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APPLIED PROBLEMS OF STRENGTH AND PLASTICITY

Nanoscale Localization of Plastic Deformation in Steel with a Bainitic Structure

Yu. F. Ivanov[a, b, *], **V. E. Gromov**[c, **], **A. M. Glezer**[d], **E. N. Nikitina**[c], **and K. V. Aksenova**[c]

[a] *Institute of High-Current Electronics, Siberian Branch, Russian Academy of Sciences, pr. Akademicheskii 4, Tomsk, 634021 Russia*

[b] *National Research Tomsk Polytechnic University, Tomsk, 634050 Russia*

[c] *Siberian State Industrial University, Novokuznetsk, 654007 Russia*

[d] *Bardin Central Research Institute of Ferrous Metallurgy TsNIICHERMET, Vtoraya Baumanskaya 9/23, Moscow, 105005 Russia*

**e-mail: yufi55@mail.ru*

***e-mail: gromov@physics.sibsiu.ru*

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Abstract—Transmission electron microscopy is used to reveal the formation of localized deformation channels on a nanoscale in 30Kh2N2MFA steel subjected to compressive deformation of 40% or more. The channels are found to be located mainly along the interfaces of neighboring bainite lamellae or along grain boundaries. The structure of the deformation channels, their sizes, and the change in their volume fraction with the strain are analyzed.

Keywords: deformation localization, deformation channels, bainite, structure, electron microscopy

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INTRODUCTION

According to modern concepts, the plastic deformation of solids proceeds on several interrelated structural levels, the scales of which are determined by the nature of the structural defects that are responsible for forming [1, 2]. As the choice of scale within the levels and the structural elements that determine plastic deformation at a certain level, the classification division of deformation into structural nano-, micro-, meso-, and macrolevels is conventional.

It was found that plastic deformation always develops nonuniformly and is susceptible to localization on microscopic (dislocation), mesoscopic, and macroscopic levels [3]. The basic laws of macroscopic deformation localization in solids under loading were found using speckle photography. In most cases, the distribution of localization zones is ordered in space and time and the type of localization is determined by the law of plastic flow [1, 2, 4].

Extended deformation localization zones, i.e., deformation channels where the shear that is higher than the average shear in a material by several tens of times is localized, were detected in drawing of low-carbon 08G2S steel [6–8] and during compression deformation of quenched medium-carbon 38KhN3MFA steel [9] under severe (megaplastic [5]) deformation on a nanoscale structural level. Structural states with the elastic curvature of crystals of a few hundred degrees per micron were detected by TEM in nanovolumes several nanometers in size under the conditions of rolling, equal-channel angular pressing, and torsion on a Bridgman anvil [10].

The consideration of a solid body as a hierarchically organized system consisting of 3D crystalline and 2D planar subsystems results in sharp enhancement of the role of the curvature of a crystal structure in describing the behavior of solids in the fields of external actions [11]. All types of deformation defects can be represented in the form of solitons of the curvature of crystal structure, which are generalized wavelike structural carriers of plastic deformation and fracture [12]. The type of deformation defect is determined by the scale level of a curvature soliton. The authors of [13, 14] developed a model to describe the formation of nanostructured states during severe plastic deformation, and this model is based on the consideration of the Kelvin–Helmholtz instability in the nanometer wavelength range.

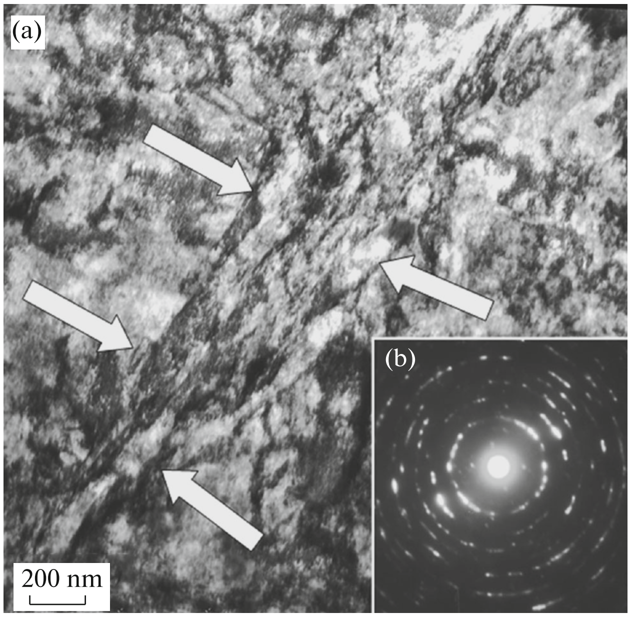

Fig. 1. Deformation channels forming in 30Kh2N2MFA steel with a bainitic structure (ε = 43%): (a) bright-field image and (b) electron diffraction pattern. The arrows in (a) indicate a deformation channel.

The deformation behavior of steels with a bainitic structure, which are widely used in various industries, has recently attracted attention of researchers in the field of physical metallurgy [15–20]. Because of the $\gamma \to \alpha$ transformation, bainitic steels have a complex multiphase structure, which forms as a result of combined shear and diffusion transformation mechanisms [15]. Knowledge of the quantitative laws and the mechanisms of strain hardening of steels with a bainitic structure at high strains makes it possible to control the structure–phase states and the mechanical properties of steel.

The purpose of this work is to detect the localization of plastic deformation at the final stages of deformation and to estimate it in structural steel with a bainitic structure.

EXPERIMENTAL

We studied 30Kh2N2MFA structural steel [21]. The steel was subjected to austenitization at 960°C for 1.5 h and was then air cooled. Samples in the form of a 4 × 4 × 6-mm rectangular parallelepiped were deformed in an Instron tensile-testing machine by uniaxial compression at a rate of $\approx 7 \times 10^{-3}$ s^{-1}. It was convenient to use compression as a deformation technique, since higher strains can be achieved in this case as compared to tension. The structure and the phase composition of the steel were analyzed by transmission electron microscopy of thin foils on an EM-125 microscope [22, 23].

RESULTS AND DISCUSSION

The bainitic transformation is characterized by the formation of a multiphase structure represented by the α and γ phases and iron carbide [15–24]. A lamellar structure forms as a result of the $\gamma \to \alpha$ bainitic transformation. Ferrite crystals have substantially different sizes: the longitudinal sizes change from several tens to several microns, and the transverse sizes change from several microns to several tenths of a micron. Ferrite lamellae are fragmented, divided into regions separated by low-angle boundaries. Deformation of the steel to failure does not change the grain and ferrite lamella sizes and significantly affects the fragment sizes.

At a strain of 36% or higher, localized deformation regions, which are located along the interfaces of neighboring bainite lamellae or grain boundaries, form in the bainitic structure. The structure of these regions is similar to the structure of the channels that form in 08G2S steel during deformation by drawing and in quenched 38KhN3MFA steel during compressive deformation (Fig. 1a) [6–9]. The deformation localization regions have speckled contrast in the dark-field images taken with matrix reflections. As a rule, the electron diffraction patterns taken from these regions consist of quasi-rings (Fig. 1b). This finding points to a small size (50–100 nm) of the crystallites that form these regions and to a predominantly high-angle misorientation of the crystallites. A deformation channel has a layered structure, which resembles the structure of a martensite packet. The deformation localization regions are several tens of microns in length and 0.5 μm in width, and the average deformation channel sizes increase with the strain.

As follows from the electron diffraction patterns, second-phase particles are present in the deformation channel volume. Their reflections are strongly distorted in both radial and azimuthal directions, which can be caused by both lattice distortions and small particle sizes [22, 23]. The electron diffraction patterns taken from the foil regions next to deformation channels are pointlike, which is characteristic of a polycrystalline material. As the strain increases, the material volume occupied by deformation channels grows and reaches a few percent at failure.

The substructure in a deformation channel is also fragmented; however, the fragment sizes are much smaller than in the base material volume. Moreover, the fragments in a deformation channel have an isotropic shape. As follows from the fragment sizes, the shear that is higher than the average shear by several times is thought to be localized in a deformation channel. The difference between the shapes of fragments in the matrix (highly anisotropic fragments) and the deformation channels (isotropic fragments) evidences different mechanisms of their formation. The isotropic shape of fragments in a deformation channel suggests different temperature conditions of their formation. For example, anisotropic fragments can be caused by cold deformation and isotropic fragments, by warm deformation [6–9].

Another specific feature of the structure of deformation channels is related to the behavior of bend extinction contours in them. Note that bend extinction contours indicate regions with the same orientation of certain reflection planes with respect to an incident electron beam [22, 23]. It was found that regions with the one or several close orientations, which are almost parallel to the long side of a channel, are present in a deformation channel and the adjacent areas. From a hydrodynamic standpoint, such regions resemble streamlines during laminar flow [6–9]. This comparison can explain the nature of the deformation channels, since a significant number of regions with turbulent flow usually appears during compression. In particular, the deformation conditions in them are so that the work of deformation in them turns out to be lower than in the neighboring areas. The key role in this case is assumed to be played by local heating of the material [6–9].

The deformation channels are also characterized by significant stress fields localized inside them and the adjacent areas. The following two mechanisms of relaxation of these stress fields were noted in [6–9]. The first mechanism is fragmentation. In this case, chains of small fragments, which have similar orientations and are located along a deformation channel, form. The second mechanism is microcracking. A comparative analysis of the structures of deformation channels in bainitic 30Kh2N2MFA steel, 08G2S steel, and 38KhN3MFA points to the same nature of their formation [6–9].

CONCLUSIONS

The study of the structure of bainitic 30Kh2N2MFA steel subjected to plastic deformation by uniaxial compression at a strain of 36% or higher revealed localized deformation channels in it. These are specific structural zones located along the interfaces of neighboring bainite lamellae or along grain boundaries. These zones are several tens of microns in length and 0.5 μm in width. The deformation channels consist of many phases and have a complex structure formed by 50- to 100-nm crystallites. As the strain increases, the material volume occupied by deformation channels grows and reaches a few percent at failure.

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