ISSN 0036-0295, Russian Metallurgy (Metally), Vol. 2017, No. 10, pp. 871–873. © Pleiades Publishing, Ltd., 2017.
Original Russian Text © E.N. Nikitina, A.M. Glezer, Yu.F. Ivanov, K.V. Aksenova, V.E. Gromov, S.A. Kazimirov, 2016, published in Deformatsiya i Razrushenie Materialov, 2016, No. 12, pp. 34–36.

APPLIED PROBLEMS OF STRENGTH AND PLASTICITY

Evolution of the Structure and the Phase Composition of a Bainitic Structural Steel during Plastic Deformation

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

[a]*Siberian State Industrial University, Novokuznetsk, 654007 Russia*
[b]*Bardin Central Research Institute for Ferrous Metallurgy, Moscow, 105005 Russia*
[c]*Institute of High Current Electronics, Siberian Branch, Russian Academy of Sciences, Tomsk, 634021 Russia*
[d]*Tomsk Polytechnic University, Tomsk, 634050 Russia*
**e-mail: gromov@physics.sibsiu.ru*

Received August 5, 2016

Abstract—The evolution of the phase composition and the imperfect substructure of the 30Kh2N2MFA bainitic structural steel subjected to compressive deformation by 36% is quantitatively analyzed. It is shown that deformation is accompanied by an increase in the scalar dislocation density, a decrease in the longitudinal fragment sizes, an increase in the number of stress concentrators, the dissolution of cementite particles, and the transformation of retained austenite.

Keywords: bainitic steel, structure, phase composition, deformation, defect substructure

DOI: 10.1134/S0036029517100159

INTRODUCTION

Bainitic steels are widely used in the manufacture of rails and high-strength industrial pipes, because of the high strength of bainite due to the small size of ferrite plates, nanosized carbide-phase particles, a high scalar density of dislocations pinned by carbon atoms, and a high level of distortion of the ferrite crystal lattice due to supersaturation with carbon atoms and alloying elements in combination with good weldability and high creep resistance [1–7]. Heat-treatment-induced bainite is the most complex structure for quantitative interpretation. The point is that bainite transforms without diffusion of iron atoms and alloying elements during high-rate carbon diffusion. This causes the formation of phases (α, γ, and carbide) with significantly different carbon contents.

The operation of products, especially under severe conditions, often causes plastic deformation, the transformation of a phase composition, and a defect substructure. Transmission electron diffraction microscopy makes it possible to perform a detailed study of the regularities of such transformations [8]. The aim of this work is to study the evolution of the phase composition and the defect substructure of a bainitic steel subjected to severe plastic deformation.

EXPERIMENTAL

We investigated a 30Kh2N2MFA structural steel [9]. The steel was subjected to austenitization at 960°C for 1.5 h and was then air cooled. Rectangular samples 4 × 4 × 6 mm in dimensions were deformed by uniaxial compression in an Instron testing machine at a rate of ~7×10^{-3} s^{-1}. (Compression is the simplest loading technique since high strains can be achieved.) The structure and the phase composition of the steel were studied by transmission electron microscopy of thin foils cut out from the center of a sample parallel to the longitudinal axis in an EM-125 microscope.

RESULTS AND DISCUSSION

Austenitization of the steel at 960°C for 1.5 h resulted in the formation of a multiphase structure, which included the α phase (bcc solid solution), the γ phase (retained austenite, fcc solid solution), and iron carbide (cementite). The characteristic arrangement of cementite particles with respect to ferrite crystals (at an angle of 55°–60° to the longitudinal axis of the crystal) and the shape of the particles (thin plates) allowed us to classify the formed structure (according to [1, 4, 8, 10]) as lower bainite. Figure 1 shows the structure of the 30Kh2N2MFA bainitic steel.

Deformation causes the transformation of the phase composition and the defect substructure of the steel. The transformation of the phase composition consists in the dissolution of cementite particles: a decrease in the average size of the cementite particles (longitudinal size from 200 to 60 nm, transverse size from 30 to 12 nm) and a decrease in the volume fraction (from 2.1 to 1.5%). Simultaneously, the preferred arrangement of cementite particles changes: the vol-

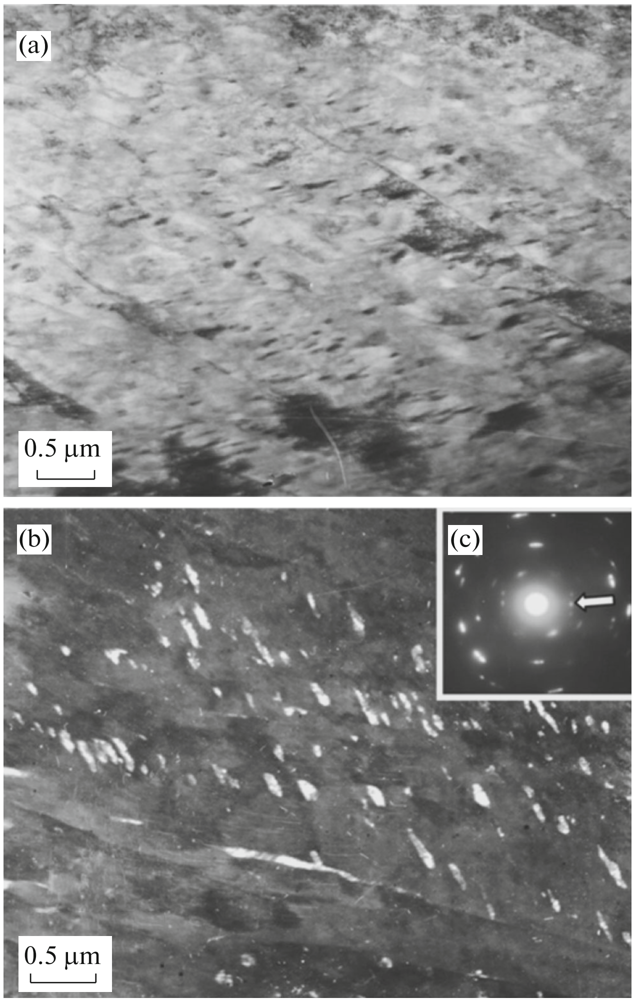

Fig. 1. Microstructure of the 30Kh2N2MFA steel in the initial state (after austenitization at 960°C for 1.5 h): (a) bright-field image, (b) dark-field image taken with the $[031]Fe_3C$ reflection, and (c) electron diffraction pattern (arrow indicates the reflection used to take the dark-field image).

ume fraction of the particles at the boundaries of ferrite plates increases, and spherical-shaped particles appear in the volume of the ferrite plates. In addition, the volume fraction of retained austenite rapidly decreases by 36% during plastic deformation: from 6% in the initial state to 0.5% after deformation.

The transformation of the imperfect substructure of the steel was analyzed by analyzing the structure of the ferrite plates. In this case, ferrite is the main phase of the material. Plastic deformation of the steel was found to increase the scalar density of dislocations [11]. In the initial state, a network dislocation substructure with a scalar dislocation density of ≈7 × 10^{10} cm^{-2} is observed in bainite plates. Deformation by ≈36% increases the scalar dislocation density to ≈1.3 × 10^{11} cm^{-2}. In this case, the type of dislocation sub-

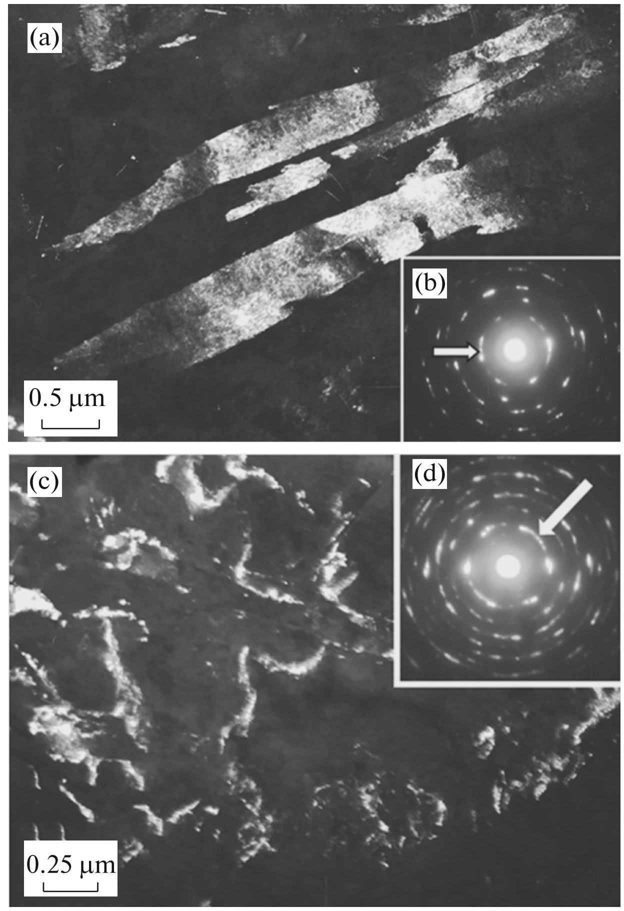

Fig. 2. Microstructure of the 30Kh2N2MFA steel after deformation by 36%: (a, c) dark-field images taken with the $[110]_{\alpha\text{-Fe}}$ reflection; (b, d) electron diffraction patterns to (a) and (c), respectively (arrow indicates the reflection used to take the dark-field image).

structure does not change: a network substructure is retained.

The formation of a substructure with a high scalar dislocation density is accompanied by the fragmentation of ferrite plates, i.e., the division of plates into regions with low-angle misorientations. Deformation decreases the average longitudinal fragment sizes (transverse fragment dimensions are limited by bainite plate boundaries and remain almost the same during deformation) increases the degree of fragment misorientation (Figs. 2a, 2b). In addition to the fragmentation of ferrite plates, deformation of the steel generates internal stress fields, which can be analyzed by studying the change in the shape, the relative arrangement, and the transverse sizes of bending extinction contours (Figs. 2c, 2d) [12–14].

Thus, an increase in the deformation leads to an increase in the density of contours (their number per unit image area) and a decrease in their average transverse sizes. This indicates that an increase in the deformation increases the number of internal stress concentrators and the lattice curvature–torsion amplitude [12–14].

CONCLUSIONS

Quantitative electron-microscopic diffraction analysis of the evolution of the phase composition and the imperfect substructure of a 30Kh2N2MFA steel during plastic deformation by uniaxial compression showed that deformation of bainitic steel is accompanied by an increase in the scalar dislocation density, a decrease in the average longitudinal fragment sizes, an increase in the degree of fragment misorientation, an increase in the number of stress concentrators, an increase in the lattice bending–torsion amplitude, the transformation of retained austenite, and the dissolution of cementite particles.

ACKNOWLEDGMENTS

This work was supported by the Russian Foundation for Basic Research–Kuzbass (project no. 16-48-420530 r_a).

REFERENCES

1. H. K. D. H. Bladeshia, *Bainite in Steels* (Inst. Mater., London, 2001).
2. G. R. Purdy and M. Hillert, "On the nature of bainite transformation in steels," Acta Met. **32** (6), 823–828 (1984).
3. G. R. Purdy, "Bainite: defect signatures," Scr. Mater. **47** (3), 181–185 (2002).
4. D. A. Mirzoev, K. Yu. Okishev, V. M. Schastlivtsev, et al., *Bainitic Transformation in Steels/Phase and Structural Transformations in Steels*, Ed. by V. N. Urtsev, (ITTs Ausfer, Magnitogorsk, 2002).
5. F. B. Pikering, *Physical Metallurgy and the Development of Steels* (Metallurgiya, Moscow, 1982).
6. Yu. I. Matrosov, D. A. Litvinenko, and S. A. Golovanenko *Steel for Main Gas Pipeline* (Metallurgiya, Moscow, 1989).
7. V. V. Pavlov, L. A. Godik, L. V. Korneva, N. A. Kozyrev, and E. P. Kuznetsov, "Railway rails made of bainitic steel," Metallurg, No. 4, 51–53 (2007).
8. L. M. Utevskii, *Diffraction Electron Microscopy in Metal Science* (Metallurgiya, Moscow, 1984).
9. M. V. Pridantsev, L. N. Davydova, and A. M. Tamarina, *Structural Steels: A Handbook* (Metallurgiya, Moscow, 1980).
10. V. G. Kurdyumov, L. M. Utevskii, and R. I. Entin, *Transformations in Iron and Steel* (Nauka, Moscow, 1977).
11. V. E. Gromov, E. N. Nikitina, and Yu. F. Ivanov, "Evolution stages of carbide and defect steel subsystems with bainite structure under deformation," Probl. Chernoi Metall. Materialoved., No. 3, 49–56 (2015).
12. N. A. Koneva and E. V. Kozlov, "The nature of substructural hardening," Izv. Vyssh. Uchebn. Zaved., Ser. Fiz., No. 8, 3–14 (1982).
13. N. A. Koneva, E. V. Kozlov, L. I. Trishkina, and D. V. Lychagin, "Long-range stress fields, bend–twist of the crystal lattice, and the stages of plastic deformation. Methods of measurement and results," in *Proceedings of International Conference on New Methods in Physics and Mechanics of a Deformable Solid* (Tomsk Gos. Univ., Tomsk, 1990), pp. 83–93.
14. Yu. F. Ivanov, E. V. Kornet, E. V. Kozlov, and V. E. Gromov, *Quenched structural steel: structure and strengthening mechanisms* (Izd. SibGIU, Novokuznetsk, 2010).

Translated by T. Gapontseva