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ENERGY STORAGE RATE AND PLASTIC INSTABILITY

ZDOLNOŚĆ MAGAZYNOWANIA ENERGII A NIESTABILNOŚĆ DEFORMACJI PLASTYCZNEJ

The energy storage rate, defined as the ratio of the stored energy increment to the plastic work increment, versus strain was experimentally estimated in the range of homogeneous deformation as well as in the range of non-homogeneous one. The experiment were performed on 304L and 316L stainless steels. It has been shown, that during straining the material reaches the state at which the energy storage rate is zero and after that it is negative. This means that a part of energy stored during previous deformation begins to release.

It has been found that the point where the energy storage rate is zero turned out to be the point of Considére stability criterion. Therefore the release of stored energy could be used as an indicator to describe the progressive predominance of damage leading to the fracture of a material. This confirms Considére construction that specimen will undergo stable deformation up to the point on the stress-strain curve, for which the strain hardening rate is equal to the flow stress. Some attempts to explain the release of stored energy in terms of microstructure phenomena has been made.

Keywords: Energy storage rate, Plastic work, Non-homogeneous deformation, Considére stability criterion

Zdolność magazynowania energii, definiuje się jako stosunek przyrostu energii zmagazynowanej do przyrostu pracy odkształcenia plastycznego. Zależność tej wielkości od odkształcenia została oszacowana eksperymentalnie, zarówno dla zakresu deformacji makroskopowo jednorodnej, jak i niejednorodnej. Eksperymenty przeprowadzono dla dwóch rodzajów stali austenitycznej: 304L i 316L. Pokazano, że podczas odkształcenia materiał osiąga stan, w którym zdolność magazynowania energii wynosi zero, a następnie staje się ujemna, co świadczy o uwolnieniu części energii zmagazynowanej w poprzednim etapie deformacji.

Zaobserwowano, że punkt, w którym zdolność magazynowania energii wynosi zero, odpowiada w przybliżeniu wartości odkształcenia, dla której jest spełnione kryterium stabilności (stateczności) Considére'a. Mówi ono, że deformacja próbki przebiega w sposób stabilny, aż do wartości odkształcenia, w którym współczynnik umocnienia jest równy naprężeniu płynięcia.

Wydzielanie się energii zmagazynowanej, może być wykorzystane jako wskaźnik opisujący stopień uszkodzenia materiału.

W pracy przedstawiono również próbę mikroskopowej interpretacji uzyskanych wyników.

1. Introduction

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

$$e_s = w_p - q_d, \tag{1}$$

where e_s, w_p and q_d are specific quantities.

The measure of energy conversion at each instant of the deformation process is the rate of energy storage $\frac{de_s}{dw_p}$.

Deformation processes modify the temperature field of the strained specimen. At the first stage of plastic deformation the temperature distribution on the specimen surface is uniform what is used as an indicator of homogeneous deformation, on the macroscopic scale [1]. With the increase in strain the temperature distribution on the specimen surface becomes non-uniform what corresponds to non-homogeneous deformation.

It is well known that just before the fracture the strain hardening rate $\frac{d\tau}{d\varepsilon}$ (τ is the yield stress and $\varepsilon = \ln(l/l_o)$ and l is the instantaneous length of gauge part of the specimen, and l_o the initial length) rapidly decreases with strain [2]. Damage mechanisms, shear banding, for

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example, appear. According to the Considére construction a tensile specimen will undergo stable deformation up to the point on stress-strain curve for which the rate of strain hardening $\frac{d\tau}{d\varepsilon}$ is equal to the flow stress τ [3].

The energy storage rate seems to be influenced by the damage mechanisms, as well. As far as the authors are aware, there is no systematic work done to confront the strain hardening with the energy storage rate, probably because the energy storage rate in the non-homogeneous deformation range is difficult to determine. A mention to this problem is included in paper by Chrysochoos [4].

The aim of the present work is to investigate a change in $\frac{de_s}{dw_p}$ and a change in $\frac{d\tau}{d\varepsilon}$ during uniaxial tensile deformation of austenitic steel and to confront one with another. Some attempts to explain the obtained results in terms of microstructure phenomena have been made.

2. Determination of energy storage rate in homogeneous deformation range

The energy storage rate $\frac{de_s}{dw_p}$ can be obtained differentiating the stored energy e_s as a function of the plastic work w_p.

The experimental method of stored energy measurement, as in the previous works by Oliferuk et al. [1, 5], was employed. The specific plastic work w_p was derived from the load-elongation curve. The dissipated energy (equal to q_d) (Eq. 1) was determined by simulation of the specimen heating process during deformation using a controlled electrical power supply $r(t_1)$ (related to the unit mass) in such a way that the temperature increase over time t_1 during the simulation was identical to that measured during 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 is equal to:

$$q = \int_0^t r(t_1)\,dt_1, \qquad r(t_1) = \frac{I^2 R(t_1)}{m}, \tag{2}$$

where I is the intensity of the electrical current, and $R(t_1)$ and m are the electrical resistance of the gauge part of the specimen and the mass of this part respectively. But

$$q_d = q - e_{te}, \tag{3}$$

where e_{te} is the energy associated with thermo-elastic coupling that appears during elastic straining. During homogeneous tensile deformation under the assumption of isotropic linear thermoelasticity, the energy of thermo-elastic coupling is equal to:

$$e_{te} = -\frac{\alpha T_o \tau}{\rho_o}, \tag{4}$$

where α is the coefficient of linear thermal expansion, T_o is the initial absolute temperature of the specimen and ρ_o is the density of the tested material.
From Eqs. (1–4) the stored energy is obtained as:

$$e_s = w_p - \int_0^t r(t_1)\,dt_1 - \frac{\alpha}{\rho_o} T_o \tau. \tag{5}$$

This method of the stored energy measurement is applicable only within the homogeneous (on a macro-scale) deformation range.

3. Estimation of energy storage rate in non-homogeneous deformation range

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 us mark as Δq_h, Δe_{sh} increments of the heat and the stored energy in the homogeneous range of straining which correspond to given increment of plastic deformation work Δw_{ph}. The increments of the same parameters in the non-homogeneous range of strain corresponding to the assumed increment of plastic deformation work $\Delta w_{pl} = \Delta w_{ph} = \Delta w_p$ are marked as Δq_l, Δe_{sl} respectively (Fig. 1).

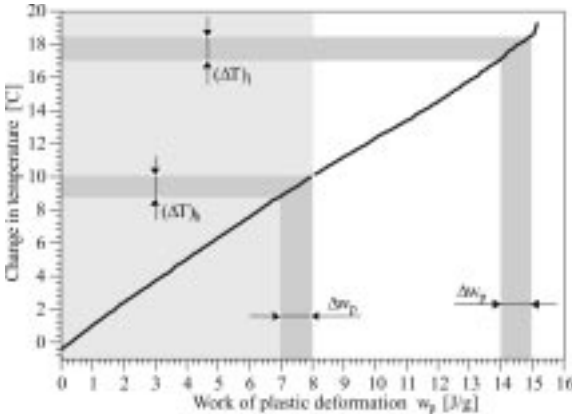

Fig. 1. The change in the average temperature of the specimen surface as a function of plastic work in tensile test of austenitic steel 316L. Schema of the n quantity determination (Eq. 7). The light gray area marks stage of homogenous deformation

Then:

$$\begin{aligned} \Delta w_p &= \Delta q_h + \Delta e_{sh}, \\ \Delta w_p &= \Delta q_l + \Delta e_{sl}. \end{aligned} \tag{6}$$

Denote

$$\frac{(\Delta T)_l}{(\Delta T)_h} = n, \tag{7}$$

where: $(\Delta T)_h$ and $(\Delta T)_l$ are the increments of the average temperature of the gauge part of specimen in homogeneous and non-homogeneous range of deformation, corresponding to the increment of the plastic deformation work Δw_p.
Measuring $(\Delta T)_h$ and $(\Delta T)_l$, the ratio $\frac{(\Delta T)_l}{(\Delta T)_h}$ denoted n can be determined.

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

$$\frac{\Delta q_l}{\Delta q_h} \rangle \frac{(\Delta T)_l}{(\Delta T)_h}. \text{ In other words: } \frac{\Delta q_l}{\Delta q_h} \rangle n \tag{8}$$

Substitute (8) into (6), so one obtains:

$$\Delta e_{sl} \langle \Delta w_p - n\,\Delta q_h, \tag{9}$$

therefore

$$\frac{\Delta e_{sl}}{\Delta w_p} \langle \frac{\Delta w_p - n\,\Delta q_h}{\Delta w_p}. \tag{10}$$

The $\frac{\Delta e_{sl}}{\Delta w_p}$ value 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 $w_p = w_{p1} + \frac{\Delta w_p}{2}$.

All parameters included in formula (10) can be determined experimentally, and in particular the heat Δq_h dissipated by the sample as a result the plastic deformation work Δw_p can be determined using the method presented in the papers by O l i f e r u k et al. [5–7] and mentioned in section 2.

The $(\Delta T)_h$ and $(\Delta T)_l$ values measured under non-adiabatic conditions are smaller than the values measured under adiabatic conditions whereas $(\Delta T)_l$ is lower more than $(\Delta T)_h$, because $(\Delta T)_l$ relates to the higher temperature. Then the n value estimated can be only lower than the n under adiabatic conditions. It gives the overestimated value of the Δw_{sl} (see Eq. 9).

The presented approach allows estimating the highest value of the energy storage rate. The real rate of energy storage cannot exceed this value; it cannot be higher.

4. Experiments

Two groups of specimens made from austenitic steels 316L and 304L were strained by using the MTS 810 testing machine at the constant deformation rate $\dot{\varepsilon} = 4.3 \cdot 10^{-3}\ s^{-1}$. The steels were initially annealed at 1100°C and water quenched. The dimensions of the gauge part of specimens were 25 mm × 10 mm × 1.5 mm. In the course of deformation process, the tensile force, elongation and temperature distribution on the sample surface as functions of time were measured and recorded. The temperature distribution on the specimen surface was determined on the basis IR radiation power emitted by the strained specimen. The radiation power was measured by IR camera.

On the basis of the mechanical and thermomechanical characteristics, the strain hardening rate and the energy storage rate as the function of the true strain in the homogeneous range of plastic deformation as well as in the non-homogeneous one were obtained (Fig. 2).

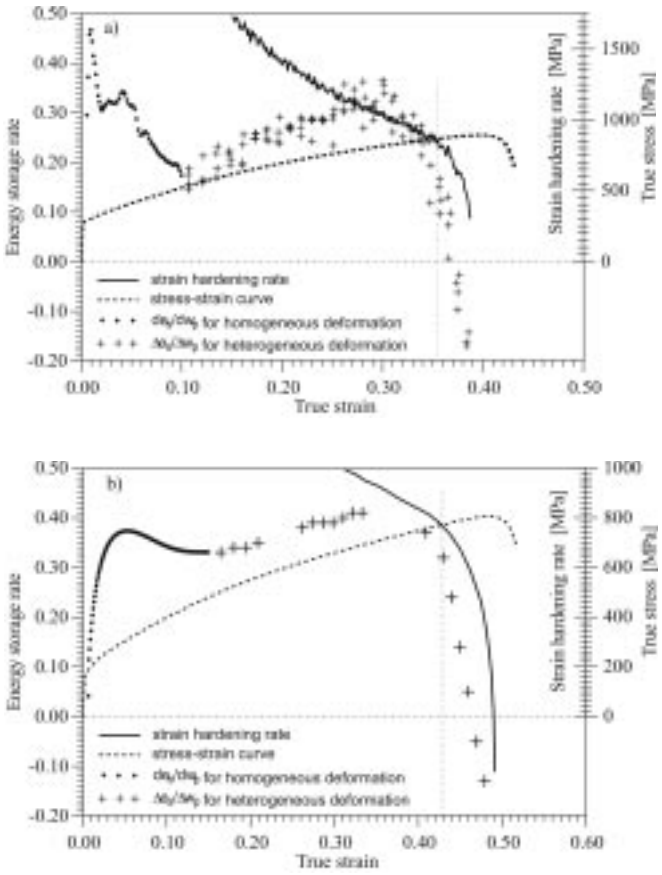

Fig. 2. The stress-strain curve, the energy storage rate and the strain hardening rate as a function of true strain for: a) the 316L austenitic steel (4 specimens), b) the 304L austenitic steel (1 specimen)

It is seen that before the fracture the energy storage rate $\frac{\Delta e_s}{\Delta w_p}$ rapidly decreases with strain and then becomes negative for both tested materials. This shows that the energy converted into heat is higher than work done during the corresponding increment of plastic deformation. It is possible only if a part of the energy stored during previous deformation begins to release.

The energy storage rate $\frac{\Delta e_s}{\Delta w_p} = 0$ at $\varepsilon = 0.36$ for the 316L steel and at $\varepsilon = 0.46$ for the 304L steel. It is easy to notice that the $\frac{\Delta e_s}{\Delta w_p} = 0$ nearly corresponds to the point on the stress-strain curve at which the Considére stability criterion $\frac{d\tau}{d\varepsilon} = \tau$ is satisfied (at $\varepsilon = 0.35$ for the 316L steel and at $\varepsilon = 0.43$ for the 304L steel, see Fig. 2). Taking into account that the real rate of energy storage cannot exceed the estimated maximal value, the discrepancy between the point corresponding to Considére criterion and the point $\frac{\Delta e_s}{\Delta w_p} = 0$ can be even smaller. This result provides the physical confirmation of the Considére criterion. The negative values of the energy storage rate correspond to the necking process (Fig. 3).

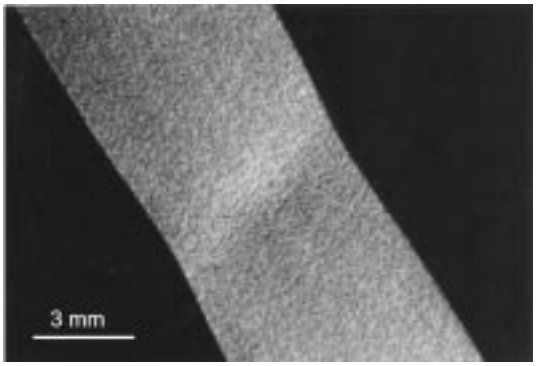

Fig. 3. Optical image of the gauge part of the 316L specimen deformed to $\varepsilon^p = 0.45$

When the energy storage rate reaches 0, the material loses an ability to energy storing. Henceforth, although energy is still supplied, the internal energy of specimen, under isothermal conditions, decreases leading to the fracture. This marks the onset of plastic instability. Accordingly the condition $\frac{\Delta e_s}{\Delta w_p} \leqslant 0$ can be used as a plastic instability criterion on the macro-scale. The release of the stored energy may be connected with evolution of damage mechanisms, which are superimposed on the dislocation movement. Thus the negative value of the energy storage rate can be used also as an indicator to describe the progressive predominance of damage leading to the fracture of the material.

5. Microstructure

An attempt to explain the results obtained on macro-scale in terms of microscopic mechanisms was made. TEM observations were performed on thin foils prepared from four kinds of the 316L steel specimens, namely from: the annealed (non-deformed) steel, the deformed specimens with a small plastic strain ($\varepsilon^p = 0.005$) and with $\varepsilon^p = 0.06$ and the deformed specimen with a large strain corresponding to a negative value of the energy storage rate.

Fig. 4 illustrates the typical microstructure of non-deformed 316 steel. It is seen that dislocations are randomly distributed and its density is low. It means, that the material is fully recrystallized.

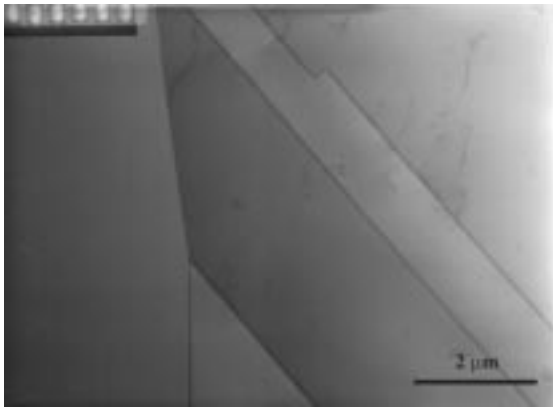

Fig. 4. The typical microstructure of non-deformed 316L steel

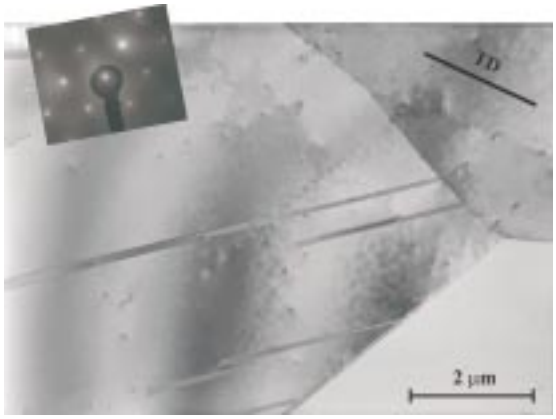

Fig. 5. The stacking faults imaged by TEM in the 316L steel deformed to plastic strain $\varepsilon^p = 0.005$ and respective diffraction pattern. (The tensile direction is marked)

The tested steel is material of a low stacking fault energy, therefore characteristic elements of microstructure at small plastic strain ($\varepsilon^p = 0.005$), except dislocations, are stacking faults (Fig. 5). Another elements of microstructure of the tested steal are twins. They are observed in the annealed steel (Fig. 5) and in deformed one at $\varepsilon^p = 0.06$ (Fig. 6) as well as at large strain ($\varepsilon^p = 0.43$) corresponding to a negative value of the energy rate (Figs.: 7 and 8). It should be noticed, that a thickness of twins related to a large strain is much smaller (~50 nm) than ones related to $\varepsilon^p = 0$ and $\varepsilon^p = 0.06$ (~5 μm). These results suggest that narrow twins were formed in deformation process, while the wide ones were created during thermal treatment. In the area of strong strain localization the twins were distorted by shear bands (Fig. 9). It should be noticed that the angle between shear band and tensile direction

is about 40°. The development of shear bands seems to be a main damage mechanism.

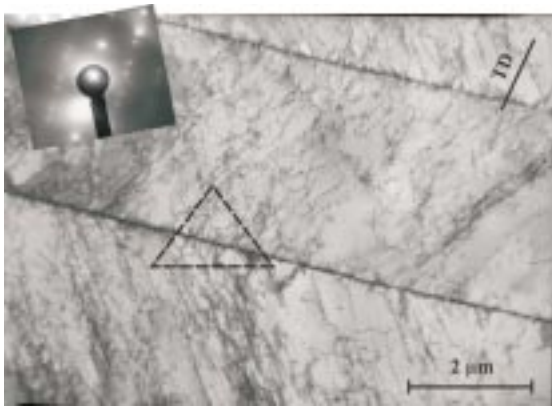

Fig. 6. The twins imaged by TEM in the 316L steel deformed to ε^p = 0.06.Diffraction pattern from the marked area and tensile direction are shown

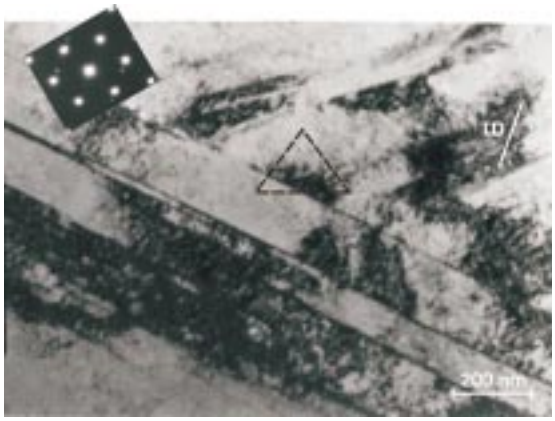

Fig. 7. The twins formed in deformation process in the 316L steel ε^p = 0.43. Diffraction pattern from the marked area and tensile direction are shown

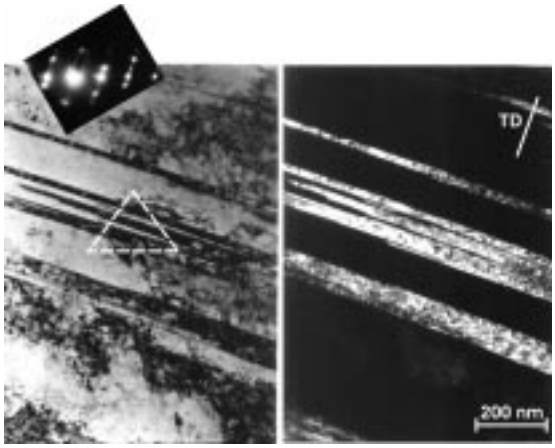

Fig. 8. The twins in the 316L steel imaged in dark and bright field ε^p = 0.43. Diffraction pattern from the marked area and tensile direction are shown

The microstructure inside and in the vicinity of shear band was different from that far away from the band. Region composed of nanosized grains inside and in the vicinity of the band have been observed (Fig. 10). The grains are equiaxial and the grain size is about 20 nm while the average grain size of the annealed material was 30 μm. Thus, formation of the shear bands and grain refinement accompanied by them correspond to the decrease in the internal energy of tested specimen. (The indicator of this decrease is negative value of the energy storage rate).

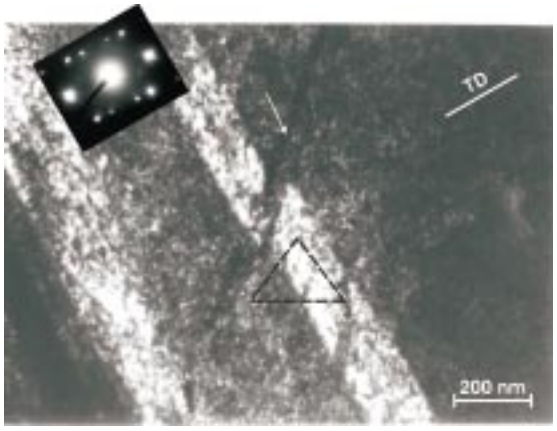

Fig. 9. Twin distorted by shear band in the 316L steel deformed to ε^p = 0.43. Diffraction pattern from the marked area and tensile direction are shown

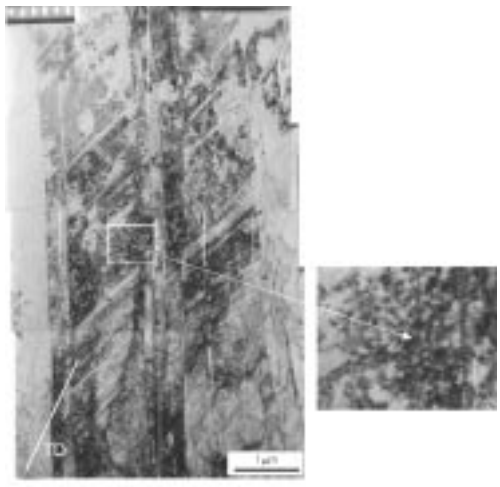

Fig. 10. The shear band and its vicinity in the 316L steel just before fracture. The grain subdivision is seen. (The tensile direction is marked)

The TEM micrograph presented in Fig. 10 is similar to that obtained by Meyers et al. [8]. It can be supposed that the evolution of plastic deformation, coupled with temperature rise leads from a dislocated and twinned structure to the break up into small regions separated by geometrically necessary boundaries, as defined by Kuhlmann-Wilsdorf and Hansen [9]. These regions initiate the process of new grain formation, which requires local grain boundary rotations in order to ensure compatibility of plastic deformation. Meyers and co-authors [8] shown that these local grain

boundary segments can rotate by 30° and generate an equiaxial microcrystalline structure. The process of new grain formation was called dynamic rotational recrystallization by Mayers et al. [10, 11]. The dynamic rotational recrystallization is the process induced by both strong localized deformation and temperature rise due to this deformation. Mataya, Carr, and Kraus [12] were the first to analyse the fine grained structure within shear bands in stainless steel.

During recrystallization process the internal energy of material, under isothermal conditions, diminishes. Thus the negative value of the energy storage rate seems to be a macroscopic manifestation of rotational dynamic recrystallization accompanying the shear banding. This hypothesis has been formulated on the strength of the comparison the presented results with the results of texture evolution described in the paper [8].

6. Concluding comments

It has been shown that during development of macroscopic strain localization the energy storage rate rapidly decreases reaching the 0 value and then becomes negative for both kind of the tested austenitic steels. This means that a part of energy stored during previous deformation begins to release. Hence, under isothermal conditions, the internal energy of the tested material decreases.

It has been noticed that the 0 value of the energy storage rate nearly corresponds to the point on the stress-strain curve at which the Considére stability criterion $\frac{d\tau}{d\varepsilon} = \tau$ is satisfied. This result provides the physical confirmation of the Considére criterion. Thus the negative value of the energy storage rate could be used as an indicator to describe the progressive predominance of damage leading to the fracture of a material.

On the basis of the comparison the presented results concerning energy stored rate and microstructure with the results of texture evolution described in the paper [8], hypothesis has been made that the negative value of the energy storage rate seems to be a macroscopic manifestation of rotational dynamic recrystallization accompanying the shear banding. In order to confirm the hypothesis the microtexture investigation is needed.

REFERENCES

[1] W. Oliferuk, S.P. Gadaj, M.W. Grabski, Mater. Sci. Eng. **70**, 131-136 (1985).

[2] Z.S. Basinski, M.S. Szczerba, J.D. Embury, Phil. Mag. **A 76**, 743-752 (1997).

[3] A.G. Considére, Annales des Ponts et Chausses, ser 6 **9**, 574 (1985).

[4] A. Chrysochoos, J.M. Murracciole, B. Wattrisse, Continuous damage & fracture, Ed.: A. Benallal, 41-51 (2000).

[5] W. Oliferuk, W.A. Świątnicki, M.W. Grabski, Mater. Sci. Eng. **A197**, 49-58 (1995).

[6] W. Oliferuk, A. Korbel, M.W. Grabski, Mater. Sci. Eng. **A220**, 123-128 (1996).

[7] W. Oliferuk, W.A. Świątnicki, M.W. Grabski, Mater. Sci. Eng. **A161**, 55-63 (1993).

[8] M.A. Meyers, Y.B. Xu, Q. Xue, M.T. Perez-Prado, T.R. McNelley, Acta Materialia **51**, 1307-1325 (2003).

[9] D. Kuhlmann-Wilsdorf, N. Hansen, Scripta Metall. Mat. **25**, 1557-1559 (1991).

[10] M.A. Meyers, U. Andrade, A.H. Chokshi, Metall. Mat. Trans. **26A**, 2881-2893 (1995).

[11] M.A. Meyers, G. Subhash, B.K. Kad, L. Prasad, Mech. Mater. **17**, 175-193 (1994).

[12] M.C. Mataya, M.J. Carr, Krauss, Met. Trans. **A 133[a]**, 1263 (1982).

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