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Microhardness of the “white layer” produced by electromechanical strengthening of carbon steels

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1. Introduction

The surface layers of machine elements are known to be subjected to intense mechanical, thermal, wear, corrosion, and other actions. The problem of effective control of the surface layer properties and the formation of a required surface layer structure is related first to the introduction of modern surface hardening technologies and second to metallographic studies and mechanical and micromechanical tests of the hardened surface. Therefore, microhardness measurement is one of the most accurate and sensitive methods for quality control and analysis of the physicomechanical properties of the surface layer and its structural constituents.

Microhardness components of surface layers hardened by various methods of high-energy fluxes became a traditional section in classic monographs [1-4]. However, in the field of electromechanical treatment (EMT), such works give incomplete information. The existing studies mainly deal with some specific aspects of the formation of microhardness in the surface layer during electromechanical hardening [5-8]. The problems posed by the effects of an initial steel structure, preliminary heat treatment (HT), and hardening regimes on microhardness of an EMT-hardened surface are still poorly understood.

The purpose of this work is to analyze and generalize the experimental data accumulated in the field of the microhardness of the surface layer in steels hardened by electromechanical treatment.

2. Experimental

We studied samples of grade 40, 45, and U7 steels in their normalized and quenched initial states. Some quenched samples were tempered from 150, 300, 500, and 700°C for 1 h. The samples were subjected to EMT under different conditions in order to produce a hardened surface layer. The samples had a cylindrical form 10 mm in diameter and 100 mm length. After electromechanical hardening, each sample was sawed in transverse direction to get several 10 mm length samples and then sawed in longitudinal (diametral) direction to produce polished microsections. The samples were normalized at 780°C and water-quenched from 850°C.

EMT is realized when a high-density low-voltage electric current passes through the zone of contact between a workpiece and the instrument, which move in mutually perpendicular directions. This current provides high-rate heating of a surface local volume and it is rapid cooled due to heat removal deep into the metal. As a result, a “white layer” (hardenite), a specific structure with high strength and wear resistance, is formed on the material surface [5, 6, 9]. Electromechanical hardening was performed under the following conditions: the current density in the treatment zone was j=400-450 A/mm^2, the voltage was U=4-5 V, and the treatment speed was v=6-9 m/min. The feed of a hardening electrode-instrument was varied to produce hardening tracks on a metal surface with different inter-track distances.

The microhardness in local volumes of the surface layer was measured on a PMT-3 device at a load of 0.5 and 1 N. The interindentation distance was 20-50 μm. Data on 50 indentations was statistically processed to obtain the average value for one experimental point. Considerable attention has been paid to the preparation of polished sections. A sample was fixed in special set-up and ground to remove almost its half-diameter; then, the surface was thoroughly polished and etched in a 4% solution of nitric acid in ethyl alcohol to reveal its microstructure. This preparation of a polished microsection allowed us to measure microhardness in the immediate edge of the surface and to compare the microhardness of the metal with its structure.

3. Results and discussion

Fig. 1 shows the depth profiles of the microhardness across the surface layer of the EMT-hardened grade 45 steel samples preliminarily subjected to different HTs.

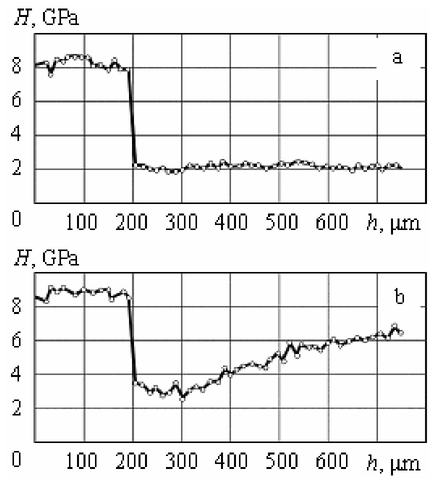

Fig. 1 Depth profiles of the average microhardness in the surface layers of the grade 45 steel samples subjected to EMT after (a) normalization and (b) quenching

The curves show that electromechanical hardening substantially changes physicomechanical properties and microstructure of the near surface layers of the metal and results in the formation of a 200 μm thick white layer with 8-8.5 GPa microhardness. The average microhardness of the hardened grade 45 steel is 3.8 times higher than that of its initial normalized state and 1.5 times higher than of its quenched state (Fig. 1, 2). The average microhardness across the depth of the white layer remains virtually constant, whereas it can be significantly different in the neighboring microvolumes of the white layer. This behavior is likely to be explained by a strongly no-uniform carbon distribution in the hardenite, which can be formed as a result of high-rate HT of steel that has a coarse-grained initial structure. This distribution provides microhardness variation within a grain.

These variations are as high as ~1500 MPa about the average microhardness in the white layer. However, some individual regions can have the hardness *H*=3500 MPa, which is relatively low for grade 45 steel; this value corresponds to carbon content of about 0.17%. In some other regions and inclusions, micro-hardness increases to *H*=14000-18000 MPa; that is, when carbon content increases to 1-1.4%. The inclusions consist of high-carbon martensite; some other inclusions consist of untransformed cementite, have approximately the same hardness, and contain 6.3% carbon.

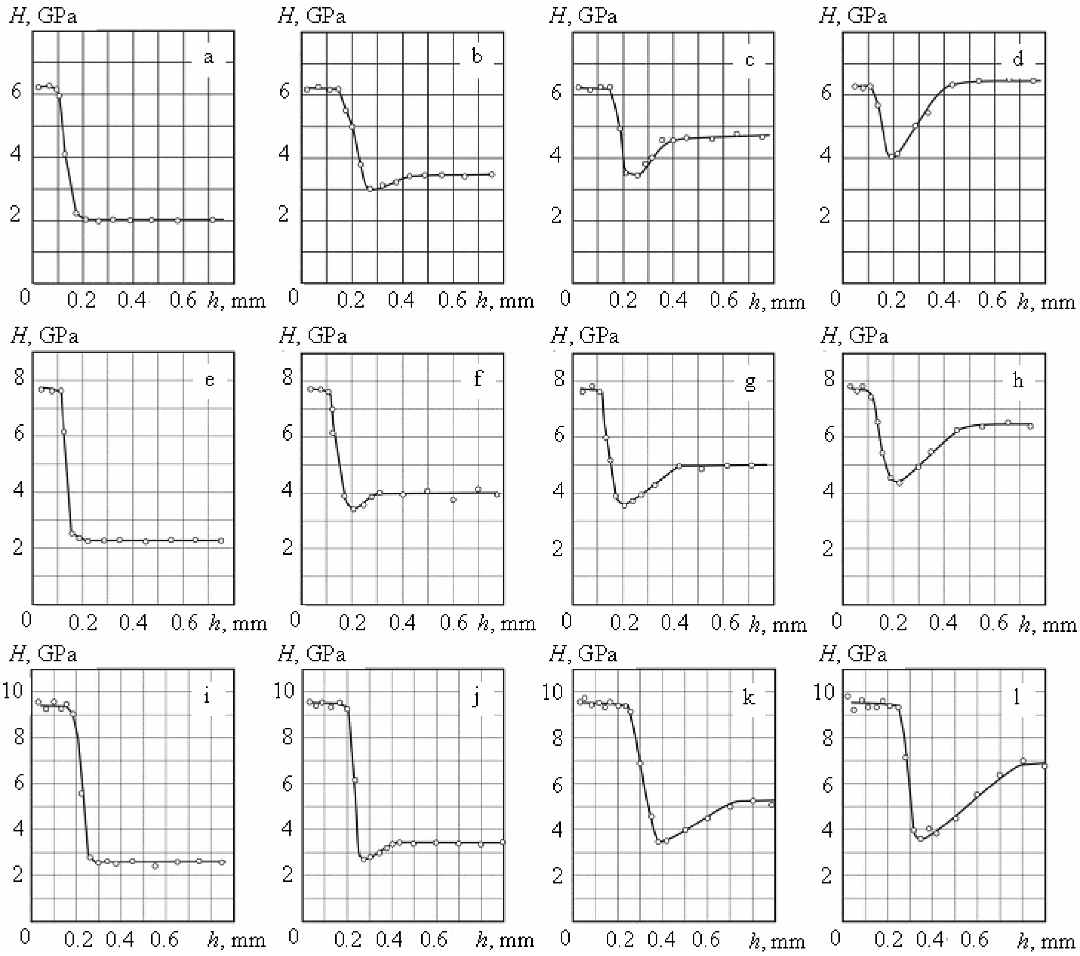

Fig. 2 Depth profiles of the average microhardness in surface layers of the steels: (a-d) grade 40; (e-h) grade 45; (i-l) grade U7 subjected to EMT after different preliminary HTs: quenching followed by tempering at (a, e, i) - 700; (b, f, j) - 500; (c, g, k) - 300; (d, h, l) - 150°C [7]

This non-uniformity of chemical composition of the hardenite results from inhomogeneous non-equilibrium austenitic structure that is formed upon rapid heating and that is fixed upon high-rate cooling. Microhardness of the former ferrite grains is *H*=3500-4000 MPa, which is much higher than the microhardness of the ferrite in the initial microstructure (~1100 MPa). This increase in microhardness of ferrite regions is explained by their quenching with the formation of low-carbon martensite, phase transformation induced hardening during the $\alpha \rightarrow \gamma$ transformation, and the strains induced by volume changes in the neighboring metal regions that have undergone martensitic transformation.

We detected no transition zone between the white layer and the base metal (Figs. 1, 2). The interface between the hardened and unhardened layers is characterized by a sharp jump from the hardness of the white layer to the hardness of the initial material for annealed or normalized steels (Fig. 1, a) or to the hardness of metal layers in heat-affected zone in the case of preliminarily quenched steel (Fig. 1, b). High temperatures (above the Ac_3 temperature) in the hardening zone exclude the possibility of incomplete quenching of the metal in the zones that border the white layer, which is known to occur upon cooling of the steel from the Ac_1-Ac_3 range, and, hence, to exclude the formation of transition zone that features a smooth decrease in microhardness to the core level. The white layer boundary formation under these conditions depends on cooling rate of the metal, which should be higher than the critical rate; otherwise, near-boundary volumes become tempered.

Fig. 2 shows the microhardness distribution in the surface and near-surface layers in steels after EMT as a function of the parameters of preliminary HT [7]. It is seen that, in a normalized steel, the white layer structure changes into the structure of the initial material at a certain depth (the transition zone width is smaller than 20 μm). In the prequenched steel, a near-surface, clearly etched zone (a heat-affected zone), which consists of softened material, to a certain degree, depends on tempering temperature. Low microhardness of the clearly etched zone is caused by secondary tempering of the steel and the depletion of this zone of carbon and other alloying and carbide-forming elements as the result of their migration from the near-surface to surface layers [1]. Depending on the temperature field characteristics, this zone can contain bainite, troostite, and the products of martensite decomposition (pearlite, sorbite, troostite, bainite). Smooth microhardness variation of the heat-affected zone is explained by gradual transition of these structures to the structure of heat-treated core [10, 11].

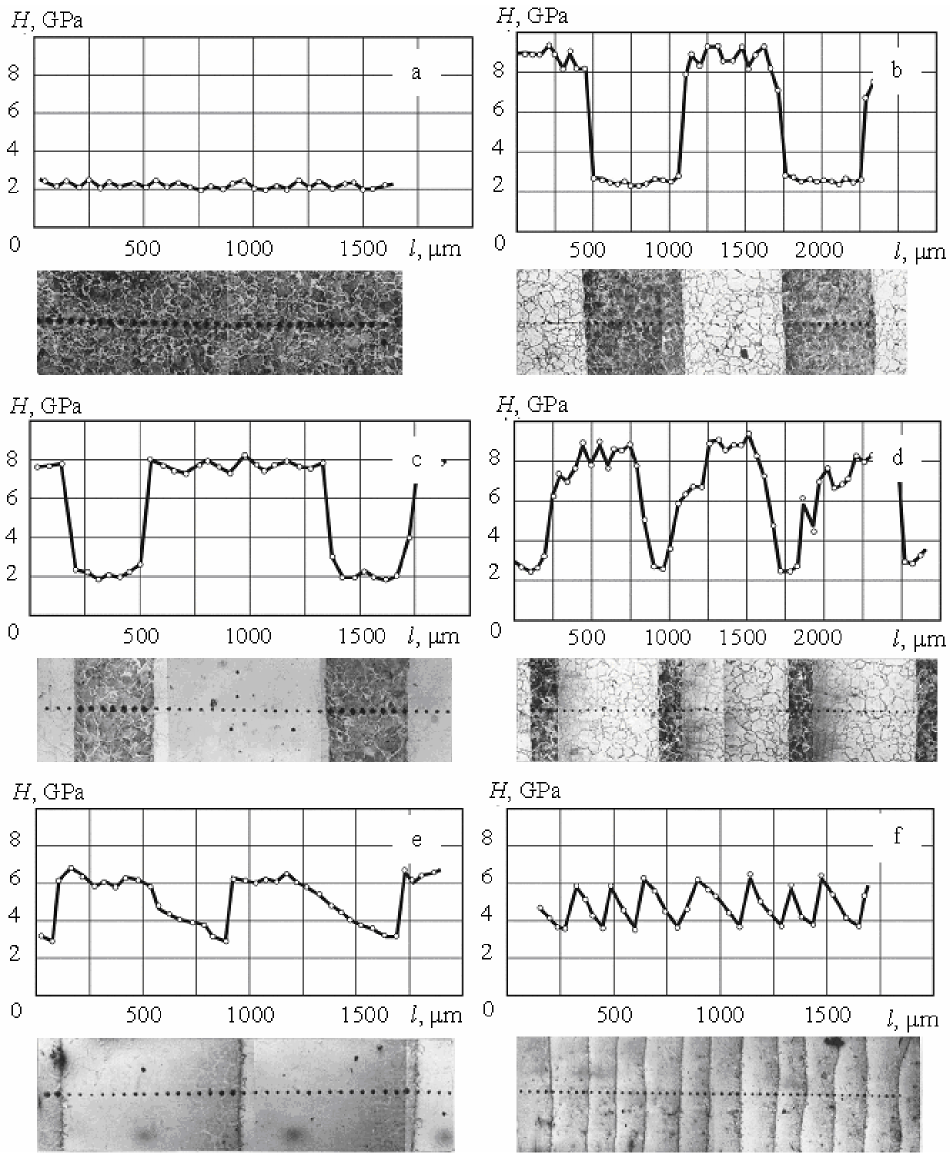

Fig. 3 Microhardness *H* distribution over the surface of the grade 45 steel along its axis *l*: (a) at the initial state and after EMT with various relative positions of white layer tracks; the gap between the tracks is (b) ~0.7; (c) ~0.3 (tempering zones are absent); (d) ~0.2 mm (tempering zones appear); (e) the tracks touch each other; (f) the tracks overlap each other

Thus, the curves show that there virtually is no softened zone in the steel that is quenched and then tempered at high temperature (Figs. 2, a; 2, e; 2, i). As the temperature of preliminary tempering decreases, both the depth of propagation and the degree of relative softening (the ratio of maximum to minimum hardness) of the near-surface layers of the initial material increase (Figs. 2, b-2, e; 2, f-2, h; 2, j-2, l). This is related with the fact that the structures formed upon low tempering are more inhomogeneous and, hence, have a stronger tendency toward softening during heat action of the hardened tracks on the base metal.

It should be noted that microhardness and depth of the white layers in the prequenched steels are somewhat higher than in the corresponding unquenched steel. This is likely due to the higher homogeneity of chemical and phase compositions of quenched metals; to grain refinement; and to a decrease in the contents of low-carbon martensite, metastable austenite, and free ferrite in steels. As carbon content in steels increases, these effects become more pronounced (Fig. 2).

To analyze the processes of secondary tempering caused by overlapping of neighboring hardened tracks during EMT and the effect of the tracks on the formation of a hardened surface structure, we measured microhardness of the surface layers in cylindrical samples of the normalized (Fig. 3) and quenched (Fig. 4) grade 45 steel along their axes after EMT at various overlapping coefficients of white layer tracks on the surface [12].

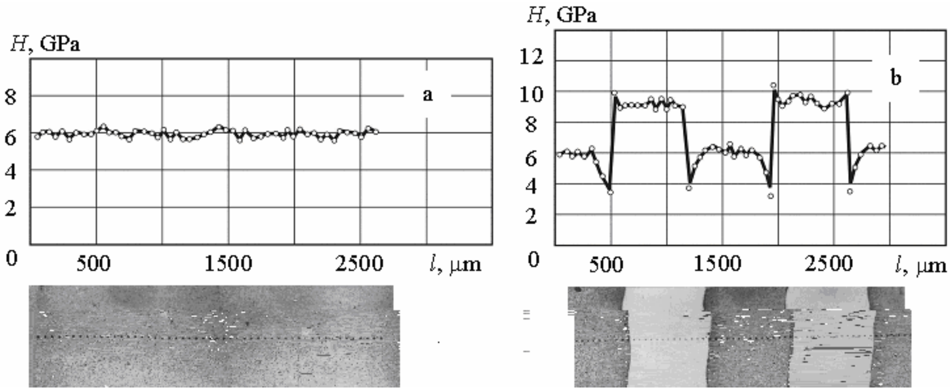

Fig. 4 Microhardness *H* distribution over the surface of the grade 45 steel along its axis *l*: (a) at the initial state; (b) after EMT at a gap of ~0.7 mm between white-layer tracks

As it can be seen from Fig. 3, a change in the relative position of white layer tracks on the surface changes the non-uniformity of the distribution of high- and low-hardness zones, the difference between maximum and minimum hardnesses, and the frequency of variation of the maximum and minimum values.

When there are no track overlapping zones (when intertrack distance is larger than a certain critical value), the surface contains the pronounced hardened zones with an extremely high hardness *H* (reaching 9000 MPa), as well as layers of the unhardened base metal with an initial hardness of about 2200 MPa (Figs. 3, b; 3, c). In the normalized steel, a secondary heat-affected zone does not influence the structural state of the metal near white-layer tracks. As noted above, the microhardness drops during the passage from hard to soft structural elements (layers) in the hardened surface layer.

As the tracks approach each other, such a picture remains unchanged until the distance between the neighboring tracks becomes smaller than the critical distance, which is equal to 0.25-0.3 mm. In this case, a radically new tendency appears: the following track begins to affect previous one, what reflects on microhardness distribution over the white layer width. If the intertrack distance is larger than 0.25-0.3 mm, microhardness of the white layer remains virtually constant. In this case, a certain zone, which undergoes secondary tempering and has a microhardness below that of the hardenite zone, forms inside a hardened track from the side adjoining the following track. Here, the microhardness varies smoothly, reflecting the influence of temperature effect (Fig. 3, d).

As noted above, the secondary heat-affected zone reaches its maximum dimensions when tracks touch each other (i.e., when the intertrack distance is zero). In this case, microhardness inside the white layer varies across its width. The maximum microhardness of the hardened surface decreases (H_{max}=7500 MPa), and the minimum hardness increases (H_{min}=2900 MPa) (Fig. 3, e).

When tracks overlap (Fig. 3, f), the effect of secondary thermal influence in tempering zone is more pronounced. In this case, the white layer hardness decreases further and the maximum and minimum microhardnesses approach each other more closely $H_{\max}$= =6200 MPa, $H_{\min}$=4000 MPa); this results in more homogeneous white layer with a lower hardness.

Microhardness distribution in the surface of the EMT-treated, prequenched steels is different. Fig. 4 shows microhardness of the surface layer in the grade 45 steel samples tempered at low temperature and then subjected to EMT. In this case, when there are gaps between the white layer tracks, the surface layer is quenched to produce hardenite with microhardness of 9000-9500 MPa and structural state of the initial material adjacent to the white layer. Contrary to the normalized grade 45 steel, where secondary heat-affected zones do not affect structural state of the initial material (ferritic-pearlitic structure), superposition of the heat-affected zone on the quenched structure (martensite) leads to structural changes in the near-surface layers, with the formation of tempering zones in the base metal. Microhardness inside these zones varies smoothly from the initial value (~6000-200 MPa) to the minimum value (3500-4000 MPa) in the zones that are adjacent to the white layer (Fig. 4, b). Such tempering zones also form in the steel tempered at medium and high temperatures; however, their dimensions and microhardnesses differ slightly from those shown in Fig. 4 and obey the tendencies shown in Fig. 2.

In all other respects, the formation of tempering zones during the EMT of quenched steels is identical to the processes that occur upon hardening of the normalized steels and that are described above.

4. Conclusions

EMT of different type steels results in the formation of a hardened surface layer, the structure and microhardness of which depends substantially on carbon content and preliminary heat treatment.

As carbon content increases, the efficiency of electromechanical hardening rises: the depth and hardening of the hardened surface layer increase and its sensitivity to etching decreases. The tendency of a steel toward phase and structural transformations during EMT, the homogeneity of the structure of the EMT-hardened surface layer, and mechanical properties of this layer increase with the degree of inhomogeneity of the initial structure produced by preliminary heat treatment and with the degree of its refinement.

Apart from the hardened zone (white layer), the surface layer in steels subjected to EMT contains the secondary heat-affected zone. In a normalized steel, the heat-affected zone is only revealed when neighboring hardened tracks overlap with each other (when the following track induces tempering of the previous one). When the tempering zone propagates into the initially normalized structure, this structure remains unchanged. In quenched steels, this zone is clearly etched and has low microhardness. It is visible as a layer between the hardened white layer and the base metal, which consists of the products of rapid EMT-induced tempering of the initially quenched structure.

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ELEKTROMECHANIŠKAI SUKIETINTŲ ANGLINIŲ PLIENŲ „BALTOJO SLUOKSNIO“ MIKROKIETUMAS

R e z i u m ė

Pateikiami elekromechaniškai sukietintų skirtingų markių plienų eksperimentinių tyrimų rezultatai, nagrinėjami paviršinio sluoksnio mikrokietumo pasiskirstymo ypatumai. Aptariami anglies kiekio pliene ir jo struktūros gautos po praqdinio terminio apdirbimo įtaka formuojant elektromechaniniu poveikiu sukietintą paviršiaus sluoksnį.

N. G. Dudkina, I. N. Zakharov

MICROHARDNESS OF THE “WHITE LAYER” PRODUCED BY ELECTROMECHANICAL STRENGTHENING OF CARBON STEELS

S u m m a r y

The depth profiles of the microhardness in the surface layers of different type steels subjected to electromechanical hardening are measured and analyzed. The effects of carbon content in a steel and its initial structure, which is produced by preliminary heat treatment, on the hardened structure formation in the surface layers (in the zone of electromechanical influence) are studied.

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МИКРОТВЕРДОСТЬ “БЕЛОГО СЛОЯ” ПОСЛЕ ЭЛЕКТРОМЕХАНИЧЕСКОГО УПРОЧНЕНИЯ УГЛЕРОДИСТЫХ СТАЛЕЙ

Р е з ю м е

Приводятся экспериментальные данные и рассматриваются характерные особенности распределения микротвердости поверхностного слоя различных марок сталей после электромеханического упрочнения. Представлены результаты исследований влияния содержания углерода в стали и ее исходной структуры, полученной в результате предварительной термической обработки, на формирование упрочненной структуры поверхности материала в области электромеханического воздействия.

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