to be seen.

4.2. Loading-rate effect

Loading rate has significant influence on temperature variation. Fig. 6 shows the experimental results of a test under the same testing conditions as previously, but instead of 0.88 kN s^{-1} (0.01 Hz), a loading rate of 88 kN s^{-1} (1.0 Hz) was employed. A data sampling rate of 20 points per second (20 Hz) was chosen. The result shows that the temperature fluctuation lies between about ± 0.12 K accompanied by a steady increase in the trend of specimen mean temperature. The irreversible strain energy is due to the external work converted into heat, which accumulated in the specimen. It is obvious that there is insufficient time for the heat transfer to relax the temperature gradient between the specimen and the environment by a higher loading rate. Excess heat accumulated in the specimen causes the mean temperature to rise quicker. Furthermore, a time lag between temperature response and stress existed in the test. The occurrence of a local peak value on the temperature curve lag behind the corresponding maximum and/or minimum stress points. This is shown clearly in Fig. 7, where the temperature history and the applied stress are plotted together.

The magnitude of temperature amplitude, instead of increasing, decreases from ~0.20 to 0.12 K as the loading rate increases from 0.88 to 88 kN s^{-1}. Confusion may occur here concerning the argument that the degree of thermoelastic cooling/heating is proportional to the loading rate [15]. There is no contradiction, because it should be noted that the phenomenon of increased temperature fluctuation with an increasing loading rate is only valid when the loading rate or cyclic frequency is still low or, in other words, by a static or quasi-static deformation process. The dissipative heat caused by kinetics of defects should be taken into account when a deformation exists with a higher strain rate ($\gtrsim 10^{-3}$ s^{-1}) or dynamic loading conditions [7, 16]. This can clearly be shown from the following experiments of uniaxial tensile tests with a different strain rate in which the maximum temperature drop was measured as an indication of the degree of influence of the thermoelastic effect. Fig. 8 is a plot of the maximum temperature drop versus the strain rate. A parabolic relationship is attained. At a lower strain rate ($\lesssim 10^{-3}$ s^{-1}), known as a quasi-static or a static loading condition, the viscous effect is small and can be neglected. The thermoelastic effect prevails. A sufficient duration in the loading and/or unloading process provides the possibility for thermal balance to occur between the specimen and the surroundings. The specimen absorbs heat from the surroundings which leads to the reduction of the maximum temperature drop. Therefore, the maximum temperature drop tends to increase with increasing strain rate. However, with a higher strain rate or a quasi-dynamic loading condition, the viscous dissipative

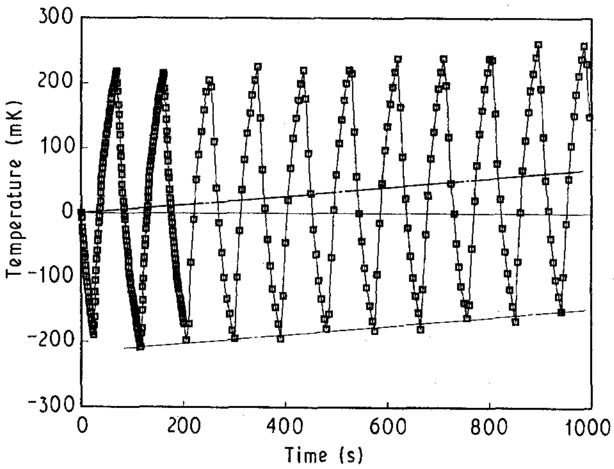

Figure 5 The relationship between temperature variation and stress in the first 11 cycles of a low stress cyclic loading test (the same test as in Fig. 4).

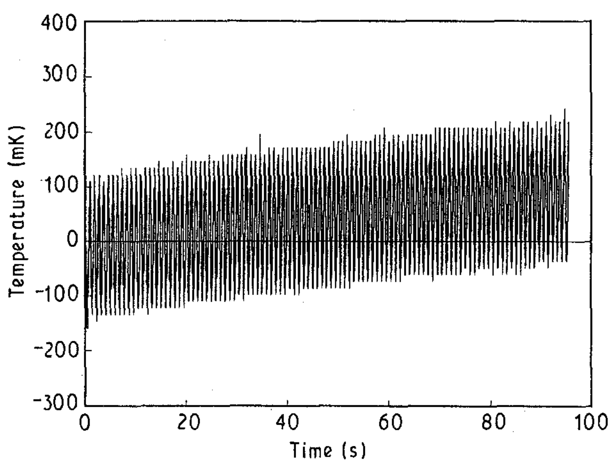

Figure 6 The temperature fluctuation of a low-stress cyclic-loading test with a loading rate of 88 kN s^{-1} (1.0 Hz).

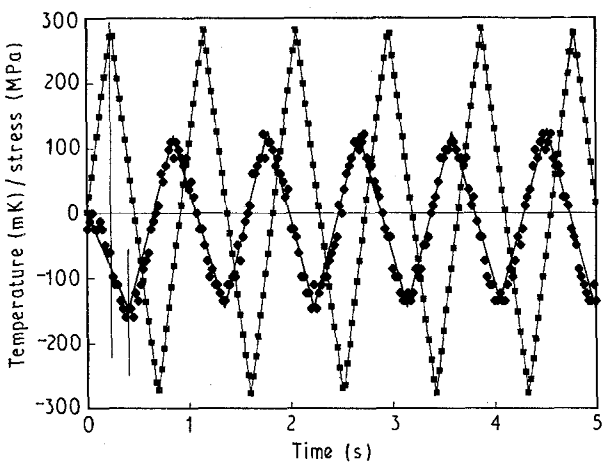

Figure 7 The relationship between (◆) temperature variation and (■) stress in the first 5 cycles of the test, which is the same as in Fig. 6.

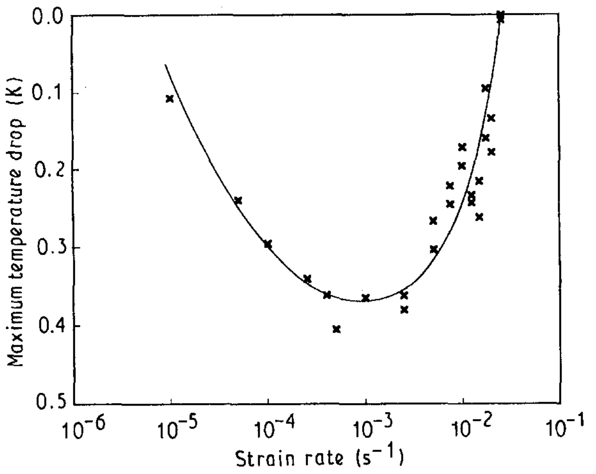

Figure 8 The maximum temperature drop obtained at a different strain rate. A parabolic relationship is attained between the temperature drop and the strain rate.

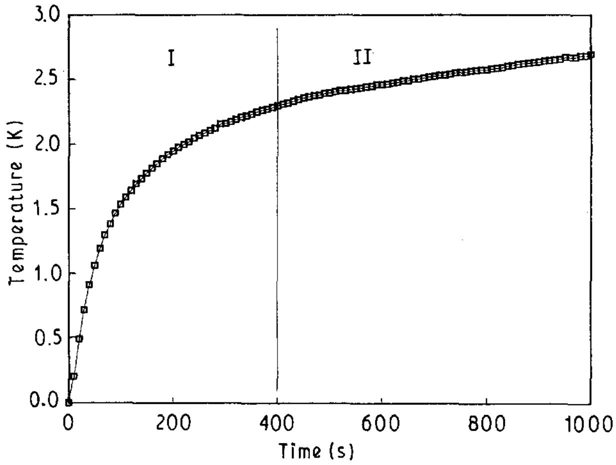

Figure 9 A plot of specimen mean temperature versus time derived from a test with a loading rate of 880 kN s^{-1} (10 Hz).

effect becomes apparent and increases with increasing strain rate. It causes heating to occur and gradually compensates the temperature drop. Furthermore, a higher strain rate also reduces the influence of heat convection from the surroundings. Less heat is transferred due to the short time. Nevertheless, it leads to a further reduction in the degree of cooling. Therefore, there exists a relative lowest point on the curve of the maximum obtainable temperature drop when they are plotted via the increase of strain rate. It has a value of about -0.35 K which is achieved by performing the test with strain rate at $\sim 10^{-3}\,s^{-1}$. Deformation with a higher strain rate would cause the maximum temperature drop to decrease gradually instead of further increasing. Empirical results show that no cooling phenomenon can be observed in a tensile test as the strain rate is raised to over $3.0 \times 10^{-2}\ s^{-1}$. Thermoelastic cooling becomes small in magnitude when compared with viscous dissipative friction heat. Fig. 9 is a plot of specimen mean temperature versus time derived from a test with a loading rate of 880 kN s^{-1} (10 Hz). A prompt temperature rise at the beginning of the test is to be seen. In 200 s, the specimen temperature had already risen almost 2.0 K. The heating rate then tends to slow down gradually due to the heat loss to the environment, and eventually the specimen temperature no longer rises because the heat generated per cycle is balanced by the heat lost to the surroundings. Fig. 10 illustrates the effect of the loading rate or cyclic frequency on the specimen mean temperature. A test with a higher frequency (loading rate) results in abundant energy accumulating in the specimen, which causes a greater heating rate and the specimen temperature is raised much quicker and higher. Specimen A has a much quicker temperature rise than the others due to the higher frequency being employed, while Specimen F has the lowest temperature rise. This has been proven and is shown in Fig. 10.

4.3. High stress-level cycling

Repeated cyclic loading at high stress levels, such as the case of low-cycle fatigue (LCF), is characterized by the formation of plastic deformation. The plastic strain is significantly predominant. The stress exerted is generally above the yielding point, and the sample probably can sustain only a limited duration or cycling before fracturing. Fig. 11 demonstrates the temperature history tested with loading conditions as follows: $R = 0$, amplitude $= 20$ kN, loading rate $= 80$ kN s^{-1} (1.0 Hz), and load controlled. Clearly, much heat will be generated due to the plastic deformation. Therefore, there is a trend of a drastic increase in the specimen mean temperature at the beginning of the test. The results in Fig. 11 show that at the beginning of the test the mean temperature increased rapidly to a maximum of ~ 1.5 K in only 4 s, and was then followed by a gradual inversion of the trend from increasing to decreasing, due to the heat loss to the surroundings. Meanwhile, the local temperature fluctuation corresponding to the loading/unloading in each cycle is clearly seen. Heat generated by plastic deformation, which heats the sample in the first few cycles, is evidently significant. But, as the torn-out dislocation is hindered by obstacles, the specimen thus

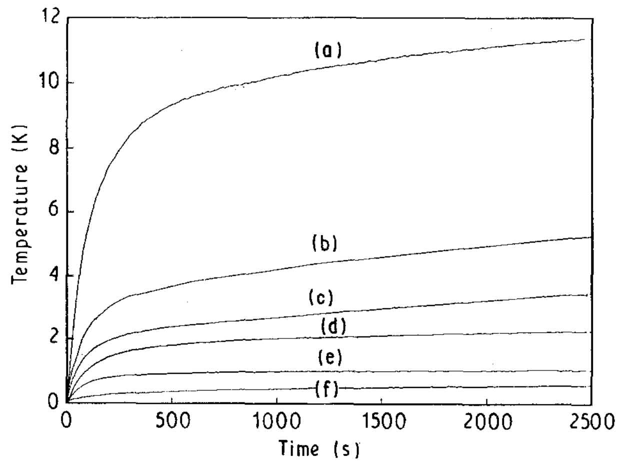

Figure 10 The effect of the loading rate on the specimen mean temperature (testing conditions: $R = -1$, amplitude $= 22$ kN, triangular waveform, and load controlled by different loading rates: (a) 1760, (b) 1320, (c) 880, (d) 440, (e) 330 (f) 220 kN s^{-1}.

becomes harder. The point of maximum loading stress, therefore, falls into the quickly extended quasi-linear elastic regime. It thus diminishes the heating rate and only remains in thermal fluctuation of heating/cooling due to the thermoelastic effect. This can be seen in the temperature history curve. A detailed temperature history, illustrated in Fig. 12, reveals the phenomenon of small, local fluctuations of cooling/-heating corresponding to each cycle.

By changing the loading rate from 80 kN s^{-1} (1.0 Hz) to 400 kN s^{-1} (5.0 Hz), the temperature history thus obtained (Fig. 13) reveals a steadily stable increase as indicated by Curve (a) in Fig. 13. The comparative temperature history of Curve (b), however, shows a diminished trend after a few cycles. With a higher loading rate and/or cyclic frequency, abundant friction heat is produced, and its magnitude is theoretically proportional to the square of the strain rate, $\dot{\varepsilon}^2$, during the loading/unloading process. It thus strongly overwhelms the effect of the temperature decrease due to the heat loss to the surroundings, and results in a steady temperature increase throughout the test. The strain-rate effect prevails.

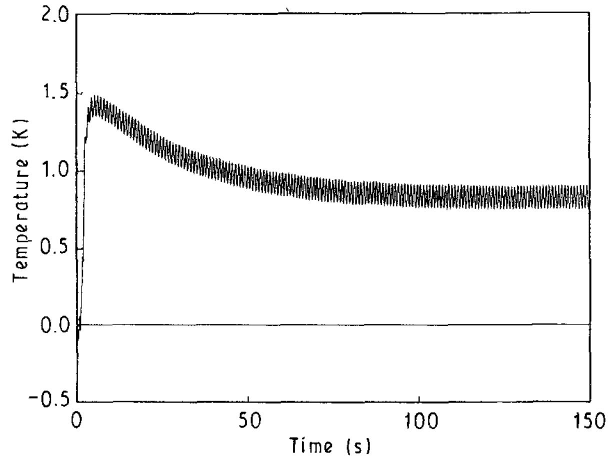

Figure 11 The temperature change by a low-cycle fatigue test with a loading condition of $R = 0$, amplitude = 20 kN, and load controlled by a rate of 80 kN s^{-1} (1.0 Hz).

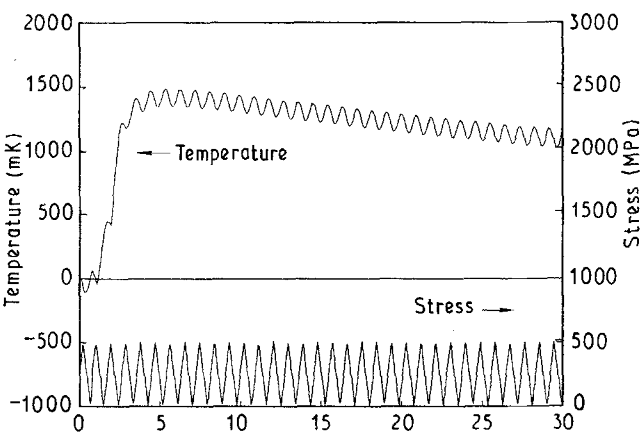

Figure 12 Detailed temperature history of a few cycles of Fig. 11 revealing the phenomenon of small, local fluctuations of cooling/heating corresponding to each cycle.

4.4. Overload effect

The overload effect is well known in fracture mechanics. It states that an inserted overload in cyclic fatigue has the effect of crack retardation, which in turn prolongs the fatigue life. The influence of overload on temperature variation was studied in the following experiments. The test was performed with stress ratio, $R = 0$, triangle waveform, and amplitude = 5 kN. The overload was applied during the time interval from 1000–1160 s with amplitude = 20 kN. The results of the temperature change and the employed stress versus time were plotted together in Fig. 14. The temperature curve in Section A–B acts as a response to the first overload cycle in time intervals between 1001 and 1041 s. The value of the characteristic points on the temperature history, together with the corresponding time and load, were particularly abstracted from the record and are listed in Table I. Tensile loading in the time period from 1001–1021 s causes cooling initially, but subsequently, it turns to heat abruptly as the tensile load is increased over the elastic limit. A prompt temperature rise is seen which lasts for a while even when the unloading has begun. The second overload cycle, however, results in only linear cooling and heating as a response to tensile

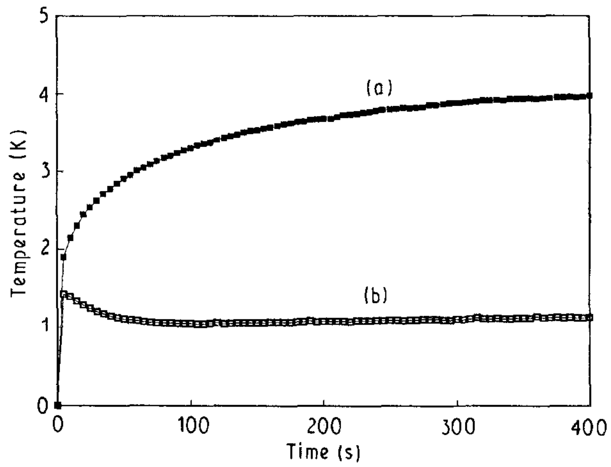

Figure 13 The temperature history obtained in a low-cycle fatigue test with loading rate of (a) 400 kN s^{-1} (5.0 Hz), (b) 80 KN s^{-1} (1.0 Hz) and $R = 0$, amplitude = 20 kN.

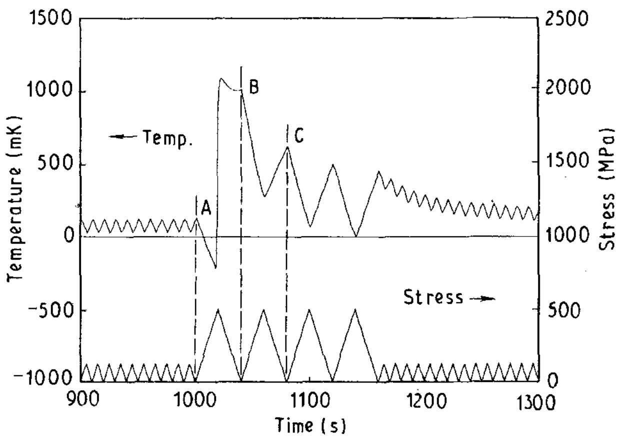

Figure 14 The results of temperature change corresponding to the employed waveform of stress in an overload test. Load conditions: amplitude = 5, 20, 5 kN; rate = 0.1, 0.025, 0.1 Hz (2.0 kN s^{-1}).

TABLE I The value of characteristic points of the temperature history in Section A–B of Fig. 14 abstracted from the record

Time (s)	Load (MPa)	Temp. (mK)	Remarks
1001	1.5 (min)	125	Point A
1018	431	– 220 (min)	Local lowest temperature
1021	505 (max)	982	Stress peak
1025	402	1071 (max)	Local maximum temperature
1041	0.78 (min)	1008	Point B

loading and unloading. The temperature history after the overload shows a gradual decrease in the trend, which is due to the heat loss to the surroundings.

5. Discussion

Temperature, in addition to stress and strain, behaves as a physical parameter which may describe the material behaviour under deformation and highlight the way to a better understanding of material failure. In repeated cyclic loading or fatigue conditions, two different types of loading situations should be distinguished: deformation at low stress levels, such as the case of high-cycle fatigue where elastic strain is developed, and deformation at high stress levels, such as the case of low-cycle fatigue where plastic strain is prevalent. The thermoelastic and viscous dissipative effects are the main concerns of deformation at low stress levels. The degree of cooling/heating due to thermoelastic effect is linearly proportional to the stress and/or strain by a constant coefficient of thermal power, K, which is defined as $K = -\alpha T_0/\rho C_v$ [14, 15] and T_0 is the reference temperature at the beginning of the test. Such an effect causes the temperature to drop/rise, corresponding to the tension/compression. Therefore, theoretically it results in a temperature fluctuation of periodic heating and cooling if repeated cyclic loading is applied. However, the heat-transfer effect becomes evident if the test is performed with a low strain rate. The temperature history thus obtained deviates from that predicted by the thermoelastic effect. For AISI 1045 mild steel, such an effect becomes significant as the strain rate is lower than, conservatively speaking, $\sim 10^{-2}\ s^{-1}$. The heat-transfer effect by such a slow deformation process is greatly affected as the strain rate is further lowered. In other words, it is depressed as a higher strain rate is employed, which causes the maximum attainable temperature drop to increase with increasing strain rate. However, as the strain rate is raised to over $\sim 10^{-3}\ s^{-1}$, the viscous dissipative heat, in turn, becomes of significance. Although the viscous dissipation effect is negligible by a lower strain rate or quasi-static loading condition, it plays an important role in the thermomechanical behaviour of fast cyclic loading. The heat generated, according to the model described in Equation 1, is proportional to the square of the strain rate. That means it is only evident at a higher strain rate. Regardless of the loading direction, it heats the sample steadily, which causes the specimen mean temperature to rise per cycle. The temperature history of the cyclically loaded specimen is constructed by these three competitive effects for a wide range of strain rates.

A closer observation of the mean temperature would reveal that it did not show a direct increase from the beginning of the test. A steady increase of the mean temperature seems to begin from the second cycle. A small drop in the mean temperature always seems to occur in the first cycle. Ample test results revealed the same phenomenon. The exact physical meaning of such a phenomenon is still not well understood. However, a possible presumption based on the atomic structure of the specimen suggests that the specimen, without loading, can be regarded as having a globally ordered but somewhat locally disordered state of atomic arrangement, with their atoms in microscale more or less deviating from their proper positions. With uniaxial tensile loading, an extra uniform constraint, in addition to metallic bonding, will be exerted on the atomic structure. This forces the system to change from a comparatively disordered state (unloaded) to a more ordered state (loaded). Thermodynamically, the system must be cooled down, which leads to the small temperature drop observed in the first cycle.

Deformation at high stress levels results in the development of thermoplasticity. Dislocations begin to move in the slip line within the material as the specimen is loaded beyond the elastic limit. Frictional heat will be generated as a response to the movement of dislocations and/or defects. Quantitatively, it is beyond the cooling/heating due to the thermoelastic effect. Therefore, a drastic temperature rise acts as a response to the sudden movement of initially sessile dislocations inside the sample. This causes a sudden inversion in the temperature history trends from cooling to heating. The relative lowest point on the temperature history coincides with that of physically defined yielding. Here, the irreversible dynamic instability occurs and the true macroscopical material flow arises [15, 17]. A further increase of loading leads to further plastic deformation. However, there is only a small percentage of external work done on the specimen stored as internal energy in the material. Most work is used in forcing the dislocations and/or defects to move within the specimen which, in turn, results in heat emission. With mechanical cyclic loading, such a phenomenon occurs only in the first or first few cycles. The cyclic hardening effect of the material would result in an immediate quick extension of the quasi-linear elastic regime in the later cycles. This may soon be above the applied maximum loading stress. Thus, the cyclic loading can be treated in the same way as the case of deformation at a low stress level. There is no further abrupt temperature rise, but fluctuations of cooling and heating continue to occur due to the thermoelastic effect on the temperature history. The trend of a gradual decrease in the mean temperature is due to the large temperature gradient between the specimen and its surroundings. This causes a much quicker heat loss, compared to the heat generated by viscous dissipation.

6. Conclusion

An attempt was made to elucidate the thermomechanical behaviour of metallic specimens under repeated mechanical cyclic loading. Experimental proof was obtained by measuring micro-temperature variation.

The results show that the thermomechanical effect causes the specimen temperature to change in accordance with cyclic loading. The temperature, which acts as a physical parameter in addition to stress and strain, reflects the material behaviour by deformation. The most significant effects concerning the heat which evolved in the specimen are as follows: the thermoelastic effect causes cooling/heating to occur in response to the elastic loading/unloading; the viscous heat dissipation effect, effective by a higher loading rate or fast cyclic loading, causes heat to generate steadily regardless of the loading direction; but the effect of heat transfer, on the other hand, becomes significant as the loading rate is lowered. It is particularly evident if a large temperature gradient is formed, or if sufficient time is necessary during the process. Moreover, cyclic loading at a high stress level causes large amounts of frictional heat to transfer. Most of the work is converted into heat, which causes a drastic temperature rise.

Recent developments in the thermomechanical coupling effect indicate that it can be phenomenal in exploring and analysing the fracture mechanism of material. However, a substantial effort in some fundamental areas, as well as experimental proof, is still needed.

Acknowledgements

The authors are grateful for the financial support by the National Science Council of Taiwan. The assistance of the co-workers in MT and A research group in carrying out the experiments is also gratefully acknowledged.

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Received 3 September 1991
and accepted 24 July 1992