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The kinetics of deformation localization nuclei for the coarse-grained Fe-3%Si alloy

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Abstract

The patterns of localized plastic deformation have been studied experimentally at the stages of linear and parabolic work hardening in the coarse-grained Fe-3%Si alloy. The distinction between the patterns observed at these stages is established and probable explanations are suggested. A scenario of transition from the stable plastic flow to necking and viscous failure via chaos is considered.

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Keywords: Polycrystalline alloy; plasticity; work hardening; localization; failure

1. Introduction

The coarse-grained Fe-Si alloys have been long used for the a study of mechanisms of plastic flow in solids (see, for example, [1-2]) in view of the fact they have a simple single phase structure (substitution solid solution of Si in α–Fe). Our previous investigations of the plastic flow localization [3-5] were performed mainly on FCC materials and there was no reliable evidence for the existence of this phenomenon for BCC materials. To fill the gap, our interest in the present work is focused on the plastic deformation localization in the course of extension of the Fe-3%Si alloy. It is very important that BCC crystals exhibit a lower extent of plasticity relative to FCC materials and the dislocation cross-slip in such crystals begins earlier [6].

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2. Material and investigation methods

The test specimens were prepared from a Fe-3wt.%Si alloy sheet 0.3 mm in thickness. They were shouldered-end ones and had working part 50×10 mm. After mechanical handling, the specimens were vacuum annealed at 1373 K to relieve the residual stresses. The alloy investigated had grain size of 4.5 ± 3 mm. The specimens were extended with the help of an "Instron-1185" test-machine at the deformation rate, $\dot{\varepsilon} = 6.67 \cdot 10^{-5}\ \mathrm{s}^{-1}$ and the temperature, T = 300 K. In order to divide the plastic flow curve $\sigma(\varepsilon)$ into stages with respective work hardening laws, true strains $e = \ln(1+\varepsilon)$ and stresses $s = \sigma(1+\varepsilon)$ [6] were used.

The analysis of the flow curves represented in the co-ordinates $\ln s - \ln e$ shows that the parabolic stage equation has the form

$$s = s_0 + K_i e^{n_i} \tag{1}$$

where s_0 = 465 MPa is the yield point, K_i – the work hardening coefficient, n_i - the parabola exponent (Fig. 1).

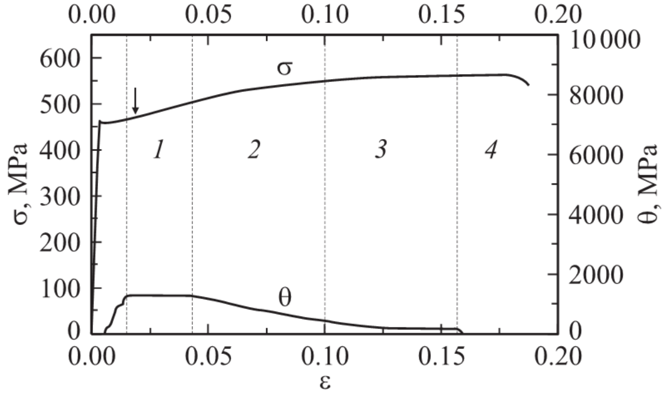

Fig. 1. The flow curve $\sigma(\varepsilon)$ and work hardening coefficient $\theta(\varepsilon)$: linear stage (1) with parabola exponent $n_1 \approx 1$, parabolic stages (2 and 3) with parabola exponent $n_1 \approx 0.5$ and $n_2 \approx 0.4$ and pre-failure stage (4)

The main method used for the study of plastic deformation localization was speckle interferometry [7]. Its application to plastic flow investigation is described elsewhere [3, 8]. This method allows one to obtain distributions of the plastic distortion tensor components (ε_{xx}, ε_{xy}, ω_z) in the specimen and to analyze their space-time evolution. Traditionally [3-5, 9], we have restricted our consideration to analysis and discussion of the local elongation $\varepsilon_{xx} = du/dx$ where u is the displacement vector component along the axis x. Thus we have investigated the flow process from yield point to failure.

The microscopical analyses of deforming specimens surface have shown that at the beginning of the process plastic deformation was localized in the slip-bands, with three and more slip systems being activated in each grain. The number of the active slip-bands increased during the deformation process.

3. The results and their discussion

The fundamental result of the current study is the following: besides the microlocalization on the slip-bands level there is the macrolocalization of plastic flow developing on the background of elementary acts of plasticity. This is demonstrated in Figure 2, which shows the plastic deformation localization pattern in the specimen. The traditional approach to the explanation of work hardening is based on the microscopic slip band characteristic data. In what follows we demonstrate that the new evidence for the deformation localization at a macroscopic level corresponding to all the stages of plastic flow has to be considered.

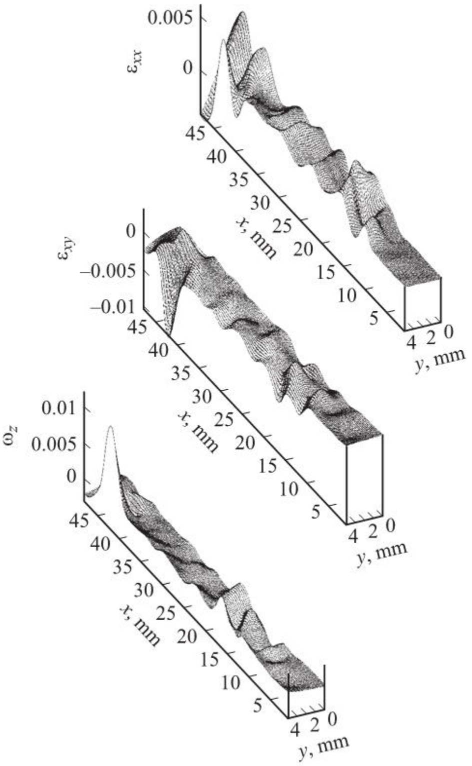

Fig. 2. The ε_{xx}, ε_{xy}, ω_z component distributions in the specimen tested.

First and foremost, the plastic flow curves obtained for the Fe-3%Si specimens contain both linear $\left(s \sim e\right)$ and parabolic $\left(s \sim e^n\right)$ stages. At the parabolic stage the parabola exponent n is not constant; therefore, this stage can be separated into two parts for which $n_1 \approx 0.5$ and $n_2 \approx 0.4$, respectively (Figure 1). At the linear stage the localized deformation nuclei are mobile and at the parabolic stage ($n_1 = 0.5$) they are immobile; however, at $0.5 > n_2 \approx 0.4$ the nuclei begin to travel again but their manner of motion is different from that observed at the linear stage.

To facilitate analysis of the above observations, the experimental data are presented in a graphic form as a dependence of the nuclei co-ordinate X on the deformation time t. Evidently, by active loading of the test specimen $t \sim \varepsilon$. From the dependence shown in Figure 3 follows that

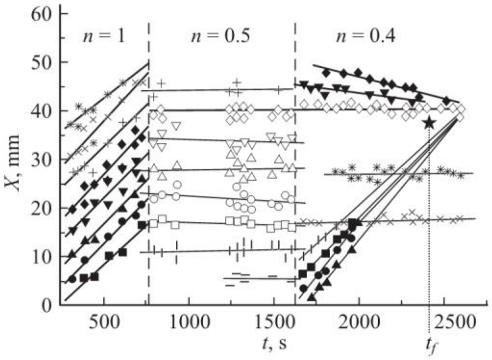

Fig. 3. The kinetics of the motion and merging of localized plasticity nuclei at the final stage of plastic flow.

- at the linear stage ($9\cdot10^{-3} \le e \le 3.8\cdot10^{-2}$) all the nuclei move along the specimen with equal propagation rates, $V_{aw} = dX/dt \approx 1.7\cdot10^{-5}$ m/s, which is confirmed by approximately equal slopes of all the straight lines. At this stage the process is characterized by wavelength, $\lambda = 5.5 \pm 0.5$ mm, i. e. at $s \sim e$ a typical wave pattern arises in the specimen tested and all the localized plastic flow nuclei move consistently;
- over the first part of the parabolic stage $(n_1 = 0.5)$ all the nuclei are immobile and the slope of all the straight lines is close to zero. Apparently, the case $n_1 \approx 0.5$ corresponds to the well-known Taylor-Mott model of work hardening for which $s \sim \sqrt{e}$ [6]. The result obtained here confirms the conclusion made in our previous papers [3-5] that the localized plastic flow nuclei are immobile at this work hardening law;
- over the second part of the parabolic stage $(n_2 = 0.4)$ the straight lines have different slopes; the lines are directed to the center of the bundle having co-ordinates $X^* = 39 \pm 3$ mm and $t^* = 2515 \pm 90$ s. At $n_2 \approx 0.4$ the nuclei move in such a way that the distance between them decreases so that finally they merge together. A similar behavior was observed earlier in the study of Zr-Nb alloy failure [10].

  Thus the motion of the nuclei in case $(n_2 = 0.4)$ is obviously described by the equation

$$X = X^* + V_{aw}^{p} \cdot \left(t - t^*\right) \tag{2}$$

where the value V_{aw}^{p} is either positive or negative depending on the initial position of the localized plastic flow nuclei. The form of the corresponding relationship is unknown so far.

Probably, the issue of special interest in the current work is the coincidence of the coordinates of the center above with the spot and moment of the crack initiation detected at the final stage of testing. The moment of crack initiation is easily detected from the drop of conventional stress on the $\sigma - \varepsilon$ curve. In the light of these findings it is claimed that the plastic flow and failure are related phenomena. Obviously, the spot and moment of liable cracking are defined by the kinetics of localized deformation nuclei before the crack is detected.

Last but not least, the localized deformation pattern changes on a transition to a new flow stage, the old pattern being completely destroyed and a new pattern arising spontaneously in the specimen (see Figure 3). One can say with confidence that the transition parts of the flow curve correspond to a chaotic distribution of elementary shears in the specimen from which a new ordered pattern originates. This suggests that the fundamental ideas of synergetics [11] can be applied to plastic deformation description as proposed in [3-5].

4. Conclusion

Plastic flow and viscous failure of solids is an indivisible continuous process of generation and evolution of localized deformation nuclei. The type of localization pattern corresponds to the work hardening law acting at the given plastic flow stage. The final stage of the process is the merging of nuclei on the spot of crack initiation.

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