

СБОРНИК НАУЧНЫХ ТРУДОВ МЕЖДУНАРОДНОЙ КОНФЕРЕНЦИИ

**АКТУАЛЬНЫЕ ПРОБЛЕМЫ
МЕХАНИКИ СПЛОШНОЙ СРЕДЫ**

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**АКТУАЛЬНЫЕ ПРОБЛЕМЫ МЕХАНИКИ
СПЛОШНОЙ СРЕДЫ**

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DISTRIBUTION OF ENERGY STORAGE RATE IN AREA OF PLASTIC STRAIN LOCALIZATION DURING TENSION

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Annotation: The presented work is devoted to the new method of energy storage rate determination that allows to obtain distribution of this quantity on the surface of deformed specimen. The method is based on the experimental procedure for simultaneous measurements of temperature, and displacement distributions on the surface of tested specimen during tensile deformation. This procedure involves two complementary imaging techniques: CCD technique and infrared thermography (IRT). It has been shown experimentally that during evolution of plastic strain localization the energy storage rate in some zones of deformed specimen drops to zero and even to negative values. To interpret this result in terms of micro-mechanisms, microstructural observations using electron back scattered diffraction (EBSD) and transmission electron microscopy (TEM) were performed on specimens in different states of deformation.

1. Introduction

When a material deforms plastically, a part of the mechanical energy w_p expended on plastic deformation is converted into heat q_d while the remainder e_s is stored within the material.

$$e_s = w_p - q_d. \quad (1.1)$$

The measure of energy conversion at each instant of the plastic deformation process is the rate of energy storage Z defined as the ratio of the stored energy increment Δe_s to the plastic work increment Δw_p :

$$Z = \frac{\Delta e_s}{\Delta w_p}. \quad (1.2)$$

The stored energy increment is equal to the difference between Δw_p and the increment of energy dissipated as a heat Δq_d :

$$\Delta e_s = \Delta w_p - \Delta q_d$$

Therefore:

$$Z = \frac{\Delta e_s}{\Delta w_p} = 1 - \frac{\Delta q_d}{\Delta w_p}. \quad (1.3)$$

The entire deformation process, from initial state to the fracture of the tested specimen, can be divided into two stages: homogeneous deformation and heterogeneous one. Two indicators of appearance of plastic strain localization are usually applied. There are: non-uniform temperature distribution on the specimen surface and non-uniform strain field on the opposite surface of this specimen.

In the previous works by Oliferuk and co-workers it has been shown that during heterogeneous deformation (localization of plastic strain) of polycrystalline material, the energy storage rate rapidly decreases reaching the 0 value and then becomes negative [1, 2]. But up to now, only the average value of the energy storage rate for the gauge part of deformed specimen was estimated [3]. The questions appear: a) What is the energy storage rate distribution along the gauge length of the strained specimen during development of plastic strain localization? b) What is relation between distribution of energy storage rate and microstructure evolution of deformed material? The purpose of the present work is to answer these questions. To reach the purpose the new method of energy storage rate determination has been designed. The method allows to obtain distribution of this quantity along the gauge length of the specimen.

2. Method of determining the distribution of energy storage rate in the area of plastic strain localization

The method is based on the experimental procedure for simultaneous measurements of temperature, and strain distributions on the surface of tested specimen during tensile deformation. This procedure involves two complementary imaging techniques: CCD technique and infrared thermography (IRT). In order to determine the strain distribution, markers in form of graphite dots were plotted on one surface

of the specimen. In this way, the surface was divided into sections, whose sizes are specified by the distance between the dots (Fig. 1).

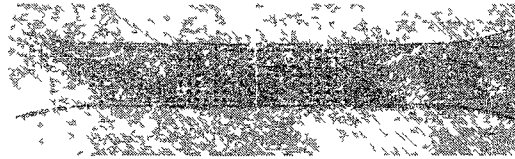


Fig. 1. The graphite dots on the gauge part of the specimen.

Displacements of the dots were recorded by means of CCD camera during deformation process. Taking into account the distance between the centers of the dots is l_0 and recording distance between these centers as a function of deformation time $l(t)$, the true local strain $\varepsilon_y(t)$ in the direction of tension was calculated

$$\varepsilon_y(t) = \ln \left(\frac{l_y(t)}{l_0} \right) \quad (2.1)$$

The true stress σ_y was determined dividing the load by the current cross-sectional area of the specimen corresponding to the given section. Assuming that a dependence of Young's modulus on strain is negligibly small, local plastic strain ε_y^p was obtained from the following formula:

$$\varepsilon_y^p(t) = \varepsilon_y(t) - \frac{\sigma_y(t)}{E}, \quad (2.2)$$

where E is Young's modulus of the tested material.

The strain and stress distributions along the axis of the tested specimen were used to calculate surface distribution of specific plastic work.

$$w_p = \frac{1}{\rho_0} \int_0^{\varepsilon_y^p} \sigma_y \cdot d\varepsilon_y^p, \quad (2.3)$$

where ρ_0 is the mass density of the tested material.

Temperature distribution on the opposite surface of the specimen was measured by means of IR Thermographic System. The surface was covered with soot to ensure its homogeneity in terms of emissivity. For each section along the axis of the specimen, the average temperature T was determined. This temperature is a function of deformation time. Taking into account, the heat flux between neighbouring sections, the heat Δq_n generated during time Δt in n -th section has been calculated according to the Fourier's law:

$$\Delta q_n(t) = c_w \cdot \Delta T + \frac{s(t) \cdot \lambda \cdot \Delta t}{\rho_0 \cdot V} \cdot \left[\frac{T(t, y_n) - T(t, y_{n+1})}{y_{n+1} - y_n} + \frac{T(t, y_n) - T(t, y_{n-1})}{y_n - y_{n-1}} \right] \quad (2.4)$$

where λ is the coefficient of thermal conductivity, c_w is the specific heat, y_n is a coordinate of the centre of the given section, s and V are its cross section and volume, respectively. Adding to each other the heat Δq_n in the successive time intervals, the time dependence of the energy dissipated as the heat $\Delta q_n(t)$ for each tested section has been obtained. Having $w_p(t)$ and $\Delta q_n(t)$ for considered sections the distribution of the energy storage rate can be determined.

3. Experiments and results Experiments were performed on austenitic stainless steel (304L). From the sheets of annealed material the specimens for tensile testing were cut out using electro-spark machining. In order to remove the technological surface layer, the specimens were electropolished. Optical metallographic and TEM observations of tested material indicated complete recrystallization and average grain size about $50 \mu\text{m}$. The dislocation density in the specimens before deformation was low; dislocations were randomly distributed in the matrix and in the grain boundaries, and no regular dislocation arrangements were observed. Grains were randomly oriented (Fig 2).

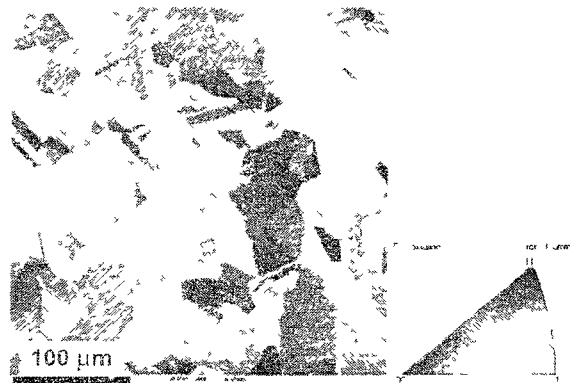


Fig 2. Distribution of grain orientation in specimen before deformation

All specimens were strained using an MIS 258 testing machine at speed's of grip displacement: $v = 1000 \text{ mm/min}$. As mentioned above, temperature distribution on the surface of the specimen, displacement field and straining force were measured as a function of deformation time t . On the basis of experimental data the energy storage rate as a function of strain was calculated for selected, local sections lying on the axis of deformed specimen (Fig. 3). The calculation was performed using MATLAB.

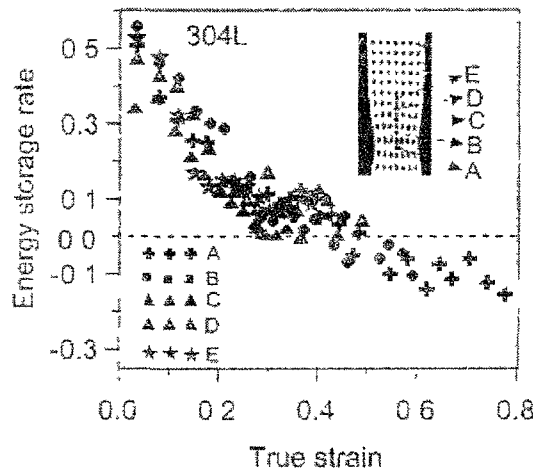


Fig 3. The energy storage rate as a function of plastic work for selected sections lying on the axis of the specimen.

The obtained results shown that the energy storage rate for all tested sections decreases with strain. During evolution of plastic strain localization some sections cease to deform, while the energy storage rate in the others drops to zero and even to negative values.

To identify micro-mechanisms corresponding to appearance and evolution of plastic strain localization microstructural characterization was performed by electron back scattered diffraction (EBSD) with orientation imaging microscopy and transmission electron microscopy (TEM). Microstructural observations were performed on specimens in different states of deformation namely: in non-deformed

state, after homogeneous deformation, in the area of plastic strain localization corresponding to non-uniform surface distribution of temperature and in area plastic strain localization corresponding to non-uniform displacement field. Typical microstructure of the strain localization area is presented in Fig. 4.

There is also a noticeable trend in the evolution of the orientation of individual grains in the direction of the two dominant texture component. The development of strain localization is accompanied by further rotation of individual grains in the direction of the two texture components. Rotation of grains proceeds in such a way, that the $\{111\}$ type planes become parallel to the planes of maximum shear stress. The angle between the trace of these planes and the tension direction is about 50° (Fig. 5). This type of texture seems to be a condition for the formation of shear bands, which corresponds to the loss of stability of plastic deformation. The macroscopic manifestation of such state was the zero value of the energy storage rate. Then, authors of the present work believe that the macroscopic criterion of plastic instability is zero value of energy storage rate.

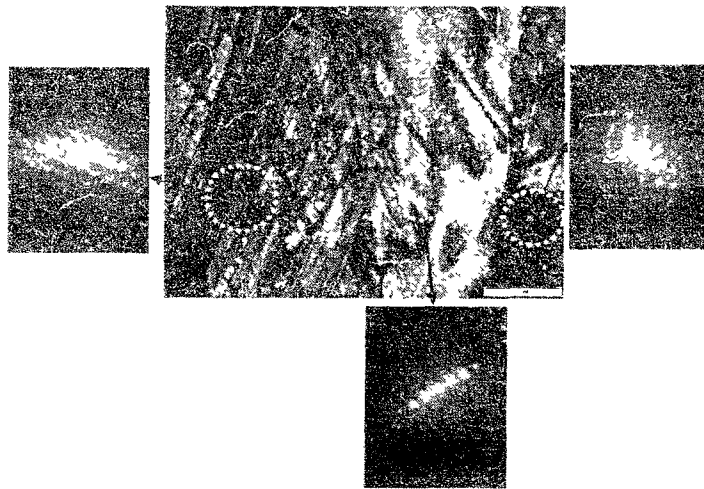


Fig. 4. Typical microstructure of the strain localization zone, It is seen two sets of intersecting deformation twins on the background of the dislocation cell structure.

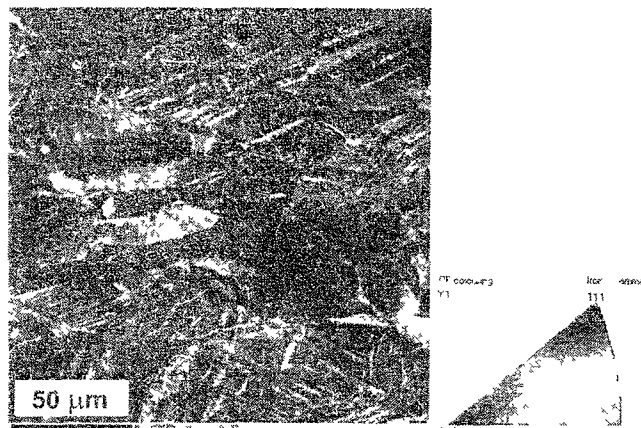


Fig. 5. Distribution of grain orientation in the neck zone. It is seen two dominant components of the texture

4. Conclusions

a) Experimental method of determination of energy storage rate distribution in the area of heterogeneous deformation has been proposed. b) In the plastic strain localization area material reaches the state, where energy storage rate reaches the 0 value and then becomes negative. This means that the material loses an ability to store the energy. Though energy supply the internal energy of the

specimen decreases. Thus, the 0 value of the energy storage rate could be regarded as the plastic instability criterion based on the energy conversion.

c) On the basis of microstructure observation it is believed that 0 value of energy storage rate corresponds to the state in which only two dominant components of the texture appear, creating conditions to crystallographic shear-banding

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