

Pre-strain direction effect on microstructure evolution and energy storage process during uniaxial tension of austenitic steel

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Abstract. In the present paper the influence of pre-strain direction on energy balance during deformation of austenitic steel was investigated and the analysis of microscopic phenomena responsible for this influence was performed. The specimens with different pre-strain directions were prepared and the ratio of the stored energy increment to plastic work increment, called energy storage rate, as a function of plastic strain was experimentally determined. At the initial stage of plastic deformation of annealed materials this quantity vs. plastic strain has a maximum. It has been shown that for specimens strained in the same direction as pre-strain the energy storage rate decreases monotonically with deformation while for specimens where strain path was changed, the maximum of the energy storage rate is observed (as in case of annealed material). The study of slip and microstructure evolution at meso- and micro-scales have shown that the change in pre-strain direction leads to the redistribution of internal stresses generated by incompatible slip in neighbouring grains of different orientation. Just after change in strain direction the accommodation of these stresses takes place not only by generation of geometrically necessary dislocations but also by micro-shear banding.

1. Introduction

The deformation process always leads to change in the temperature of deformed material what is a macroscopic manifestation of phenomena proceeding on the level of its microstructure. Thermal effects accompanying the deformation process were investigated by many researchers in last years [1]. The plastic work w_p equal to total energy expended on irreversible deformation can be presented as a sum of energy stored in the material e_s and energy dissipated as a heat q_d . Thus

$$e_s = w_p - q_d, \quad (1)$$

where e_s, w_p, q_d are the specific quantities.

The energy stored during deformation process is defined as a change in internal energy measured after unloading and describes the state of the cold worked material. As a measure of the energy conversion at each instant of straining the energy storage rate $\Delta e_s / \Delta w_p$ was used. This macroscopic quantity is influenced by many micro-scale mechanisms. Both the microstructure evolution and energy storage

process during monotonic deformation were studied extensively in many papers [2]. In accordance with LEDSS hypothesis developed by Hansen and Kuhlmann-Wilsdorf, the evolution of dislocation structures during monotonic deformation tends towards the configurations of lower energy [3]. In recent years the rapid development of methods of material properties improvement using strain path change is observed. Therefore, it is important to study the pre-strain direction effect on the energy storage process. Thus, the aim of this paper is to study the effect of pre-strain direction on energy storage rate and to find the interpretation of obtained results on the basis of microstructure analysis.

2. Experimental procedure and results

2.1. Determination of energy storage rate

The experiments were performed on austenitic stainless steel 316L. The steel sheet was initially annealed at 1100°C and water quenched. Firstly, large specimens (500mm x 105mm x 1.5mm) were cut out and pre-strained to $\varepsilon^p = 0.068$. From such prepared material, three groups of specimens (*L*, *S* and *T*) were cut out using electro-erosion machine (figure 1).

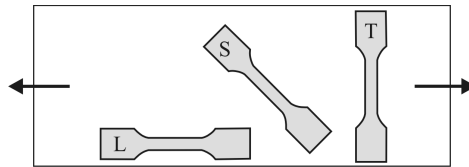


Figure 1. Orientation of the specimens (pre-strain direction marked).

These specimens and the θ ones, made of non-deformed sheet, were strained with constant strain rate $\dot{\varepsilon} = 7 \times 10^{-3} s^{-1}$. During tension the temperature distribution on the surface of the specimen was measured using IR thermography. Simultaneously the stress and strain were determined. Like in the previous reports, a method of the stored energy determination without interrupting the deformation and without using a calorimeter was employed [4]. The stored energy e_s was determined as a difference between plastic work w_p and energy dissipated as a heat q_d . The plastic work was derived directly from the load-displacement curve under assumption that elastic properties do not change for this range of deformation. The energy dissipated as a heat q_d was determined by simulating the process of specimen heating during deformation using a controlled electrical power supply in such a way, that the temperature increase over time during simulation was identical to that measured by IR camera during tensile testing. When straining and simulation are conducted under identical conditions then the heat, 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 can be calculated from electrical parameters.

The energy storage rate as a function of plastic strain is presented in Figure 2. It is seen that for *L* specimens, strained in direction of pre-strain, this quantity decreases monotonically with deformation while for specimens where strain path was changed (*S* and *T*) the maximum of $\Delta e_s / \Delta w_p$ is observed (as in case of annealed material).

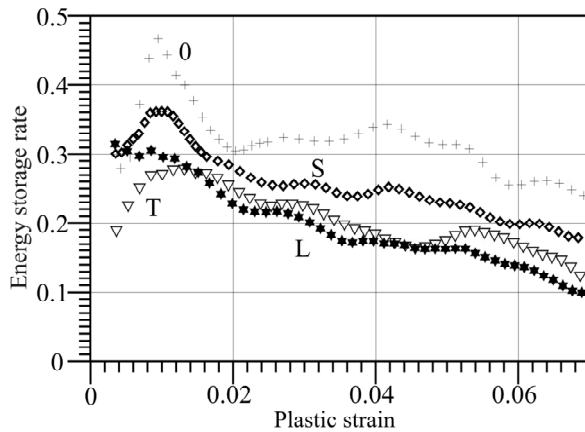


Figure 2. Energy storage rate vs. plastic strain.

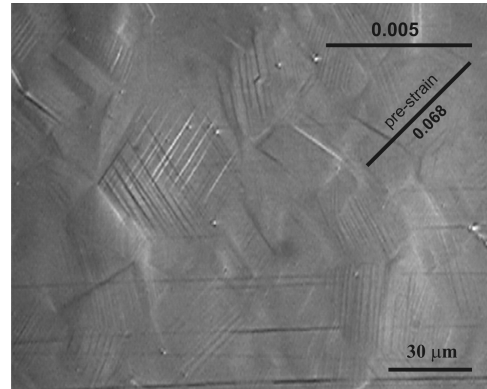


Figure 3. The surface of the *S* specimen after polishing and subsequent straining.

2.2. Analysis of material structure

The study of material structure was performed in two scales: the slip evolution was studied using optical microscopy with Differential Interference Contrast (DIC) whereas an evolution of dislocation structures was investigated using Transmission Electron Microscopy (TEM).

2.2.1. Slip evolution. The specimens with different pre-strain direction (*L*, *S* and *T*) and that at annealed state 0 were electropolished in order to obtain mirror-like surface. Such prepared specimens were strained to small amount of plastic strain $\epsilon^p = 0.005$. Then, their surfaces were analysed using optical microscopy with DIC at magnification up to 600x. The advantage of this method is that it reveals effects generated during last stage of deformation. In figure 3 the surface of the *S* specimen after polishing and subsequent straining is shown. In particular grains the slip bands are seen. It is characteristic that for the *L* specimen strained in direction of pre-strain, only one set of slip bands dominate in particular grains, whereas when strain path was changed, more than one family of slip band appears. The quantitative analysis of percentage of grains $\eta = \frac{L^*}{L_t} \cdot 100\%$ with more than one set

of slip bands was performed. L^* and L_t are the number of grains with more than one set of slip bands and the total number of grains, respectively. The results of the analysis are presented in table 1.

Table 1. Percentage of grains with more than one set of slip bands.

Specimen	L^*	L_t	$\eta = \frac{L^*}{L_t} \cdot 100\%$
$L_{+0,005}$	39	2000	1,9
$S_{+0,005}$	189	2000	9,4
$T_{+0,005}$	174	2000	8,7
$0_{+0,005}$	106	2000	5,3

It is seen that the η value is significantly lower in case of *L* specimens than for *S* and *T* ones where an additional set of slip bands were observed just after change in strain direction. This extra set of slip bands is necessary to accommodate intergranular stresses generated between neighboring grains after change in direction of external load with respect to pre-strain direction.

2.2.2. Microstructure evolution. The thin foils for TEM studies were cut out from the same specimens for which the slip analysis was performed. The observations were carried out at magnifications up to

20000x. In Figure 4 the microband crossing the dislocation structure is presented. This element of microstructure is typical for *S* and *T* specimens and is not observed in case of *L* one. Micro-shear bands cut across the grain boundary are seen in Figure 5. This deformation mechanism is characteristic for advanced stages of deformation during monotonic straining. The micro-shear bands were observed in *T* specimens only (strained perpendicularly to pre-strain direction).

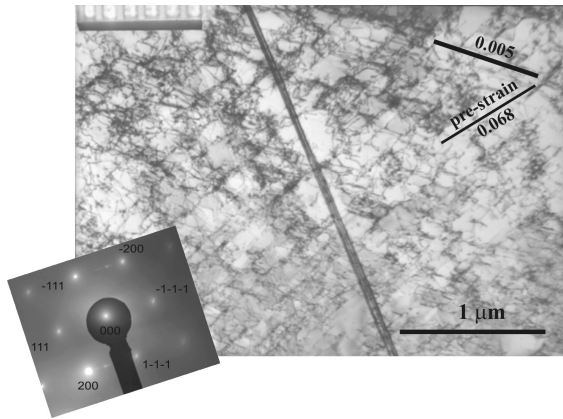


Figure 4. Microband crossing the dislocation structure in the *S* specimen.

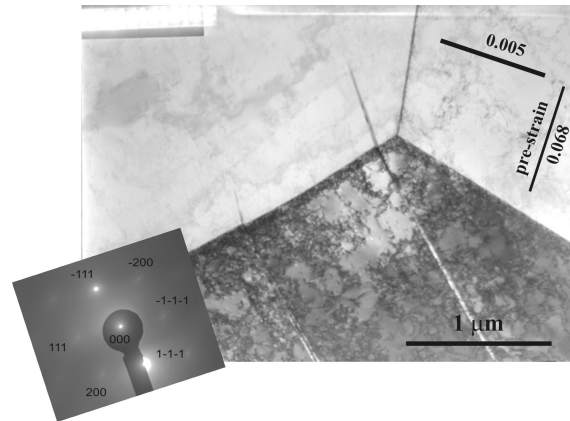


Figure 5. Micro-shear bands crossing the grain boundary in the *T* specimen.

3. Concluding remarks

It has been shown that maximum of the energy storage rate occurs not only for annealed specimens *O* but also for specimens *S* and *T* for which strain path was changed whereas for the *L* specimens $\Delta e_s / \Delta w_p$ decreases monotonically with strain according to LEDSS hypothesis.

The studies in mesoscale show that change in strain direction leads to activation of additional operating slip systems. This extra set of slip bands are necessary to accommodate intergranular stresses generated between neighboring grains after change in direction of external load. Microstructure investigations using TEM have shown that accommodation of these long-range internal stresses takes place not only by generation of geometrically necessary dislocations but also by micro-shear banding. Although this additional deformation mechanism is typical for more advanced stages of monotonic deformation process, it can be easily induced by strain path change.

Acknowledgements

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