NANOSIZE PHASES FORMATION UNDER LOW CARBON STEEL THERMOMECHANICAL STRENGTHENING

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ABSTRACT

The quantitative regularities of structure phase states formation in different H-beam cross sections under accelerated cooling in different regimes are established. The gradient structure-phase states formation being characterized by the regular change of dislocation substructure parameters, nanosized range α-phase fragments and cementite particles on cross section are revealed by methods of transmission electron diffraction microscopy.

Key words: structure-phase states, dislocation substructure, strengthening, H-beam

INTRODUCTION

Currently, the production of rolled steel uses thermo-mechanical hardening technology, providing enhanced mechanical properties without the use of expensive alloying additives [1-3]. Targeted management of the rolled steel operational properties, and development of optimal modes of its hardening should be based on knowledge of the structure-forming process under various technological operations [1-3].

The aim of this study was to investigate the formation of nanosize structural-phase states of 09G2S steel H-beam subjected to thermomechanical strengthening (accelerated cooling).

MATERIALS AND METHODS

Temperature-speed parameters of rolling and accelerated cooling of two technological options are presented in *Table. 1*. As the research material we used H-beam DP155 made from 09G2S steel (0.095 wt. % C, 1.560 wt. % Mn, 0.660 wt. % Si).

Analysis of structure phase states and dislocation structures were performed by transmission electron microscopy of thin foils on the different distances from cooling surface.

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Table 1. The modes of accelerated cooling

Mode Number	Rolling speed, V, m/s	T, ºC			Water pressure at water supply, atm				
					I		II		I
		after 3rd roll stand	after 9th roll stand	when entering the cooler	1b	2t	3b	4t	1m
P1	4.5	1050 - 1150	1040 - 1080	690-730	1.5	1.5	2.5	2.5	3.5
P2	6.0	1050 - 1160	1060 - 1100	800-850	1.5	1.5	2.5	2.5	3.0

The plates with thickness of 0.3 mm were cut out from the segment parallel to the inner surface of the profile of the H-beam at a distances of 4, 7 and 10 mm from the surface cooling, and in addition, the layer structure, directly adjacent to the cooling surface was analyzed.

The diffraction analysis with the dark-field technique and subsequent indexing of microelectron diffraction pictures was used for identification of the phases. The images of material's fine structure (bright-field image) were used to classify the morphological features of the structure; determine the size, the volume fraction and the localization of the particles of the second phases; measure the scalar ρ dislocation density [4, 5].

RESULTS AND DISCUSSION

Thermostrengthening of the 09G2S steel of the H-beam performed on the device of accelerated cooling according to regimes P1 and P2, leads to the formation of a multilayer (surface, transitional and central layers) of the microstructure of the H-beam profile. The structure of the stele in the transition layer and the central zone of the shelve under these cooling conditions resulted from the transformation according to diffusion mechanism, and consists of ferrite, perlite, a "degenerate" pearlite and carbide precipitates along the ferrite grain boundaries. The structure of the surface layer is formed as a result of the intermediate (regime P2) and shear (regime F1) mechanisms of $\gamma \Rightarrow \alpha$ transformation, followed by "self-tempering" process. Quantitative characteristics of the surface (hardened) layer, reflecting the most significant effect of hardening regime on the substructure of steel and identified according to the results of electron microscopic studies are presented in *Table. 2*.

Accelerated cooling of the surface is accompanied by formation of the gradient of the structure phase states. Quantitative relationships that characterize the gradient nature of the organization of the defect substructure of H-beam subjected to forced water cooling are shown in Fig. 1.

Table 2. Quantitative characteristics of the structure of the 09G2S steel hardened layer

Process mode	The parameters of the structure							
	ΔV_1	d_1, μm	ρ_1, 10^{10} cm^{-2}	ΔV_2	d_2, μm	ρ_2, 10^{10} cm^{-2}	$<\rho>$, 10^{10} cm^{-2}	$<d>$, μm
P1	0.9	0.2	5.0	0.1	0.5	2.8	4.78	0.23
P2	0.6	0.3	4.8	0.4	0.5	3.6	3.84	0.38

Note: ΔV_1, ΔV_2 - the volume fraction of lamellar (martensite or bainite) and subgrain type, respectively; d_1, d_2 - the average transverse sizes of plates and subgrains, respectively; ρ_1, ρ_2 - the scalar density of dislocations arranged in plates and subgrains, respectively; $<\rho>$ - the average scalar density of dislocations in the layer (taking into account the types of structures); $<d>$ - the average size of the substructure in the layer (taking into account the types of structures).

Analysis of the results presented in this figure confirms the conclusion about the gradient nature of the defected substructure. Namely, the closer to the cooling surface the scalar density of dislocations in the ferrite grains (*Fig. 1*, curve 2) and ferritic interlayers of pearlite grains (*Fig. 1*, curve 1), are increasing and the average size of fragments of the ferrite (*Fig. 2*, curve 1) and particle size of cementite (*Fig. 2*, curve 2) are reducing.

It can be seen that in the surface layer of H-beam the state is formed, which based on the average size of fragments of α-phase and cementite particles can be regarded as a nanostructure.

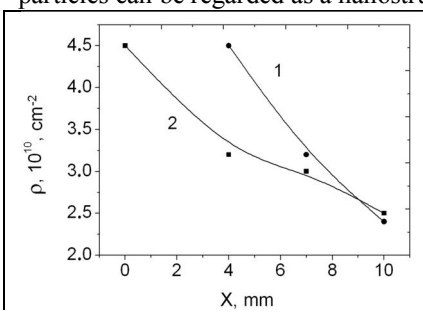

Fig. 1 – Dependence of the scalar density of dislocations located in the ferrite component of the pearlite grains (curve 1) and ferrite grains (curve 2) on the distance to the surface of treatment

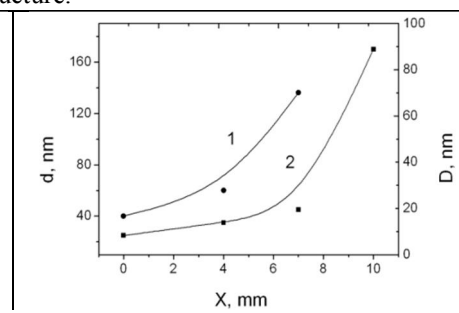

Fig. 2 – Dependence of the cementite fragments average size (curve 2) and ferrite fragments D average size (curve 1) on the distance to the surface of treatment

Formation of nanostructured phases during thermomechanical hardening

Analysis of the results presented above gives us grounds to conclude that the formation of nanoscale phase in the studied steel under thermomechanical processing and subsequent accelerated cooling of rolled products is possible with the implementation of such a processes. First, by dispersing of pearlite cementite plates colonies by cutting them by moving dislocations. Secondly, in

the process of dissolution of pearlite colonies cementite plates and repeated precipitation of cementite particles on the dislocations, the boundaries of blocks, subgrains and grains. Third, during the decay of solid solution of carbon in the α-iron, formed under the conditions of accelerated cooling of the steel ("self-tempering" martensite). Fourth, when during the final transformation of the retained austenite in the structure of carbideless beinite with the formation of α-iron and cementite particles. Fifth, in the implementation of the diffusion mechanism of $\gamma \Rightarrow \alpha$ transformation under the conditions of high degree of deformation and high temperature treatment.

Dispersion of the pearlite colonies cementite plates by cutting them by moving dislocations

Fig. 3 shows electron microscopy images of the pearlite colony, the cementite plates which are divided into separate fragments (the blocks). Sizes of fragments vary from 5 to 30 nm. Simultaneously, cementite particles are found in ferritic interlayers of the pearlite colony, the sizes of whose particles vary from 5 to 10 nm (Fig. 3, the particles are indicated by arrows).

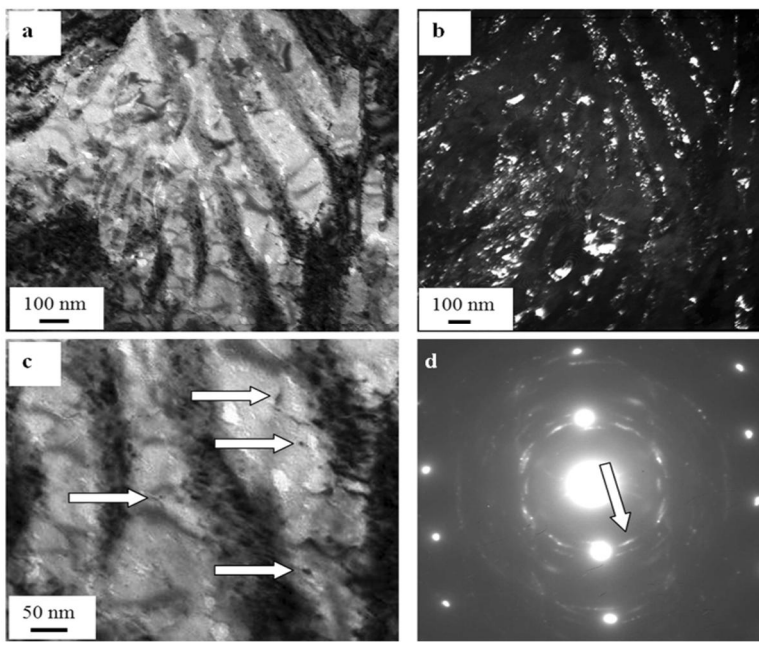

Fig. 3 – The fragmentation of the cementite plates of perlite grains, a, c – light-field image, b - dark field image obtained in the reflection [121] Fe_3C; d - electron diffraction pattern image, the arrow indicates the reflection, in which a dark field image was obtained. On c) the arrows indicate cementite particles located in the plates of ferrite

Nanoscale range of the cementite structure of given pearlite colony is confirmed by quasicircular construction of the electron diffraction image derived from this plot foils (Fig. 3, d). Presented micrographs of the steel structure suggest that the thermomechanical processing is accompanied not only by mechanical destruction of the plates of cementite, but also their dissolution of with the departure of the carbon atoms on the dislocation and the subsequent precipitation in the body of ferrite plates.

Dispersion of the cementite plates may be accompanied by the formation of the block (subgrain) structure (*Fig. 4*). The newly evolved cementite particles in such a structure are located at block boundaries, stabilizing their sizes.

Dissolution of cementite plates of the pearlite colonies and repeated precipitation of the cementite particles on the dislocations, the boundaries of the blocks, subgrains and grains

Removal of carbon atoms from destructed particles of cementite is possible and even at much greater distances. Studies of the block (subgrain) structure of α-iron grains by methods of dark-field analysis revealed the cementite particles in the body of the blocks on the dislocations and block boundaries (*Fig. 5*). Particles have a rounded shape, particle sizes vary from 5 to 15 nm.

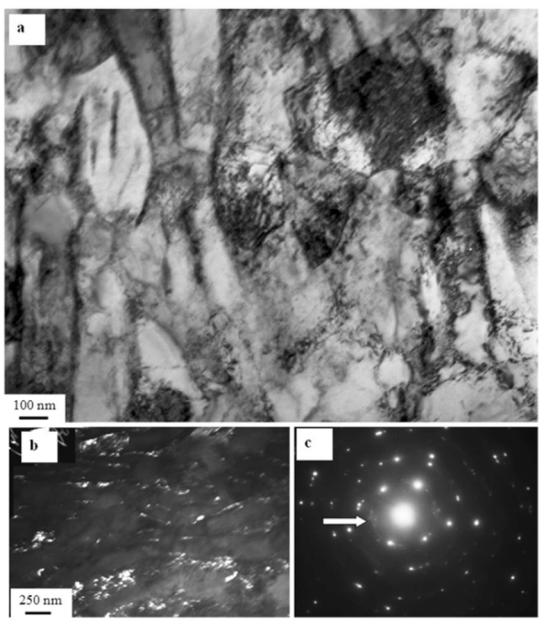

Fig. 4 – The formation of a subgrain structure of the steel and fragmentation of the pearlitic grain cementite plates a - light-field image, b - dark field image obtained in the reflection [121] Fe_3C; c - electron diffraction pattern image, the arrow indicates the reflection, in which a dark field image was obtained

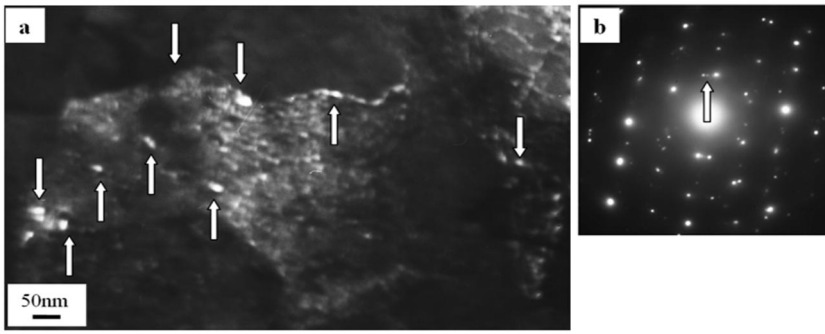

Fig. 5 – Precipitations of second phase particles (cementite) within the body and at the boundaries of α-phase subgrains: a - dark field image, obtained in the reflections [012] Fe_3C + [110] α-Fe (particles indicated by arrows), b - electron diffraction pattern image, the arrow indicates the reflection, in which a dark field image was obtained.

The decay of solid solution of carbon in the α-iron, formed under the conditions of accelerated cooling of steel ("self-tempering" of martensite)

Accelerated cooling of the H-beam leads to the formation of the martensitic structure in the surface layer. Subsequent "self-tempering" of the steel under the influence of the residual heat is accompanied by relaxation of the dislocation substructure, which manifests itself in reducing the scalar density of dislocations, the destruction of low-angle boundaries of martensite crystals, precipitation on dislocations within the body of martensite crystals (*Fig. 6a*) and along the boundaries of cementite particles (*Fig. 6b*). The sizes of particles located on dislocations, vary between 5 ... 10 nm (*Fig. 6a*), located on the borders - in the 10 ... 30 nm range.

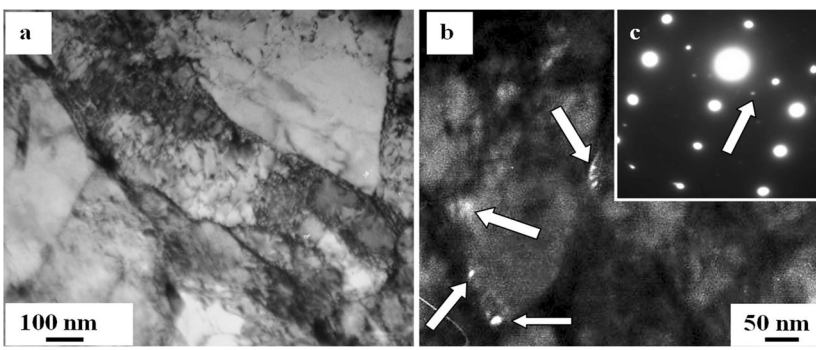

Fig. 6 – The microstructure of the hardened layer of the H-beam, cooled by P1 regime, a - bright-field image, b - dark field image obtained in the reflection [120] Fe_3C; c - electron diffraction pattern image, the arrow indicates the reflection, in which a dark field image was obtained. On (b) the arrows indicate cementite particles.

Formation of cementite particles during the process of complete transformation of retained austenite presented in the structure of carbideless bainite

In the surface layer of the steel sample cooled according to P2 regime, along with grain-subgrain structure the structure of plate type, the so-called carbideless bainite was observed. As shown above, the plates are arranged parallel to each other and there was an alternation of plates of light and dark contrast. Microdiffraction analysis of these structures revealed the presence of only the reflections of α-phase. Reflections of the retained austenite and carbide phase particles are not detected. At the same time, mottled contrast reminiscent of the contrast from the pre-precipitates of second phase particles (*Fig. 7*) is revealed within the structure of the darker plates (formed, presumably as a result of the process of complete transformation of residual austenite).

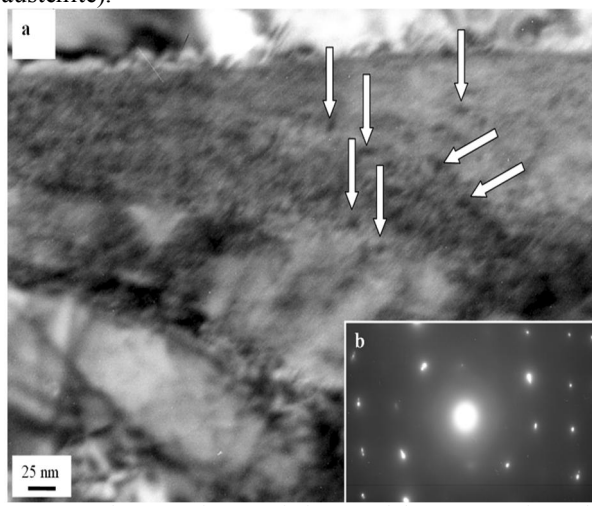

Fig. 7 – Electron microscopic image of the structure formed at the transformation of the residual austenite; a - light field image, b - electron diffraction pattern image of (a). Arrows indicate pre-precipitates of second phase particles

Formation of nanosize phases as a result of polymorphic $\gamma \Rightarrow \alpha$ transformation

The high level of steel plastic deformation, which is realized by thermomechanical processing of rolled products, leads to dispersion of structures formed in the process of diffusion of the $\gamma \Rightarrow \alpha$ transformation. *Fig. 8* shows electron microscopy images of the structure of lamellar pearlite. The measurements show that the thickness of plates of α-phase, separated by the plates of carbide, is about 70 nm; the thickness of the plates of the carbide phase of ~ 25 nm.

Formation of nano-sized particles of the carbide phase, is also observed in the formation of the so-called pseudoperlite, namely ferrite grains, containing particles of cementite of globular morphology (Fig. 9). The sizes of particles of cementite in these grains vary in the range 40 ... 60 nm.

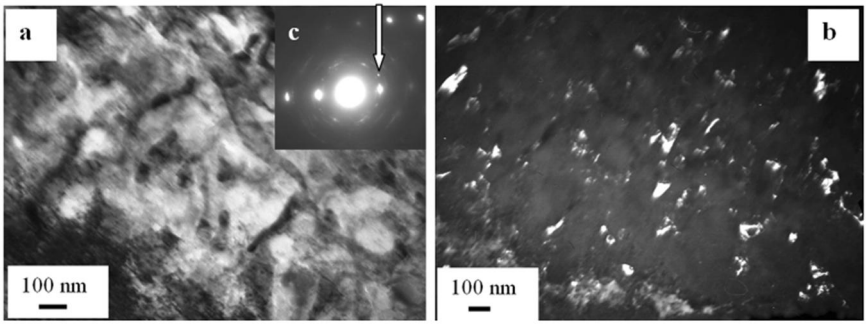

Fig. 8 – Electron microscopic image of the structure of the lamellar (plate) perlite: a – light field image, b - dark field image obtained in [021] Fe_3C the reflection; c – electron diffraction pattern image, the arrow indicates the reflection, in which a dark field image was obtained

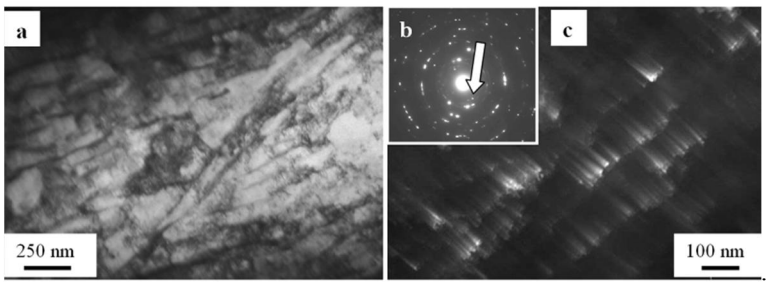

Fig. 9 – Electron microscopic image of the pseudoperlite structure: a – light field image, b - dark field image obtained in the reflection [012] Fe_3C; c - electron diffraction pattern image, the arrow indicates the reflection, in which a dark field image was obtained.

CONCLUSIONS

A study of the H-beam's structure phase states after thermomechanical strengthening was carried out using the methods of transmission diffraction electron microscopy.

The formation of gradient structure, characterized by regular changes of parameters of the structure-phase states and dislocation substructure as it approaches to the surface of the accelerated cooling was revealed. It was established that nanosize structure-phase states are formed in the surface layer.

The analysis of the processes leading to the formation of the structure within the beam profile of 09G2S steel nanoscale phases was carried out.

It is shown that the formation of nanoscale phases was carried out possibly in the implementation of the following processes. First, during dispersing of the cementite plates of pearlite colonies by cutting them by

moving dislocations. Secondly, during the dissolution of pearlite colonies cementite plates and repeated precipitation of the cementite particles on the dislocations, the boundaries of blocks, subgrains and grains. Third, during the decay of solid solution of carbon in the α-iron, formed under the conditions of accelerated cooling of steel ("self-tempering" of martensite). Fourth, during final transformation of the retained austenite in the structure of carbideless beinite with the formation of α-particles of iron and cementite. Fifth, during the implementation of the diffusion mechanism of $\gamma \Rightarrow \alpha$ transformation under the conditions of high degree of deformation and high temperature processing.

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