EFFECT OF DEFORMATION MECHANISMS ON DYNAMIC RECRYSTALLIZATION OF FERRITE STAINLESS STEEL

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ABSTRACT

The relationship between mechanisms of plastic deformation and microstructural evolution has been investigated in the ferrite stainless steel. The fragmented structure is formed during deformation at T=600°C. The dislocation climb along fragmented grain boundaries according to the Nix-Ilschner mechanism is dominant deformation mechanism at steady state. New grains appear at the places of prior fragments as a result of transformation of fragmental type grain boundaries in grain boundaries of a common type. The formation of new grains is not observed during deformation both at temperatures below 600°C and above this temperature.

INTRODUCTION

The mechanisms of plastic deformation of b.c.c.-metals having relatively high values of stacking fault energy (SFE), as well as its microstructural evolution at intermediate temperatures ($T=0.4\text{-}0.6T_m$) is subject to some debate. Only systematic studies of dislocation structure evolution at large strains have been performed [1-5]. Purely experimental results cause the appearance of controversy viewpoints on possibility of dynamic recrystallization (DRX) in these materials. Some authors argue that the dynamic recovery caused by easily cross-slip inhibits the DRX [3]. However, experimental results reported in [4,5] are contrary to this approach. The aim of the present work was therefore to investigate structural changes and their close relation with deformation mechanisms in this class of materials. It has been shown [6], that such an approach allows to derive a general concept of plastic flow and explains an influence of deformation condition on microstructural evolution.

MATERIAL AND EXPERIMENTAL PROCEDURE

Coarse grained Cr25 ferritic steel (Fe-25% Cr-0,9% Ti-0,13% C) having high SFE was used in this study. Axial compression tests were carried out on an Instron 1185 and Schenck RMS-100M universal testing machines over a temperature range of T=400-900°C at strain rates of $\dot{\varepsilon}=10^{-2}\text{-}10^{-4}s^{-1}$. Details of techniques of threshold, effective stress and material activation characteristics calculations have been described previously [7-10]. Metallographic analysis of the specimens was performed on optical microscopes (Metaval, Neophot-32), and a structural analyzer (Epiquant). Deformation relief tests were carried out on IMASH-20-78 testing machine in vacuum at high temperatures. Topological observations of the slip line traces and investigations of thin foils were performed using an SEM Jeol JSM-840 and TEM JEM-2000EX, respectively.

RESULTS

Mechanical properties. Examination of deformation behavior of the ferritic steel at the steady state in terms of threshold stress revealed that the dependence of threshold stresses and effective stresses vs temperature within the temperature range 600-900°C is not linearly (figure 1) [9,10]. The increase of deformation temperature from 600°C to 700°C leads to a dramatic drop of threshold stress. The positive temperature dependence of effective stress takes place at these temperatures.

Microstructural evolution. The influence of temperature on structural changes during plastic flow is unusual too (the table) [11]. The recrystallized grain formation has been observed at t=600°C, only. At other temperatures DRX develops very slowly or does not occur at all. Proceeding from traditional concepts on DRX it seems impossible to explain the obtained extreme dependence .

Table. The volume fracture of recrystalized grains, γ, (ε=70%).

T, °C	900	800	700	600	500	400
γ, %	15	5	2	40	15	0

Surface observation. The surface investigations revealed a dependence of slip morphologies on temperature deformation. In region T=700-900°C homogeneous predominantly single slip takes place (figure 2a) [10]. There are a great number of fine slip lines on the surface of grains. The spacing between these slip lines is 1-2 µm. Most of them are straight.

At T=600°C a deformation relief is quite different. At the early stage of plastic flow long parallel slip lines crossing initial grains dominate (figure 2b). Very fine wavy lines of secondary slip are arranged between coarse lines of primary slip at an angle of 45°. The steady state is accompanied by localization of plastic deformation. Deformation microbands are formed [2,11,12]. Microbands of only one system are observed in some grains. The spacing between them varies from one to tens of microns, the broad constitutes 4-6 µm and the length reaches several tens of microns. Within other grains short (the length does not exceed 2-4 µm) primary system microbands are arranged close to each other at an angle to primary microbands and combined into mesoscale bands, their length being several hundreds of microns (figure 2c).

At lower temperatures (400-500°C) deformation becomes homogeneous again, although sliding planarity is more than at T=700°C [11]. Coarse wavy slip traces intersect initial grains (figure 2d). The spacing between them does not exceed 10 µm. There are evidences of cross-slip near grain boundaries. In the interior of initial grains slip features are straight. A single sliding system prevails.

Fine structure. Subgrain structure is formed after small strain at T=700°C. The increase in strain does not lead to a significant growth of subboundary misorientations. The formation of recrystallized grains is not observed up to the true strain e=1.5.

At T=600°C at the early stage of plastic flow the material fine structure consists of "dislocation rich layers" and microbands [2,12]. Fragmentation occurs in the material at the steady state [1]. The third structural component appears in the fine-grain structure. It comprises mutually intersecting fragments and "infrafragments" [12]. On their sites the recristallized grains are formed with increasing the strain; DRX occurs [12].

The fine-grained structure consists of dislocation pile-ups and dislocation rich layers in the interval of a lower deformation temperature [2,11]. The evidences of microband, subgrain or fragmental structure formation have not been revealed.

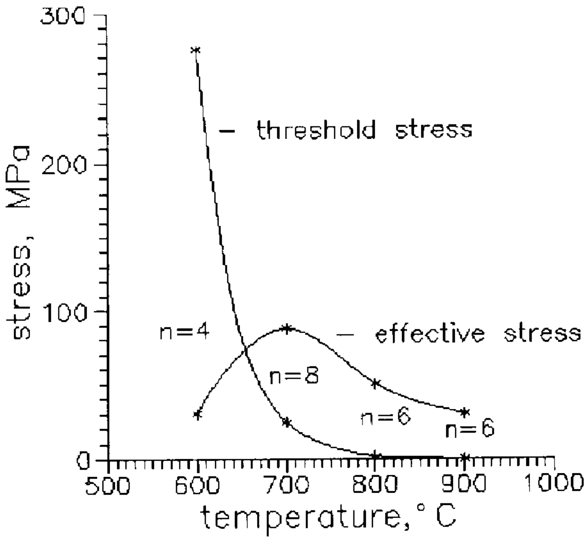

Figure 1. The threshold stresses and the effective stresses vs temperature.

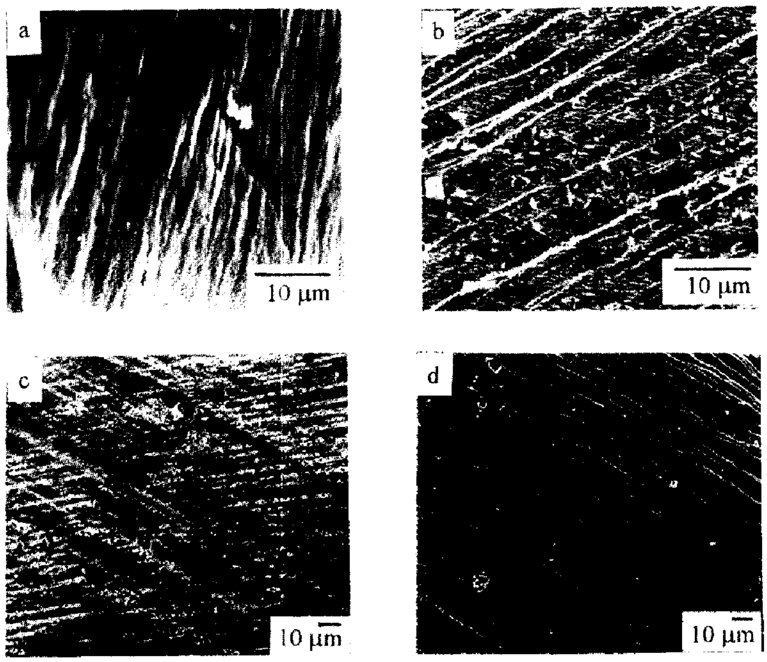

Figure 2. Topographical features; *a* - 800°C, ε=30%; *b* - 600°C, ε=8%; *c* - mesoscale bands formation, 600°C, ε=15%; *d* - 500°C, ε=15%.

DISCUSSION

Inspection of the obtained experimental results shows that only the comparative analysis of microstructural changes and operative deformation mechanisms allows to explain the origin of abnormal temperature influence on DRX. In three temperature regions distinguished by specific structural changes different deformation mechanisms act. The deformation behavior of steel in these regions can be described only using different models of plastic flow [10].

In the temperature interval 700-800°C the activation energy of deformation, which has been determined taking into account the threshold stresses, undergoes changes from 280 to 240 kJ/mol with increasing the applied stresses. The deformation model suggested by Blum [13] has demonstrated the best correlation with the experimental data. This model is based on the assumption that deformation is controlled by dislocations recovery near the subgrain boundaries. There is a dynamic equilibrium between dislocation absorption from the matrix and dislocation release into the matrix [14]. This model shows good fit with experimental results. In model [13] the activation energy is given by:

$$Q=0.5k_fG_ob^2d-\sigma_hV^* \quad (1)$$

where k_f is a coefficient of obstacle strength, G_o is the shear modulus at T=0K, b is the Burgers vector, σ_h is effective stress in the sub-boundaries, d is the stacking fault width at zero stress, V^* is the activation volume. For obstacles of moderate strength (k_f=0.6) it constitutes 290-210 kJ/mol. The occurrence of threshold stresses at these temperatures is caused by the presence of dispersion carbides in the structure of the material [9]. The effect of the deformation mechanism at this stage consists in slow increase of subboundary misorientations. As a result, a stable network of subboundaries is formed during plastic flow. Recrystallized grains have no time to form if strain is not too large.

Deformation behavior and microstructural evolution at T=600°C are determined by the development of fragmentation at the steady state [1,12].

Firstly, it leads to appearance of high threshold stress (σ_o=270 MPa). Consideration of disclination hardening model at large strain [15] allows to prove this. In the latter model [15], it is assumed that flow stress for b.c.c.-metals are originated from interaction between dislocations and partial disclination kinks. The kinks constitute dipole configurations with the size, c, and have twist components, ω_z. Flat layers of kink dipoles arrange at the distance of Δ_2 from each other. The distance between dipoles within one layer is a. The spacing between layers is Δ_1. Then the stress for screw dislocations moving at some deviation from the symmetric axis of the twist dipole should be determined by interaction of the dislocations with these kinks [15]:

$$\sigma=\beta G\omega_z ca/(\Delta_1\Delta_2) \quad (2)$$

where $\beta\sim1$ is the numerical coefficient depending on mutual location of dipoles within layers, G is the shear modulus. Assuming $c/\Delta_2=0.5$, $\omega_z=0.02$, a=0.5 μm and Δ_1=1 μm [12,15] the magnitude of σ is about 250MPa. This value is in excellent agreement with the experimental magnitude for threshold stress.

Secondly, hot plastic deformation at the steady state occurs through the Nix-Ilschner model [10,14,16]. The latter model [16] considers deformation as superposition of two independent mechanisms. Dislocation motion in the hard region (i.e. fragmental boundaries) occurs by diffusion-controlled recovery and is described by the power law:

$$\dot{\varepsilon}_h=3000(DGb/kT)(\sigma/G)^4 \quad (3)$$

where $\dot{\varepsilon}_h$ is the strain rate in the hard region, D is the diffusion coefficient, k is the Boltzmann's constant, T is the temperature. In the soft region (i.e. subgrain interior) the obstacle-limited dislocation glide takes place. It leads to exponential law of deformation:

$$\dot{\varepsilon}_s=0.5\times10^{12}(\sigma/G)^2\exp(-(0.5k_fG_ob^2d-(\sigma-\sigma_b)V^*)/RT) \quad (4)$$

where $\dot{\varepsilon}_s$ is the strain rate in the soft region, R is the universal gas constant, σ_b is the long range back stress. Thus the strain rate, ε, is the sum of two terms (3) and (4) [16]:

$$\dot{\varepsilon}=\dot{\varepsilon}_h+\dot{\varepsilon}_s \quad (5)$$

The relationship between contributions of these two mechanisms to the total deformation determines the phenomenology of plastic flow. The best agreement between experimental data and strain rates that predicted by equations (3) and (4) is observed at $(\sigma-\sigma_b)=0.55\sigma$ and $k_f=0.55$. It is seen that at lower stresses the "fragmental boundaries" mechanism is dominant. This conclusion is supported by the experimental value of the true stress exponent n=4 at t=600°C. The change of deformation mechanism operating in hard region (i.e. grain boundaries of dislocation origin) is a cause of an effective stress reduce with decreasing the temperature.

Climb of dislocations along fragmental boundaries results in their transformation to high angle boundaries of a common type. The occurrence of DRX at this temperature is caused by fragmentation at early stage of plastic flow and operation of Nix-Ilschner mechanism at moderate strains. At other temperatures such a combination of the deformation mechanism is absent and DRX does not occur.

At temperature lower than 600°C the deformation is accomplished by intragranual dislocation sliding and described by equation (4). The prevailing of single sliding ceases formation of subgrains. Consequently, the recrystallization nucleates do not appear, and DRX is not observed.

CONCLUSION

Thus it has been shown that the positive temperature dependence of effective stress and abnormal temperature dependence of structural evolution in Cr25 ferritic steel are caused by influence of temperature on mechanisms of plastic flow. The occurrence of fragmentation in the intermediate temperature range initiates a special deformation mechanism consisting in dislocation climb along fragmental boundaries. This results in their transformation to grain boundaries of a common type and formation of recrystallized grains at the steady state.

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