

Redistribution of Carbon in the Deformation of Steel with Bainite and Martensite Structures

K. V. Aksenova^{a, *}, V. E. Gromov^{a, **}, Yu. F. Ivanov^{b, c, ***},
E. N. Nikitina^{a, ****}, and D. A. Kosinov^{a, *****}

^aSiberian State Industrial University, Novokuznetsk, Russia

^bTomsk Polytechnic University, Tomsk, Russia

^cInstitute of High-Current Electronics, Siberian Branch, Russian Academy of Sciences, Tomsk, Russia

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

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

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

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

*****e-mail: kosinov.dima@rambler.ru

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Abstract—Recent years have been marked by considerable increase in the use of high-strength steel—especially martensitic and bainitic steel—for the manufacture of key industrial components and structures. The high strength depends on strain hardening of the steel. It is important to understand the strain hardening of steel of different structural classes with active plastic deformation, in order to ensure specified structural and phase states and mechanical properties. In the present work, by transmission electron-diffraction microscopy, the evolution of the structure, the phase composition, and the state of the defect substructure is compared for steel samples with martensite and bainite structure in active plastic deformation to failure. After austenitization at 950°C (1.5 h) and subsequent quenching in oil (for 38KhN3MFA steel) and cooling in air (for 30Kh2N2MFA steel), multiphase structure (α phase, γ phase, and cementite) based on packet martensite (38KhN3MFA steel) and lower bainite (30Kh2N2MFA steel) is formed. Quantitative results for the structural parameters of steel in plastic deformation permit analysis of the distribution of the carbon atoms in the structure of the deformed steel. The points of localization of carbon atoms in the martensite (quenched 38KhN3MFA steel) and bainite (air-cooled 30Kh2N2MFA steel) are identified. Deformation of the steel is found to be accompanied by the destruction of cementite particles. For quenched martensitic steel, the total quantity of carbon atoms in the solid solution based on α and γ iron is reduced, while their content at structural defects is increased. The redistribution of carbon atoms in the bainitic steel with increase in the strain involves the increase in the quantity of carbon atoms in the α iron, defects in the crystalline structure, and cementite at the intraphase boundaries; and the decrease in the content of carbon atoms in the cementite particles within the bainite plates and the γ iron.

Keywords: high-strength steel, bainite structure, martensite structure, carbon atoms, localization, deformation, defects

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The redistribution of carbon and alloying elements in plastic deformation helps to determine the structure and phase states of steel. The carbon in steel may be present in a solid solution based on α or γ iron, at dislocations, at phase boundaries and intraphase boundaries, and in carbide particles, as shown in [1–7]. The quantity of carbon in the α and γ solid solutions is usually estimated in terms of the relative change in the lattice parameter [8–10]. The quantity of carbon in carbide particles is estimated on the basis of the chemical composition of the carbide, the type of crystal lattice, and the volume content of carbide particles in the steel [11]. The quantity of carbon at defects is very difficult

to estimate, and practically no direct experimental data are available [2, 7].

Martensite and bainite are the most complex structures formed in steel on heat treatment; their quantitative interpretation is correspondingly difficult. Quantitative knowledge regarding the formation and evolution of the carbon distribution in martensite and bainite permits the regulation of the structural and phase states and defect substructure of the steel and ultimate control of its mechanical properties.

In the present work, we analyze the redistribution of carbon atoms in the structures of martensitic and bainitic steel on deformation.

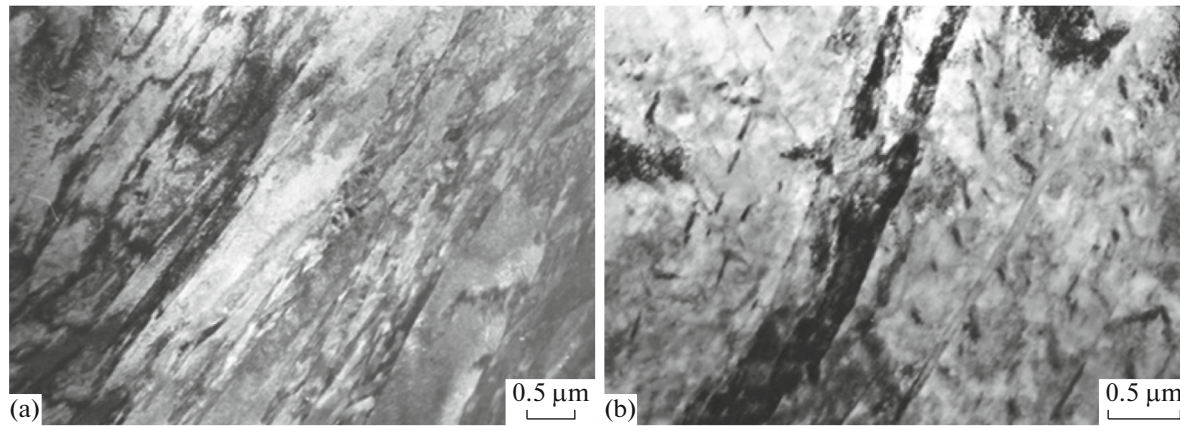


Fig. 1. Transmission electron-microscope image of packet martensite in 38KhN3MFA steel (a) and lower bainite in 30Kh2N2MFA steel (b).

We investigate 38KhN3MFA and 30Kh2N2MFA structural steel [12]. The steel is austenitized at 950°C for 1.5 h. Then 38KhN3MFA steel is quenched in oil to martensite; and 30Kh2N2MFA steel is cooled in air to form bainite structure. The steel is deformed at an Instron-1185 test machine by uniaxial compression of $4 \times 4 \times 6$ mm pegs at a rate of about $7 \times 10^{-3} \text{ s}^{-1}$. The structure and phase composition of the steel are determined by electron-diffraction microscopy of thin foil [13, 14].

Martensitic and bainitic transformations in the steel give rise to a multiphase structure, with the following main components: α phase (a solid solution based on a bcc lattice); γ phase (residual austenite with a solid solution based on an fcc lattice); and iron carbide (cementite in low- and moderate-carbon steel) [15–17].

After heat treatment, we note primarily packet martensite in 38KhN3MFA steel [17, 18]; and lower bainite in 30Kh2N2MFA steel (Fig. 1) [19, 20].

Previous electron-microscopic research revealed the behavior of the steel's structure and phase composition [17–20]. In 38KhN3MFA steel, the longitudinal dimensions of the martensite fragments are

decreased with increase in the strain. In addition, we note increase in the density of microtwins, the scalar and excess dislocation density, the linear density of flexural extinction contours, and the amplitude of the long-range stress fields. The phase composition of the quenched 38KhN3MFA steel changes in the course of deformation on account of conversion of the residual austenite.

In 30Kh2N2MFA steel, likewise, the longitudinal dimensions of the martensite fragments are decreased with increase in the strain. We again note increase in the density of microtwins, the scalar and excess dislocation density, the linear density of flexural extinction contours, and the amplitude of the internal long-range stress fields. These processes result in the formation of regions with critical substructure inclined to microcrack formation, with subsequent sample failure.

Carbon may occupy the following positions in the steel, as established in [19, 20]: in carbide particles, in a solid solution based on α or γ iron, or at structural defects (dislocations, subboundaries, phase boundaries, and intraphase boundaries). The quantity of carbon in each location may be estimated by means of the following formulas:

Position of carbon	Approximate formula	Source
Solid solution based on α iron	$\Delta C_{\alpha} = \Delta V_{\alpha} = \frac{a_{\alpha} - a_{\alpha}^0}{39 \pm 4} 10^3$	[8]
Solid solution based on γ iron	$\Delta C_{\gamma} = \Delta V_{\gamma} = \frac{a_{\gamma} - a_{\gamma}^0}{44} 10^3$	[10]
Carbide particles	$\Delta C_{ca} = \Delta V_{ca} k;$ $k(\text{Fe}_3\text{C}) = 0.07$	[11]
Structural defects	$\Delta C_{de} = C_0 - (\Delta C_{\alpha} + \Delta C_{\gamma} + \Delta C_{ca})$	[12]

Here ΔV_{α} , ΔV_{γ} , and ΔV_{ca} denote the volume fractions of α and γ iron and carbides, respectively; a_{α} and a_{γ} denote the lattice parameters of the α and γ phases; $a_{\alpha}^0 = 0.28668 \text{ nm}$; $a_{\gamma}^0 = 0.3555 \text{ nm}$; and c_0 is the mean carbon content in the steel.

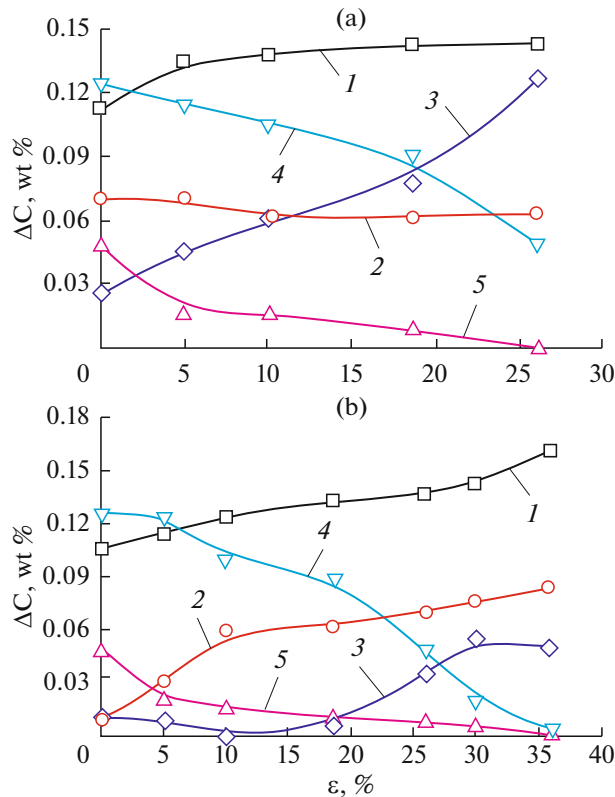


Fig. 2. Influence of the strain ϵ on the concentration of carbon atoms in the structure of quenched (martensitic) 38KhN3MFA steel (a) and 30Kh2N2MFA steel (b) with bainite structure: (1) in the α iron lattice; (2) in Fe_3C particles at intraphase boundaries; (3) at structural defects; (4) in Fe_3C particles within martensite packets and bainite plates; (5) in the γ iron lattice.

Note that the quantity of carbon concentrated in the crystal lattice of cementite is estimated on the assumption of a stoichiometric composition of the phase. In Fig. 2, we present estimates of the quantity of carbon concentrated in different positions of the steel structure.

The deformation of quenched 38KhN3MFA steel is accompanied by the solution (disintegration) of cementite particles [18]. With increase in the strain ϵ , the total quantity of carbon atoms in the solid solutions based on α and γ iron declines, while the quantity of carbon atoms at structural defects increases. The transfer of carbon atoms to defects is especially vigorous when $\epsilon \geq 0.2$.

The results show that, with increase in the strain of bainitic steel, we note larger quantities of carbon atoms in the solid solution based on α iron (Fig. 2b, curve 1), in carbide particles at intraphase boundaries (Fig. 2b, curve 2), and at lattice defects (Fig. 2b, curve 3). We note smaller quantities of carbon atoms in cementite particles within the bainite plates (Fig. 2b, curve 4) and in the solid solution based on γ iron (Fig. 2b, curve 5). Thus, the plastic deformation of bainitic steel is asso-

ciated with significant redistribution of the carbon atoms. Whereas most of the carbon atoms are concentrated in the cementite particles initially, most of the carbon atoms are in the crystal lattice based on α iron in the final stage of deformation.

CONCLUSIONS

The deformation of martensitic steel is accompanied by the destruction of cementite particles. The carbon atoms released pass to the solid solution based on α iron and to structural defects of the steel.

In bainitic steel, increase in the strain is associated with increase in the quantity of carbon atoms in the α iron, defects in the crystalline structure, and cementite particles at the intraphase boundaries; and decrease in the content of carbon atoms in the cementite particles within the bainite plates and in the solid solution based on γ iron.

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