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Formation of surface layer structure produced by electromechanical strengthening of carbon steels

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1. Introduction

With the development of technologies based on high-energy fluxes, the possibilities of modifying surface structures to obtain unique mechanical and tribotechnical properties were considerably enhanced. High-energy fluxes are usually associated with jets and bunches of low temperature plasma, high-density beams of electrons and ions, focused pulsed and continuous laser radiation with various wavelengths, high-density electric currents, and some others.

Based on the simultaneous thermal and pressure effect on a surface metal layer [1], electromechanical treatment (EMT) is not inferior to other methods of metal treatment by high-energy fluxes in the efficiency and intensity of strengthening and seems to be the most reasonable method for commercial production. This is mainly connected with the simplicity of equipment and, as a consequence, the convenience of introducing this technique into basic technological processes. In addition, EMT is characterized by high efficiency, material and energy savings, and environmental safety [2].

As for the methods of surface strengthening by high-energy fluxes, the structural and metallographic aspects of this effect have been studied comprehensively [3–5]. However, as to electromechanical treatment, similar studies are still necessary; available investigations mainly deal with particular problems of the formation of a surface structure in the course of electromechanical strengthening [1, 6, 7]. The purpose of this study is to analyze and summarize the experimental data on structural and phase transformations in the surface layer of steels during electromechanical strengthening.

2. Experimental

Grade 45 and U8 steels in the as-normalized and as-quenched states were studied. Specimens were electromechanically treated to produce a strengthened surface layer to be examined by the metallographic, electron microscopic, and X-ray diffraction methods.

Electromechanical treatment is realized by applying high-density electrical current (10^8–10^9 A/m^2) and low voltage (2–6 V) across the contact zone between a specimen and deforming electrode–tool (roll or plate) that move in mutually perpendicular directions with velocities v and s, respectively. In this case, due to significant release of Joule heat, high-rate heating of local surface microvolume occurs with its concurrent plastic deformation and subsequent intense cooling because of heat transfer into the metal bulk. As a result of this strong thermal shock, strengthened "white layer" is formed, which represents specific martensitic structure (hardenite) characterized by high strength and wear resistance [1, 3].

The surface of specimens prepared for metallographic examination was polished and etched with a 4% solution of nitric acid in ethanol. The microstructures were photographed using an MIM-3 microscope under magnifications of 100, 200, and 400.

The structures were examined by the replica method using a UEMV-100K electron microscope under magnifications of 6200 and 12000. Specimens were electrically polished in a chloroacetic elecrolyte (1:9). They were also chemically etched in the following reagent: 4 g picric acid+5 ml hydrochloric acid+alcohol added to 100 ml and heated to 50–60°C. The specimen surfaces were then washed in a KOH-saturated aqueous solution, water and a 3% solution of hydrochloric acid in alcohol.

X-ray diffraction analysis was carried out by the photographic method on URS-55 apparatus equipped with RKD-57 camera using the asymmetric scheme of recording, as well as on DRON-3.0 diffractometer using Fe radiation. Reflections (211) were recorded to determine the lattice parameter and tetragonality of martensite; reflections (110) and (220) were used to analyze the characteristics of a fine structure, namely, the microstresses and sizes of mosaic fragments (coherent domains).

3. Results

Metallographic analysis shows that the electromechanical treatment of steels tracks (separate strengthened bands formed due to the tool application) in the heat-affected zone of the surface and, in some cases, isolated fragments of the white layer (for alternative-current EMT). The structure of this white layer is characterized by reduced chemical activity (low etchability) in comparison with the base metal (Fig. 1). This white layer observed optically has no acicular or any characteristic crystal structure and looks like a continuous uniform bright field (Fig. 1).

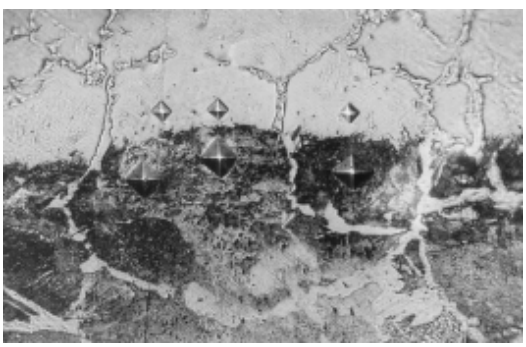

Fig. 1 Micrograph of the interface (×400) between white layer and initial material (normalized grade 45 steel after EMT)

The analysis of transition zone between the strengthened layer and the initial material indicates the formation of a distinct boundary that separates the white layer from the matrix metal inside the same pearlitic grain (Fig. 1).

Electron microscopic analysis indicates that the dispersity of white layer structure is very high. Even using an electron microscope, we failed to observe either a grained or acicular structure. The structure of the strengthened zone looks like a continuous quasi-melted volume with globular inclusions 2×10^{-4}–10^{-6} mm in size (Fig.2, a), which is less than the grain size in the steel subjected to conventional heat treatment by a factor of 2–4 [3–6]. Under large magnifications, we observed extremely fine carbides, which had no time to be dissolved during high-rate heating, and a small amount of islands of retained austenite.

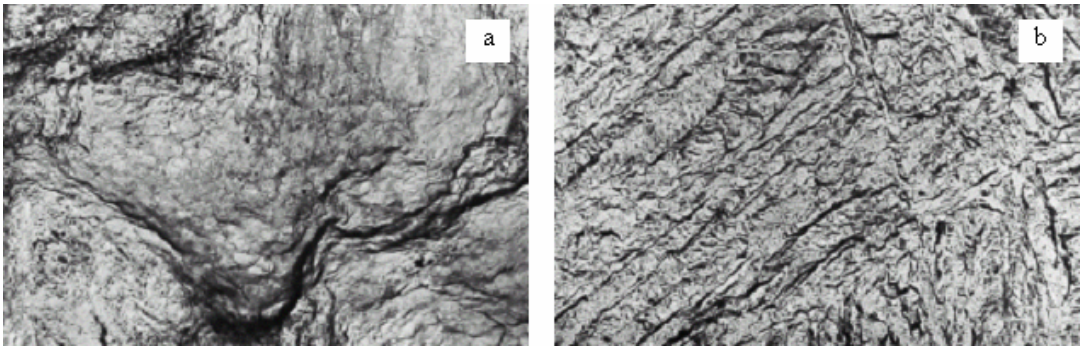

Fig. 2 Electron micrograph: a - of hardenite (×6200) and b - martensite of quenched 45 steel (×12000)

The experimental results obtained clearly indicate the absence of acicular structure in the white layer. Its structure (Fig. 2, a) is dissimilar to acicular martensitic structure (Fig. 2, b). The structure and properties of the white layer physicomechanical, electrochemical, corrosion, and other properties are of the amorphous state of the metal rather than those of structures obtained by conventional quenching [3].

Note that often used interpretation of the structure of white layer as fine martensite is probably incorrect in this case. The absence of zones with fine martensite in the white layer volume indicates either a low cooling rate in this volume or insufficient heat removal and secondary tempering of the white layer with the formation of tempered martensite. In this case, the average microhardness of strengthened zones is higher than the microhardness of fine martensite by 15–20 %, which can also be a criterion that helps to correctly identify the white layer structure.

When electromechanically treated by alternating current (ac), the strengthened track represents a set of separate fragments of white layer, where the formation of each fragment corresponds to a single electrical (thermal) pulse (Fig. 3). A single fragment of the white layer has a shape close to an ellipsoid and is surrounded (as was already noted) by the secondarily heat-affected zone. When the adjacent fragments of the white layer overlap one another, their initial shape is lost because of mutual tempering and repeated quenching for hardenite. As a result, regular discrete macrostructure consisting of separate islands ("flakes") of hardenite is formed at the surface strengthened electromechanically using alternating current (Fig. 3).

In micrographs obtained using REM-200 scanning electron microscope (Fig. 3), visible are (*1*) separate fragments of the white layer that represent a strengthened track and appear due to ac pulse thermal action, (*2*) tempered zones of the prequenched metal, and (*3*) the zones of thermal interaction of neighboring hardenite fragments. Note that these zones do not form (Fig. 4) if martensitic trans-

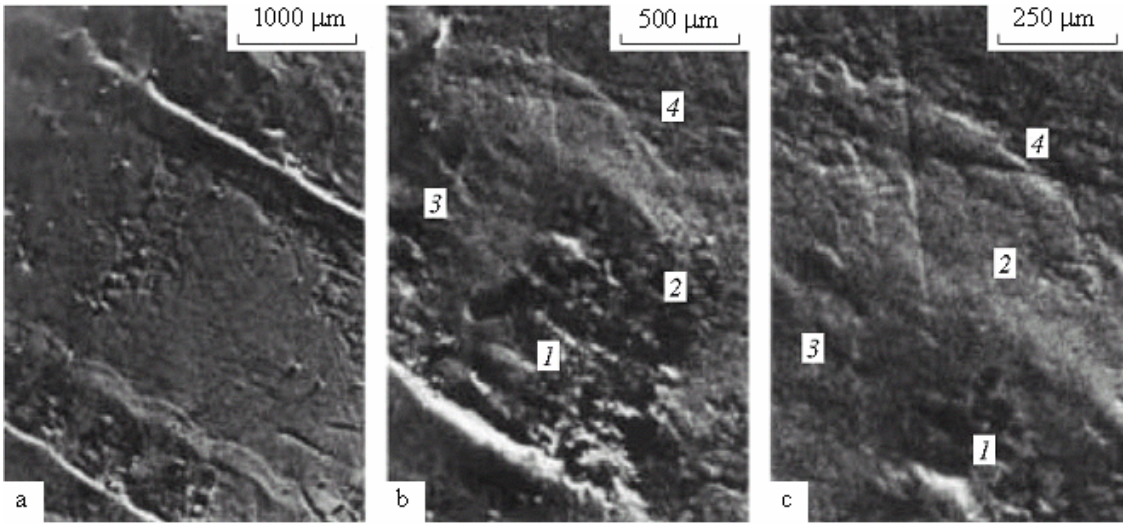

Fig. 3 Micrographs: a–c of neighboring fragments of hardenite and heat-affected zone at the surface of quenched grade 45 steel: *1* - hardenite; *2* - heat-affected zone in the initial structure; *3* - the zone of thermal interaction of neighbor fragments of white layer; *4* - the initial structure (coarse-needled martensite)

formation in previous fragment begins later than the subsequent heat pulse and corresponds to the stage of cooling (quenching) of adjacent volume.

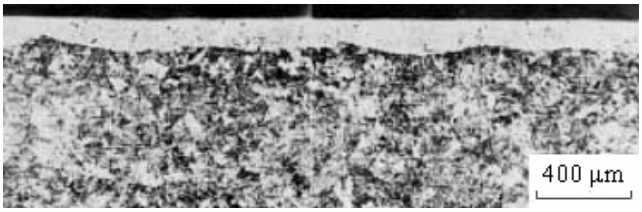

Fig. 4 Micrograph of a longitudinal section of white layer track in normalized grade U7 steel (no zones of thermal interaction of neighbor fragments)

Pay attention to an interesting fact that is shown in the micrographs (Fig. 3). It is seen that, on one side (on the left) of the strengthened track, a bead of metal takes place; its appearance can probably be explained by hot plastic deformation, i.e. by drawing the material from the zone of treatment to the periphery at transverse (with respect to the track of white layer) feed of the strengthening tool.

To understand the nature of the steel structure formed in the zone of strengthening, fine surface structure of grade 45 and U8 steels EMT strengthened in the normalized initial state and that of grade U8 steel after furnace quenching were analyzed by X-ray diffraction. As reference specimens, the above steels in annealed state were used. The results of this detailed comparative analysis are given in Tables 1–3.

The calculation of X-ray diffraction patterns aimed at determining phase composition shows that, in all cases, the material has the lattice of α iron, but differences in interplanar distances indicate the formation of a supersaturated solid solution (martensite). In the diffraction pattern of grade U8 steel treated electromechanically, X-ray diffraction peaks of iron oxides Fe_3O_4 and Fe_2O_3 are also observed. A martensitic doublet was clearly resolved only for grade U8 steel in EMT strengthened zone; in other cases, no splitting of lines was observed.

The lattice parameters of martensite (a and c) were determined using the known method [8]. Carbon content in the martensite of strengthened specimens was calculated by Kurdjumov formulas

$$c = a_0 + 0.118p;\ \ a = a_0 - 0.015p$$

where p is carbon content in the martensite (wt %) and a_0 is the lattice parameter of ferrite, which is equal to 2.8664 Å for carbon steel.

The results obtained (Table 1) show that martensite in the white layer in the EMT strengthened specimens is characterized by higher tetragonality and carbon content in comparison with ordinary quenched martensite. Note that the accuracy of determination of lattice parameters considerably depends on the concentrations of alloying elements in the strengthened zones of the steel. According to [3], Fe_3C carbides and iron oxides Fe_2O_3 and Fe_3O_4 appear in the white layers of carbon steels. Moreover, high carbon concentration and rapid quenching can fix Fe_4C (2.6% C) or Fe_3C hexagonal phase based on ε-Fe, which also has a high carbon content.

Table 1

Specimen*	a, Å	c, Å	c/a	C, %
1	2.856	2.941	1.0296	0.64
2	2.843	3.049	1.0725	1.547
3	2.835	3.114	1.0984	2.097

* Specimen 1 is grade 45 steel treated electromechanically; specimen 2 is grade U8 steel after conventional quenching; specimen 3 is grade U8 steel treated electromechanically.

To determine the characteristics of the fine structure, we used the approximation method [8]. The experimental total broadenings B of the lines (110) and (220) of specimens 1–3 and true intrinsic broadenings β corrected to the instrumental broadening of lines and the presence of doublets are given in Table 2. Analysis of the results obtained shows that X-ray diffraction lines for the specimens subjected to the electromechanical strengthening are characterized by considerable broadening (by a factor of 1.3–4.5) in comparison with not only the annealed steel (reference specimen) but also the martensite produced by furnace quenching. This broadening of the diffraction lines of martensite is generally related with residual microstrains in fine crystal structure (microstresses of the second kind) and with the refinement of mosaic fragments (coherent domains).

Table 2

Specimen*	hkl	B, rad	β, rad
1	110	0.01567	0.00702
	220	0.04680	0.02888
2	110	0.00620	0.00316
	220	0.01787	0.01113
3	110	0.01690	0.01414
	220	0.02420	0.01694

* See the footnote in Table 1.

The microstrain ($\Delta a/a$) and the size of mosaic fragment (D_{hkl}) were calculated by the following formulas, according to the recommendations of [8]

$$D_{hkl} = \frac{0.94\lambda_\alpha}{m\cos\theta};\ \ \frac{\Delta a}{a} = \frac{n}{4\,tg\theta}$$

where m and n are the contributions of the fragment refinement and microstrains to intrinsic broadening of X-ray diffraction pattern, respectively; these values are determined from a set of four equations written for any two lines of X-ray diffraction pattern. In this case, subscripts 1 and 2 correspond to the (110) and (220) lines, respectively:

$$\beta_1 = \frac{(m_1 + 2n_1)^2}{m_1 + 4n_1};\ \ \beta_2 = \frac{(m_2 + 2n_2)^2}{m_2 + 4n_2}$$

$$\frac{m_2}{m_1} = \frac{\cos\theta_1}{\cos\theta_2};\ \ \frac{n_2}{n_1} = \frac{tg\theta_2}{tg\theta_1}$$

Knowing the microstrains $\Delta a/a$ and Young's modulus (E), the microstresses were estimated as

$$\sigma_{II} \approx \frac{\Delta a}{a} E$$

The results given in Table 3 show that EMT strengthening of steels causes considerable refinement of fragments (to 30-40 nm, i.e., by a factor of 2.5 in comparison with the quenched martensite) and a threefold increase in the microstrains in heat-affected zone. In this case, the second kind micro stresses reach high values (250-290 MPa).

Table 3

Specimen*	D_{hkl}, Å	$\Delta a/a$	σ_{II}, MPa
1	404.9	0.001276	255.2
2	751.6	0.000407	81.4
3	307.8	0.001443	288.6

* See the footnote in Table 1.

4. Discussion of the results

The specific features of this white layer are explained by the appearance of peculiar structureless martensite (hardenite) [9–12] characterized by a highly disperse structure, considerable concentration inhomogeneity, and appreciable distortions of crystal structure [3, 9].

The unique properties, finest dispersity, and low etchability of hardenite are due to the specific features of heating and cooling of the material during electromechanical strengthening. This structure has the same nature as martensite. This is a supersaturated interstitial solid solution—the product of allotropic transformation having undergone phase hardening. However, upon hardenite formation, the nucleation of the centers of a new phase is the determining factor due to inhomogeneity, defects, and imperfections of austenite structure; concentration fluctuations; and thermal motion of atoms. The shear mechanisms of growth, which are characteristic of martensitic transformation and represent the cooperative, strongly oriented, and ordered reconstruction of austenite lattice, are suppressed to a considerable degree. Thus, the hardenite formation is caused by concurrent appearance of a large number of martensite nucleation centers (due to extremely fine grains, the concentration inhomogeneity and imperfection of the austenite structure because of intense action of temperature and load) and absence of the possibility for their growth, since it is limited by adjacent nuclei, grain boundaries, and the concentration inhomogeneity of austenite.

As was noted in [9–11], the hardenite formation requires a small size of austenite grains (e.g., produced by short holdings above Ac_1 for fractions of a second), considerable inhomogeneity of austenite (e.g., austenite newly formed in the place of pearlite), and the presence of numerous carbides (or other phases) in austenite. In other words, the hardenite formation, in addition to car-bon-content inhomogeneity, small grain size, and the presence of barriers, also requires an increased carbon content in the initial austenite, which is then inherited by hardenite. In this case, the conditions indicated in [12] contradict in many respects those of the formation of ordinary acicular martensite. Due to high dispersity of hardenite and low size dilatation of its fragments, the surface layer strengthened, in spite of increased chemical inhomogeneity, has not only quasi-uniform mechanical properties but also high corrosion resistance because of the equalization of electron potential between the bulk of a grain and its boundary and between neighbor fragments [12].

5. Conclusions

The results obtained indicate that, upon electromechanical treatment, a specific martensitic structure (hardenite) is formed, which represents the structureless martensite with a number of unique features, such as highest dispersity and the absence of acicular martensitic structure, saturation with carbon and other alloying elements, distortion of crystal structure, high residual microstresses, and so on.

In spite of contradictions in the opinions connected with the properties of white layers and the mechanisms of their formation, it can be concluded that the common characteristic for all white layers is their low etchability and high hardness in comparison with quenched martensite [3].

The low etchability is explained by the formation of the specific structureless martensite (hardenite) in the surface layer, the coherency of interphase boundaries, peculiar concentration inhomogeneity of the structure, its high dispersity, and the presence of carbides and nitrides.

High hardness of white layers is caused by high dispersity of the structure; considerable distortions of the crystal lattice of hardenite; its concentration inhomogeneity; the presence of carbides, nitrides, and oxides; and the change in electron structure and chemical bonds of individual phases because of high temperatures and pressures that take place in the zone of high-energy fluxes.

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ELEKTROMECHANINIAI SUKIETINTO ANGLINIO PLIENO PAVIRŠINIO SLUOKSNIO STRUKTŪROS FORMAVIMAS

R e z i u m ė

Straipsnyje pateikti normalizuoto ir grūdinto anglinio plieno elektromechaniniai sukietinto paviršinio sluoksnio metalografinių, elektroninių mikroskopinių bei rentgenostruktūrinių tyrimų rezultatai. Nagrinėti kai kurie ypatingi medžiagos sukietinto paviršiaus („baltojo sluoksnio“) smulkios struktūros ypatumai, atsiradę didelio energijos poveikio zonoje, esant elektromechaniniam sukietinimui.

V. Bagmutov, N. Dudkina, I. Zakharov

FORMATION OF SURFACE LAYER STRUCTURE PRODUCED BY ELECTROMECHANICAL STRENGTHENING OF CARBON STEELS

S u m m a r y

The results of metallographic, electron microscopic, and X-ray diffraction examinations of the surface layer in normalized and quenched carbon steels strengthened by electromechanical treatment are represented. Some specific features of the fine structure of the strengthened surface layer (“white layer”) formed in the region of high-energy effect upon electromechanical strengthening are considered.

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ФОРМИРОВАНИЕ СТРУКТУРЫ ПОВЕРХНОСТНОГО СЛОЯ ПРИ ЭЛЕКТРОМЕХАНИЧЕСКОМ УПРОЧНЕНИИ УГЛЕРОДИСТЫХ СТАЛЕЙ

Р е з ю м е

Представлены результаты металлографических, электронно-микроскопических, рентгеноструктурных исследований поверхностного слоя нормализованной и закаленной углеродистой стали, упрочненной электромеханической обработкой. Рассматриваются некоторые отличительные особенности тонкой структуры упрочненного поверхностного слоя («белого слоя») материала, полученного в области высокоэнергетического воздействия при электромеханическом упрочнении.

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