

ESTIMATION OF ENERGY STORAGE RATE DURING MACROSCOPIC NON-HOMOGENEOUS PLASTIC DEFORMATION OF POLYCRYSTALLINE MATERIALS

WIERA OLIFERUK

*Institute of Fundamental Technological Research, Polish Academy of Sciences
e-mail: wolif@ippt.gov.pl*

ANDRZEJ KORBEL
WŁODZIMIERZ BOCHNIAK

*Academy of Mining and Metallurgy, Cracow
e-mail: ankorbel@uci.agh.pl*

The experimental method of estimation of the energy storage rate $\Delta e_s / \Delta w_p$ in the stage of macroscopic non-homogeneous plastic deformation is presented (is the stored energy and w_p is the energy expended in the plastic deformation). A non-uniform temperature distribution on the surface of the loaded sample as an experimental indicator of the macroscopic non-homogeneous plastic deformation is used. It is shown that during the development of strain localization, a part of the energy stored in the deformed material during previous deformation is released in the form of heat.

Key words: energy storage rate, non-homogeneous deformation, energy release

1. Introduction

Determination of energy balance during plastic deformation is of prime importance in the understanding of processes which take place in a deformed material.

A part of the energy w_p expended in plastic deformation remains stored in the material. The rest of the expended energy appears as a heat q_d evolved in the sample.

The deformation process follows the first law of thermodynamics

$$w_p = e_s + q_d \quad (1.1)$$

where e_s is the stored energy.

The energy storage phenomenon in metals was discovered by Taylor and Quinney (1933). The balance energy during the deformation process still remains the subject of a large number of experimental works, cf for instance, Mason *et al.* (1994), Mandal and Baker (1995a,b), Liu *et al.* (1997), Kapoor and Nemet-Nasser (1998), and theoretical studies given by Zehder (1991), Soós and Badea (1997), Rosakis *et al.* (2000) etc.

In the present work, a method of determination of energy balance without interrupting the deformation and without using a calorimeter is employed. The details of the method are described by Oliferuk *et al.* (1985, 1993, 1995, 1996) and Oliferuk (1996).

The energy w_p is found from the load versus elongation curve. The heat q_d is determined by simulating the process of sample heating during deformation by means of controlled supply of electrical power $r(t_1)$ in such a way that the temperature increase with time t_1 during the simulation is identical with that measured during the tensile testing. When the straining and the simulation are conducted under identical conditions, then the heat q , which would have been transferred to the surroundings if the temperature of the unloaded sample had returned to the initial value, is the same in both cases and equal to

$$q = \int_0^t r(t_1) dt_1 \quad q_d = q - e_{te} \quad (1.2)$$

where e_{te} is the energy associated with the thermoelastic coupling that appears during loading and elastic unloading of the sample. During homogeneous tensile deformation, a linear and isotropic law for the elastic behaviour is assumed

$$e_{te} = -\frac{\alpha T_0 \tau}{\rho_0} \quad (1.3)$$

where α is the coefficient of linear thermal expansion, T_0 is the initial absolute temperature, τ is Cauchy's stress tensor and ρ_0 the density of tested material.

From equations (1.1) and (1.2), the stored energy is obtained as

$$e_s = w_p - \int_0^t r(t_1) dt_1 - \frac{\alpha}{\rho_0} T_0 \tau \quad (1.4)$$

The method makes it possible to measure *in situ* the energy balance only under the condition of homogeneous deformation.

The present work deals with experimental studies of energy balance during a uniaxial tensile test, in the range where the plastic deformation becomes non-homogeneous on a macroscopic scale. The studies are based on the comparison of the increase in temperature of the sample related to the given increment of the expended energy Δw_p in plastic homogeneous deformation (for example, $\Delta w_p = 1 \text{ J}$) with the increase in average temperature related to Δw_p in non-homogeneous deformation.

The isothermal surface of the sample was used as the indicator of homogeneous deformation in the macroscopic scale. When macroscopic non-homogeneous deformation occurs, the temperature in a certain area of the sample becomes higher than the temperature of other regions because of the deformation gradient. The surface of the tested sample is no longer isothermal. The onset of a heterogeneous temperature distribution on the surface of the tested sample can be assumed as an experimental criterion of the non-homogeneous deformation on a macroscopic level.

The results obtained by Korbelt and Richert (1985), Korbelt and Martin (1986, 1988), Korbelt *et al.* (1986) show that in a given mode of loading, the onset of non-homogeneous deformation and its evolution depend on the history of deformation of the tested material. Therefore, they can be controlled by the pre-strain.

The energy balance during a uniaxial tensile test of the annealed austenitic steel, Fe-Si alloy and the rolled one are studied in this paper.

2. Estimation of energy storage rate in non-homogeneous deformation

According to the first law of thermodynamics, the given increment of the plastic deformation work Δw_p is related to the increment of the heat Δq emitted by the sample and the increment of the stored energy Δe_s .

Let Δq_h , Δe_{sh} be increments of the heat and the stored energy in the homogeneous range of straining, which correspond to the given increment of the plastic deformation work Δw_{ph} .

Δq_l , Δe_{sl} are increments of the same parameters in the non-homogeneous range of strain corresponding to the increment of the plastic deformation work $\Delta w_{pl} = \Delta w_{ph} = \Delta w_p$ (Fig. 1).

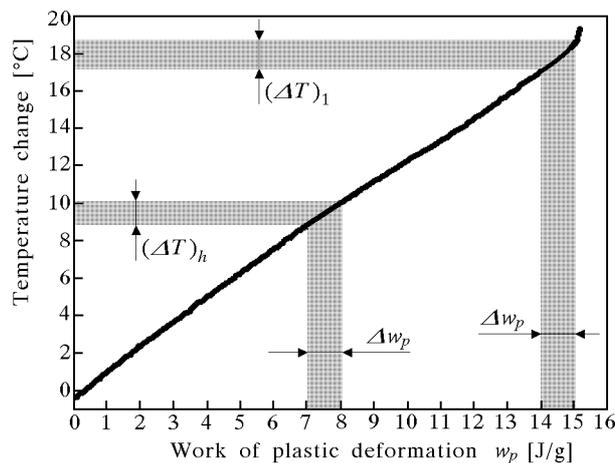


Fig. 1. Changes in the average temperature of the sample surface as a function of the plastic deformation work in a tensile test of the Fe-Si alloy. The scheme of the determination of the quantity n , Eq. (2.3)

Then

$$\Delta w_p = \Delta q_h + \Delta e_{sh} \quad \Delta w_p = \Delta q_l + \Delta e_{sl} \quad (2.1)$$

Denote

$$\frac{(\Delta T)_l}{(\Delta T)_h} = n \quad (2.2)$$

where $(\Delta T)_h$ and $(\Delta T)_l$ are increments of the average temperature of the gauge part of the sample in homogeneous and non-homogeneous ranges of deformation corresponding to the increment of the plastic deformation work Δw_p .

Measuring $(\Delta T)_l$ and $(\Delta T)_h$, the ratio n can be determined.

Having regarded the non-adiabatic conditions of the measurement, and neglecting the effect of the microstructure on the specific heat, one may put

$$\frac{\Delta q_l}{\Delta q_h} > n \quad (2.3)$$

Substitute (2.3) into (2.1)₂, so one obtains

$$\Delta e_{sl} < \Delta w_p - n \Delta q_h \quad \frac{\Delta e_{sl}}{\Delta w_p} < \frac{\Delta w_p - n \Delta q_h}{\Delta w_p} \quad (2.4)$$

The value $\Delta e_{sl}/\Delta w_p$ is the average rate of the energy storage in the range of deformation corresponding to the plastic deformation work w_p . If $\Delta w_p = w_{p2} - w_{p1}$, then $w_p = w_{p1} + \Delta w_p/2$.

All parameters included in formula (2.4)₂ can be determined experimentally, including the heat (Δq_h) dissipated by the sample as a result the plastic deformation work (Δw_p). The Δq_h can be determined using the method presented by Oliferuk *et al.* (1985, 1993, 1995, 1996) and Oliferuk (1996) and mentioned in the present work.

Values of $(\Delta T)_h$ and $(\Delta T)_l$ measured under the non-adiabatic conditions are lower than the values measured under the adiabatic conditions, and $(\Delta T)_l$ is more lowered than $(\Delta T)_h$ because $(\Delta T)_l$ relates to higher temperatures. Then the estimated value n can be only lower than the value n under the adiabatic conditions. It gives an overestimated value of Δe_{sl} (see formula (2.4)₁).

The present approach allows for the estimation of the highest value of the energy storage rate. The real rate of the energy storage can not exceed this value; it can not be higher.

3. Experiments

The commercial Fe-Si alloy in the form of 2.5 mm thick sheet has been chosen for the experiments. The first part of the sheet was cold-rolled to 1.5 mm in thickness and the other one was cold-rolled to the thickness of 1.9 mm. Then, both parts were annealed at 700°C during 1 h. From the first part of the sheet a group of samples (T) perpendicular to the primary rolling direction was machined afterwards.

The second part of the annealed sheet was cold-rolled to 0.2 true rolling strain perpendicular to the primary rolling direction. From the thus prepared material, a next group of samples ($2T$) was cut out in the direction of secondary rolling and perpendicular to the primary one.

The third group of samples (B) was prepared from the austenitic steel. The samples were annealed at 1100°C during 2 h to produce a homogeneous microstructure with the grain size 80 μm .

All samples used in tensile tests had the same shape and dimensions. The gauge length of the sample was 25 mm. They were strained at the constant deformation rate of 10 mm/min. The corresponding strain rate was $\dot{\epsilon} = 4 \cdot 10^{-3} \text{s}^{-1}$.

In the course of the tensile test, the tensile force, elongation and temperature distribution on the sample surface as functions of time were measured and recorded. The temperature distribution on the sample surface was determined on the basis of IR radiation power emitted by the strained samples.

The samples were coated with a carbon powder to ensure a homogeneous IR emissivity of their surface.

The IR power was measured by means of a thermovision camera equipped with a system which allows to digitise the video signal into a 12-bit numerical one at the sampling frequency of 1 MHz. The software allows for digital processing of thermal images.

The film of IR images (16 frames per second) was the basis to obtain the temperature distribution on the surface of the strained sample in the course of the deformation process.

4. Results and discussion

Figure 2 shows stress-strain curves and the increase of the average temperature of the gauge part of the sample during tension of the samples with different initial histories.

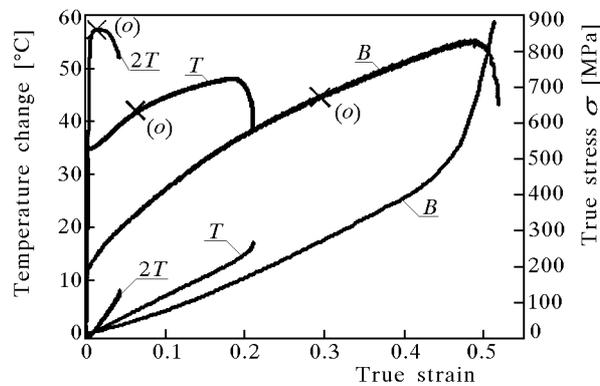


Fig. 2. Stress-strain curves and the temperature increase for annealed (T and B) and prestrained samples ($2T$). The symbol (o) marks the onset of macroscopic non-homogeneous deformation

During straining, the deformation of annealed samples (T and B) was stable and homogeneous until the onset of necking, while in cold-rolled samples ($2T$) it was unstable and non-homogeneous from the beginning of straining.

The results of measurements of the stored energy as a function of the plastic work during the homogeneous deformation are shown in Fig. 3. The zero reference energy level in the strained sample was assumed to correspond to the state at which the temperature minimum was recorded. The drop in the temperature is a result of the thermoelastic effect (visible in Fig. 2).

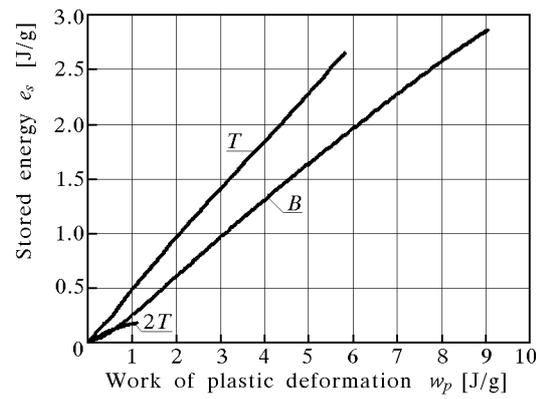


Fig. 3. The relations between the stored and the expended energy during homogeneous deformation in a tensile test of annealed (T and B) and prestrained samples ($2T$)

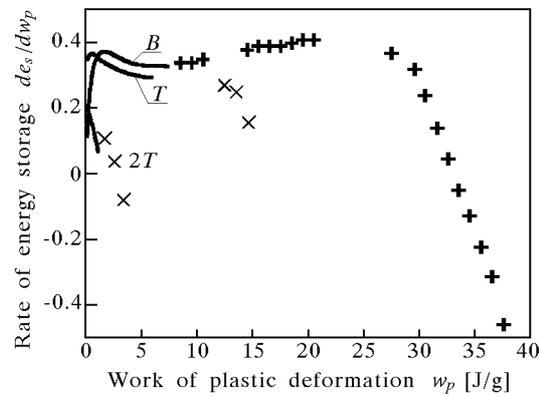


Fig. 4. The energy storage rate (de_s/dw_p) versus plastic deformation work during homogeneous straining (continuous line) and average values of the energy storage rate (points), during non-homogeneous plastic deformation

The curves in Fig. 3 were differentiated to obtain the rate of energy storage de_s/dw_p during homogeneous straining (Fig. 4, continuous line). In the initial stage of plastic deformation of samples (T) and (B), the dependence of de_s/dw_p versus w_p has a maximum. The results are similar to those obtained by Rosakis *et al.* (2000) in the case of a high strain deformation rate of the 2024-T351 aluminium (the minimum of the fraction β of the plastic work rate corresponds to the maximum of de_s/dw_p). Therefore, it can be supposed that

mechanisms responsible for the maximum of de_s/dw_p are similar. There are at least two mechanisms responsible for the maximum of the energy storage rate: formation of high energy dislocation structures and creation of internal stresses due to incompatible slip in grains of different orientation. The maximum of the energy storage rate is also closely related to the change of the mode of deformation from homogeneous multi-system slip into micro-shear banding. The development of micro-shear bands is associated with a decrease in the energy storage rate.

During unstable plastic flow in samples ($2T$), the rate of energy storage sharply decreases. Probably, it results from the second rolling that destabilizes the dislocation structure and promotes replacement of the multi-system slip by shear banding. Hence, an appropriate pre-strain can be used to control the mode of plastic deformation.

Employing the method presented in Section 3, the average value of the energy storage rate during the development of strain localization has been estimated (Fig. 4, points). As it was pointed out, the real value of the energy storage rate can be only lower than the estimated one.

The $\Delta e_s/\Delta w_p$ reaches a negative amount during non-homogeneous deformation in tension (Fig. 4 – $2T$ and B curves). This shows that the energy converted into heat is higher than the work done during the corresponding increment of plastic deformation. It is only possible when a part of the energy stored in the previous deformation is released during plastic flow.

The presented results confirm that the rate of energy storage during plastic deformation of polycrystalline metals depends on strain. They also show that the parts of the energy balance strongly depend on their deformation histories (on the pre-strain of the tested material), in other words – on varying mechanisms of plastic deformation. Probably for that reason it is difficult to propose a theoretical thermodynamic model for the partition of the plastic work into heat and stored energy in metals that would be in accordance with experimental results.

5. Conclusions

A non-uniform distribution of temperature on the surface of a deformed sample as the indicator of non-homogeneous plastic deformation on a macroscopic level has been used.

The method of estimation of the energy storage rate during non-homogeneous deformation has been presented.

It has been shown that during the development of strain localization, a part of the energy that was stored in the previous deformation, is released in the form of heat.

The change of "strain path" enhances the development of non-homogeneous plastic deformation on a macroscopic level.

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Oszacowanie zdolności magazynowania energii podczas makroskopowo niejednorodnej deformacji plastycznej w polikryształach

Streszczenie

Przedstawiono metodę szacowania zdolności magazynowania energii $\Delta e_s/\Delta w_p$ w zakresie makroskopowo niejednorodnej deformacji plastycznej (e_s – energia zmagazynowana, w_p – energia zużyta podczas deformacji plastycznej). Jako wskaźnik niejednorodnej deformacji przyjęto nierównomierny rozkład temperatury na powierzchni deformowanej próbki. Pokazano, że w końcowej fazie niejednorodnej deformacji, podczas rozwoju makroskopowej lokalizacji odkształcenia część energii zmagazynowanej we wcześniejszym etapie deformacji wydziela się w postaci ciepła.

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