Distributions of energy storage rate and microstructural evolution in the area of plastic strain localization during uniaxial tension of austenitic steel

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Abstract. The presented work is devoted to an experimental determination of the energy storage rate in the area of strain localization. The experimental procedure involves two complementary techniques: i.e. infrared thermography (IRT) and visible light imaging. The results of experiments have shown that during the evolution of plastic strain localization the energy storage rate in some areas of the deformed specimen drops to zero. To interpret the decrease of the energy storage rate in terms of micro-mechanisms, microstructural observations using Transmission Electron Microscopy (TEM) and Electron Back Scattered Diffraction (EBSD) were performed. On the basis of microstructural studies it is believed that a 0 value of energy storage rate corresponds to the state in which only two dominant components of the texture appear, creating conditions for crystallographic shear banding.

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 as an energy related to defects of crystal lattice, mainly dislocation structure:

\[ e_s = w_p - q_d. \]

The stored energy represents a change in internal energy of the deformed material and it is an essential measure of its cold-worked state. This energy was discovered in calorimetric tests performed by Taylor and Quinney [1]. Further experimental studies have shown that the ratio of the stored energy to the plastic work depends on the deformation level of the tested material [2–14]. Thus a measure of energy conversion at each instant of the plastic deformation is the rate of energy storage \(Z\) defined as the ratio of the stored energy increment \(\Delta e_s\) to the plastic work increment \(\Delta w_p\):

\[ Z = \frac{\Delta e_s}{\Delta w_p}. \]

The stored energy increment is equal to the difference between \(\Delta w_p\) and the increment of energy dissipated as heat, \(\Delta q_d\), \(\Delta e_s = \Delta w_p - \Delta q_d\). Therefore:

\[ Z = \frac{\Delta e_s}{\Delta w_p} = 1 - \frac{\Delta q_d}{\Delta w_p}. \]
The deformation process, from the initial state to the fracture of the tested specimen, consists of two stages: homogeneous deformation and a heterogeneous one. There are two indicators of the appearance of plastic strain localization: a non-uniform temperature distribution and a non-uniform strain on the surface of the tested specimen.

In the previous works of 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 [13, 15]. But up to now, only the average value of the energy storage rate for the gauge part of deformed specimen was estimated. 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 the relation between the distribution of energy storage rate and microstructural evolution? The purpose of the present work is to answer these questions. To reach the purpose a new method of energy storage rate determination has been designed. The method allows one to obtain the distribution of this quantity along the gauge length of the specimen. The results obtained are related to the microstructure evolution.

2. The method of determining distribution of energy storage rate

The energy storage rate can be calculated by a determination of the plastic work increment $\Delta w_p$ and the corresponding increment of energy dissipated as heat $\Delta q_d$, see (1). An experimental technique for simultaneous measurements of temperature, and strain distributions on the surface of tested specimen during tensile deformation was used [16]. This procedure involves two complementary imaging techniques: a CCD camera and infrared thermography (IRT). In order to determine the strain distribution, markers in the form of graphite dots were plotted on one surface of the specimen (figure 1). In this way, the surface was divided into sections, whose sizes are specified by the distance between the dots.

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

$$
\varepsilon_y(t, y_n) = \ln\left(\frac{l_y(t, y_n)}{l_0}\right).
$$

The true stress $\sigma_y$ was determined by 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 $E$ on strain is negligibly small, the local plastic strain $\varepsilon^p_y(t, y_n)$ was obtained from the following formula:

$$
\varepsilon^p_y(t, y_n) = \varepsilon_y(t, y_n) - \frac{\sigma_y(t, y_n)}{E}.
$$
The strain and stress distributions along the axis of the tested specimen were used to calculate the surface distribution of specific plastic work

\[ w_p(t, y_n) = \frac{1}{\rho(t, y_n)} \int_0^{\varepsilon_{yp}(t, y_n)} \sigma_y(t, y_n) \, d\varepsilon_y, \quad (2) \]

where \( \rho(t, y_n) = \frac{m}{V(t, y_n)} \) is the current mass density of a particular section, where \( m = \text{const} = \rho_0 \cdot V_0 = \rho(t, y_n) \cdot V(t, y_n) \) is the mass of a section and \( V(t, y_n) \) is the current volume of a particular section.

The energy dissipated as a heat causes an increase in the temperature of the specimen. This increase depends on the strain rate. In the area of the strain localization, the distribution of the strain rate is not uniform. This heterogeneity is manifested by a non-uniform temperature field on the specimen surface. The temperature field during the deformation process was recorded by means of an IR thermography system and the average temperature \( T(t, y_n) \) as a function of time for each \( n \)-th section along the axis of the specimen was determined. Such a selection of positions of sections allows avoiding the influence of the specimen edges on the measured temperature values.

The initial size of each, considered section is identified by the distance between the centres of the dots and the thickness of the specimen. Thus, the initial volume \( V_0 \) of each section was equal to \((1.3 \times 1.3 \times 2) \text{mm}^3\) and the initial cross-section \( S_0 \) was \((1.3 \times 2) \text{mm}^2\). Dimensions of the sections were changing during the tensile process. These changes were determined by tracking dot centres in the visible range by means of the CCD camera. All these data have been used to calculate the heat \( \Delta q_d(t, y_n) \) generated during a time interval \( \Delta t \) in the \( n \)-th section.

The interval \( \Delta t \) is the reciprocal of the sampling frequency. In order to avoid the influence of the heat convection phenomenon, the displacement rate 2000 \( \text{mm/min} \) was chosen. Nevertheless, despite the relatively high displacement rate the deformation process was non-adiabatic mainly due to the heat transport to the grips of the testing machine. Thus, taking into account the phenomena considered above and the heat expended for compensation of the drop in temperature caused by the thermo-elastic effect, the heat \( \Delta q_d(t, y_n) \) generated during time \( \Delta t \) in the \( n \)-th section has been calculated according to the following formula:

\[
\Delta q_d(t, y_n) = c_w \cdot \Delta T(t, y_n) + \frac{\alpha T(t, y_n) \Delta \sigma_y(t, y_n)}{\rho(t, y_n)} + \\
+ \frac{S_{n/n+1}(t, y_n) \cdot \lambda \cdot \Delta t}{\rho_0 \cdot V_0} \cdot \frac{y_{n+1} - y_n}{T(t, y_n) - T(t, y_{n+1})} + \\
+ \frac{S_{n/n-1}(t, y_n) \cdot \lambda \cdot \Delta t}{\rho_0 \cdot V_0} \cdot \frac{y_{n-1} - y_n}{T(t, y_{n-1}) - T(t, y_n)} 
\]

(3)

where \( \alpha \) is the coefficient of linear thermal expansion, \( T(t, y_n) \) is the mean absolute temperature of the section considered, \( \Delta \sigma_y(t, y_n) \) is the increase in the stress during subsequent time intervals \( \Delta t \), \( \lambda \) is the coefficient of thermal conductivity, \( c_w \) is the specific heat and \( V_0 \) is the volume of the considered section. \( S_{n/n+1}(t, y_n) \) and \( S_{n/n-1}(t, y_n) \) are cross-section areas between neighbouring sections \( n/n + 1 \) and \( n/n - 1 \). The first component of equation (3) expresses the heat needed to raise the temperature of a unit mass of the tested material by \( \Delta T \). The second describes the heat expended for compensation of the temperature drop due to the thermo-elastic effect. The third and fourth components, according to Fourier’s law, take into account the heat transfer between the given section \( n \) and its neighbours \( n/n + 1 \) and \( n/n - 1 \), respectively. It is worth noticing that Fourier’s law refers to a heat flux. Thus, in order to determine the heat related to a mass unit, the heat flux should be divided by the mass of the section and multiplied by \( \Delta t \) and by \( S_{n/n+1}(t, y_n) \) or \( S_{n/n-1}(t, y_n) \) respectively.
Adding up the heat increments $\Delta q_d(t, y_n)$ in the successive time intervals, the time dependence of the energy dissipated as heat $q_d(t, y_n)$ for each tested section has been obtained. The energy storage rate for a particular section is defined as:

$$Z = 1 - \frac{\Delta q_d(t, y_n)}{\Delta w_p(t, y_n)}.$$  \hfill (4)

During non-uniform deformation in the equal time intervals $\Delta t$, the increments of plastic work $\Delta w_p$ are not equal. Thus, $\Delta q_d$ was determined for an equal increments of $\Delta w_p$. In further analysis $\Delta w_p = 2 J_g$ was taken. Such a value was selected in order to reduce the dispersion of ratio $\frac{\Delta q_d}{\Delta w_p}$. Having $w_p(t, y_n)$ and $q_d(t, y_n)$ for the considered sections and using the procedure mentioned above the distribution of the energy storage rate was determined.

3. Experiments and results

Experiments were performed on austenitic stainless steel (304L). From sheets of the 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 electro-polished. Optical metallographic and TEM observations of tested material indicated complete recrystallization (figure 2) and an average grain size of about 50 $\mu$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 (figure 3).

All specimens were strained using an MTS 858 testing machine. During the tension the displacement rate was controlled and equal to 2000 $\text{mm min}^{-1}$. For such a displacement rate and given geometry of the specimen the corresponding mean value of the strain rate was equal to 0.6 $\text{s}^{-1}$.

In the course of the deformation process infrared and visible range image sequences were recorded simultaneously. The experimental setup is presented in figure 4.
The taking frequency of both cameras was equal to 538 Hz. Such a frequency was selected in order to take into account the heat transfer between neighbouring sections. Simultaneously, the straining force as a function of time \( t \) was measured. The analysis of the displacement fields (based on markers tracking) and the assignment of them to the appropriate temperature distributions were performed using MATLAB software. From the experimental data, tensile curves for selected local sections: A, B, C, D, E, lying on the axis of the specimen, were calculated (figure 5).

**Figure 4.** Experimental setup for simultaneous measurement of displacement and temperature fields.

**Figure 5.** Stress-strain curves for selected sections of the specimen.

It is easy to see that with an increase in strain, individual sections of the specimen stop to deform, whereas others are still deforming. This is a result of the localization of plastic deformation. On the basis of the stress-strain dependences, the plastic work as a function of time for the selected sections lying on the specimens axis were calculated (equation 2). From the surface temperature field, the distribution of energy dissipated as heat along the specimen
axis was determined using a local form of the heat equation (equation 4). Then, using formula (1) the energy storage rate $Z$ for each of the considered sections was obtained. The results, as a function of true strain, are presented in figure 6. The results obtained for different sections are marked by different symbols with different grey intensities, corresponding to the stress-strain curves shown in figure 5. It is easy to see that the energy storage rate decreases with strain for all the considered sections. During the evolution of plastic strain localization some sections cease to deform, which causes a halt in the energy storage process in this region, whereas the energy storage rate in the other sections (where deformation still proceeds) drops to zero.

**Figure 6.** Energy storage rate as a function of true strain for selected sections of the specimen.

The zero value of the energy storage rate can be treated as a plastic instability criterion based on energy conversion. Negative values of this quantity could be explained by a release of the energy stored in previous deformation stages.

To identify micro-mechanisms corresponding to the appearance and evolution of plastic strain localization microstructural characterization was performed by transmission electron microscopy (TEM), and electron back scattered diffraction (EBSD) with orientation imaging microscopy. Microstructural observations were performed on specimens in different states of deformation namely: at the onset of strain localization and in the state just before fracture. The results are presented in figures 7–10.

The non-uniform strain distributions was used as an indicator of the onset of plastic strain localization. The characteristic elements of the microstructure corresponding to this state of deformation are deformation bands activated by deformation twins in the neighbouring grains (figure 7) and evolution of grain orientation in the direction of the two dominant components of the texture (figure 8).
The microstructure of the material, just before the fracture of the stretched specimen is shown in figure 9.

It is easy to see two sets of intersecting deformation twins in the background of the dislocation cell structure. It means that the contribution of twinning in the deformation process is growing. The development of strain localization is accompanied by further rotation of individual grains in the direction of the two texture components (figure 10).

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° (figure 10). 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 above analysis shows that in the necking zone, just before the fracture (see figure 10), the macroscopic shear of the localized area is possible without a change of a crystallographic plane. In other
words, the conditions for the crystallographic shear banding are created [17]. The macroscopic manifestation of such a state is the zero value of the energy storage rate. The preliminary results presented have shown, the that the zero value of the energy storage rate may be treated as the criterion of plastic instability.

4. Conclusions
The experimental determination of the energy storage rate distribution in the area of heterogeneous has been presented.

In the plastic strain localization area the material reaches the state, where the energy storage rate reaches the 0 value and then becomes negative. This means that the material loses an ability to store the energy. Although an energy supply to the specimen, its internal energy decreases, thus, the 0 value of the energy storage rate could be regarded as the plastic instability criterion based on the energy conversion.

On the basis of microstructural observations it is believed that the 0 value of the energy storage rate corresponds to the state in which only two dominant components of the texture appear, creating conditions for crystallographic shear-banding.

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