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RESEARCH INTO THE PATTERNS OF FORMATION OF THE STRUCTURE OF TOOL HIGH-SPEED STEELS DURING SURFACE ELECTRON BEAM TREATMENT

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ДОСЛІДЖЕННЯ ЗАКОНОМІРНОСТЕЙ ФОРМУВАННЯ СТРУКТУРИ ІНСТРУМЕНТАЛЬНИХ ШВИДКОРІЗАЛЬНИХ СТАЛЕЙ ПРИ ПОВЕРХНЕВІЙ ЕЛЕКТРОННО-ПРОМЕНЕВІЙ ОБРОБЦІ

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The objective of the research was to study the modes of electron beam hardening on the structure and properties of surface layers of tool high-speed steels. The limiting modes of electron beam hardening were determined experimentally, which allow obtaining the maximum microhardness of the hardened layer without melting the surface being treated. Based on the results of experimental studies, a comprehensive parameter of the treatment mode was proposed, according to which the intensity of heating and cooling of the surface layer of the tool can be determined - the power density of the beam. This parameter includes all other parameters of the hardening treatment mode: diameter, power, and speed of beam movement relative to the tool surface. It has been established that the maximum hardness of the hardened layer during electron beam treatment can be achieved by high-temperature hardening without melting the treated surface. Hardening without melting also ensures the formation of a highly dispersed structure throughout the entire depth of the hardened layer. Melting of the surface of a tool undergoing electron beam hardening should be considered an extremely undesirable processing option. In the case of melting of the surface layer in a tool made of high-speed steels, a significant decrease in microhardness is observed. At the same time, the surface layer contains a significant amount of residual austenite. Hardening with melting, in which a significant amount of residual austenite is formed, is the main reason for the sharp decrease in the content of carbide phases in the surface layer. Together, all this leads to a decrease in the wear resistance of tool high-speed steels. In the case of hardening with melting, there is also a deterioration in the tool's resistance to large plastic deformations at elevated temperatures in the cutting zone. It has been established that the depth of the hardened layer significantly depends on the initial structure of the steels. The maximum depth of the hardened layer in tool high-speed steels can be obtained by their preliminary heat treatment in the form of volumetric hardening and tempering. Within the framework of the experimental studies, a range of optimal values of the overlap coefficient was established, which corresponds to the minimum values of the tempering zone width.

Key words: *high-speed steels, heat treatment, martensite, carbides, austenite, microhardness.*

Introduction. Over the last ten to fifteen years, electron beam strengthening of tool steels has become quite widely used in industry [1]. On the one hand, this is due to the fact that the intensity of electron beam heating, unlike laser beam heating, does not depend on the condition of the surface being treated, and on the other hand, significant achievements in the development and manufacture of equipment for electron beam treatment. In particular, as of today, installations for strengthening electron beam treatment without the use of high vacuum are being mass-produced. This allows such installations to be used for strengthening cutting tools even in mass production conditions. On the other hand, numerous problems related to the development of technological processes for surface strengthening remain unresolved. Modern software allows for fairly accurate calculation of temperature fields in products subjected to electron beam treatment, taking into account their configuration and heat exchange with the environment. However, when modelling structural and phase transformations, significant problems arise due to the fact that these transformations occur at extremely high heating and cooling rates [2]. Therefore, as of today, the main method of studying the effect of electron beam treatment modes on the structure and properties of the materials being treated remains the experimental method.

One of the most important criteria for optimising the parameters of electron beam hardening treatment of cutting tools is the microhardness of the hardened layer. Reduced microhardness of the surface layer of the tool indicates either underheating or overheating of this layer during processing, which is clarified by microstructure analysis. The electron beam treatment mode is characterised by a fairly large number of parameters. However, analysis of works [3–5] shows that the main optimisation task in the development of electron beam treatment technology for cutting tools is to determine the electron beam power density at which maximum microhardness and maximum depth of the hardened layer are achieved.

According to [6, 7], high-alloy tool steels, in particular high-speed and stamping steels, are characterised by low diffusion mobility of carbon atoms. Therefore, with insufficient specific energy of the electron beam, the homogenisation of austenite may be incomplete. Under such conditions, the hardened layer will contain low-alloy martensite, which is characterised by relatively low microhardness and wear resistance. If the specific power of the electron beam is too high, especially if the surface layer melts, a large amount of (up to 80 vol. %) of residual austenite, which has low microhardness and poorly resists plastic deformations that occur during tool operation [7].

Thus, strengthening electron beam treatment of high-speed and high-alloy stamping steels should ensure the formation of a hardened layer containing high-alloy martensite and highly dispersed carbide phases. At the same time, it is extremely important to prevent excessive dissolution of carbide phases and, as a result, the formation of an excessive amount of residual austenite in the hardened layer.

The objective. The objective of the article is to determine the optimal modes of strengthening electron beam treatment of high-speed and stamping steels; the optimisation criteria are maximum microhardness and maximum depth of the layer hardened from the solid state.

Research problem. 1. To determine the optimal power density of the electron beam that allows obtaining a hardened layer with maximum depth and microhardness.

2. To evaluate the influence of the initial structure of tool high-speed steels on the depth and microhardness of the hardened layer obtained by electron beam treatment.

Research methodology. The following tool steels were used in the research: P18, P6M5, P6M5K5, X12M. Before electron beam treatment, the steels were subjected to the following types of preliminary heat treatment: isothermal annealing [7]; quenching and high tempering [7].

Electron beam treatment was carried out on the “ELA-15” installation. Electron beam power: 1.2 kW, beam diameter: 2.5 mm, electron beam velocity (V): 4 - 12 mm/s. Thus, the change in the power density of the electron beam was varied by changing the velocity of the electron beam. Experimental studies were carried out on plate samples measuring 50 x 50 x 10 mm.

The microstructure of the hardened layer was determined using a MIM-8M optical microscope, and the microhardness of the hardened layer was measured on a PMT-3 microhardness tester.

Results of experimental studies and their analysis. The power density of the electron beam varied from $0.45 \cdot 10^4$ to $1.35 \cdot 10^4$ W/cm^2 due to changes in its relative velocity. Figure 1 shows the dependence of the maximum microhardness of the hardened layer on the power density of the electron beam. Microhardness was measured at a distance of 0.1 mm from the surface of the samples that was in direct contact with the electron beam. At the first stage of experimental research, the optimal power density of the electron beam was determined, which ensures the formation of a hardened layer with maximum microhardness.

In the case of electron beam processing of high-speed steel P6M5, the maximum microhardness (9200 MPa) corresponds to the electron beam power density (q) of $1.0 \cdot 10^4$ W/cm^2. At an electron beam power density of $0.45 \cdot 10^4$ W/cm^2, the maximum microhardness is 7800 MPa, and at $q = 0.75 \cdot 10^4$ W/cm^2, it is 8500 MPa. When the power density of the electron beam is increased to $1.35 \cdot 10^4$ W/cm^2, the maximum microhardness decreases to 8000 MPa (fig. 1). With a further increase in q, the surface of the samples melts, and the maximum microhardness of the surface layer decreases to 6900 MPa.

During laser treatment of P6M5K5 and P18 steels, the maximum microhardness values (9650 - 9820 MPa) are achieved at a laser radiation power density of $1.3 \cdot 10^4$ W/cm^2. At a radiation power density of $0.4 \cdot 10^4$ W/cm^2, the microhardness is 8050 MPa, at a radiation power density of $0.9 \cdot 10^4$ W/cm^2 – 8500 MPa, at a radiation power density of $1.1 \cdot 10^4$ W/cm^2 – 8850 MPa (fig. 1). An increase in radiation power density above $1.4 \cdot 10^4$ W/cm^2 is undesirable, since this results in the formation of a melted layer with a significant content of residual austenite and relatively low microhardness (up to 7200 MPa).

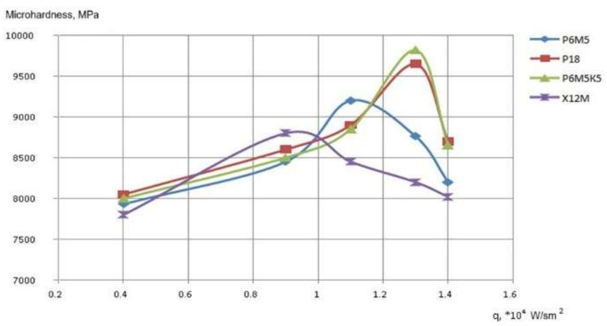

Fig. 1. The influence of electron beam power density on the maximum microhardness of the hardened layer: initial state of samples – hardening and high tempering according to typical modes [7]

The maximum microhardness of the hardened layer of X12M stamped steel (8900 MPa) corresponds to an electron beam power density of $0.8 \cdot 10^4$ W/cm^2. When the electron beam power density is increased to $1.0 \cdot 10^4$ W/cm^2, the maximum microhardness decreases to 8000 - 8150 MPa (fig. 1). If q is further increased, there is a sharp decrease in the maximum microhardness of the hardened layer to 6600 MPa due to surface melting.

The melting zone in all samples is characterised by a typical dendritic structure. Despite the high dispersion of this structure, its microhardness is 6700 - 7200 MPa, depending on the grade of tool steel. The melted layer is separated from the base metal by a narrow transition zone (figs. 2, 3).

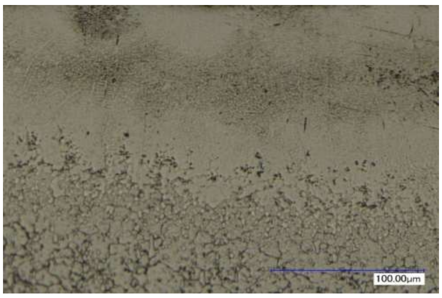

Fig. 2. Microstructure of the surface layer of P6M5K5 steel after electron beam treatment with melting: $q = 1.35 \cdot 10^4$ W/cm^2 (V = 11 mm/s); x600

Fig. 3. Microstructure of the surface layer of P18 steel after electron beam treatment with melting: $q = 1.35 \cdot 10^4$ W/cm^2 (V = 11 mm/s); x600

If electron beam treatment is performed without surface melting, the main structural components of the hardened layer are martensite and excess carbides; the residual austenite content is minimal (fig. 4).

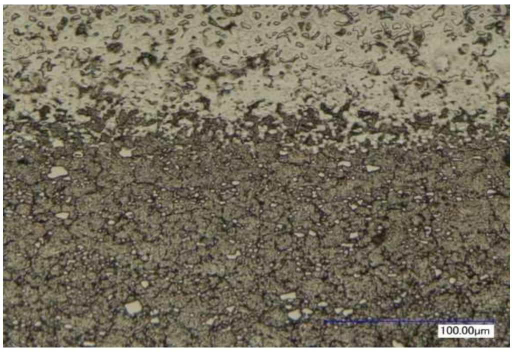

Fig. 4. Microstructure of the surface layer of P6M5K5 steel after electron beam treatment: $q = 1.2 \cdot 10^4$ W/cm^2 (V = 11 mm/s); x600

The objective of the second stage of research was to determine the effect of preliminary heat treatment of steels on the depth of the hardened layer. Electron beam treatment was carried out at settings that ensure the formation of high-alloy martensite in the hardened layer and prevent surface melting. The graphs showing the distribution of microhardness across the depth of the hardened layer are presented in figs. 5 - 8. The maximum thickness of the hardened layer (0.55 - 0.65 mm) is achieved when the steel undergoes volume hardening and tempering prior to electron beam treatment [7]. The relatively large thickness of the hardened layer formed during electron beam treatment of steels that have been previously subjected to volume hardening and tempering is due to their low thermal conductivity after such preliminary treatment. The depth of the hardened layer on steel samples that underwent isothermal annealing prior to electron beam treatment is almost half that of samples that underwent volumetric hardening and tempering (figs. 5 - 8).

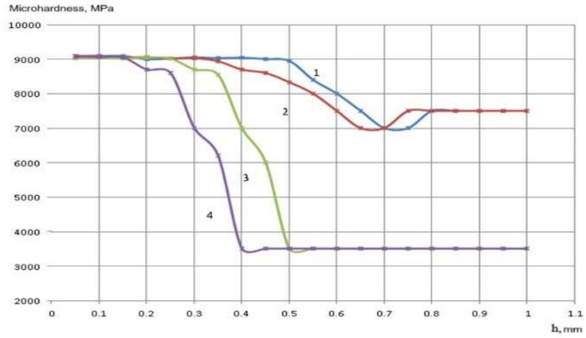

Fig. 5. The effect of preliminary heat treatment on the microhardness of the hardened layer of P6M5 steel: q = 1.0·10^4 W/cm^2: 1 - hardening and tempering according to standard modes, V = 9 mm/s; 2 - hardening and tempering according to standard modes, V = 11 mm/s; 3 – isothermal annealing, V = 9 mm/s; 4 - isothermal annealing, V = 11 mm/s

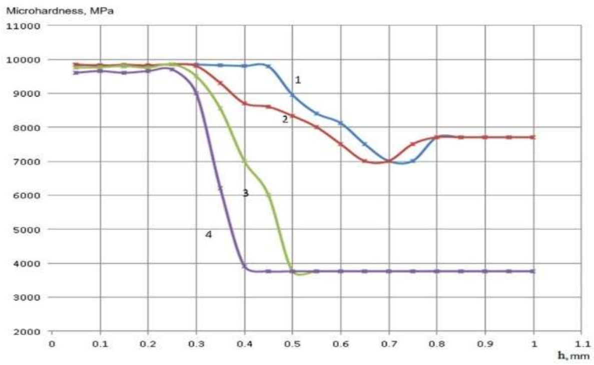

Fig. 6. The effect of preliminary heat treatment on the microhardness of the hardened layer of P6M5K5 steel: q = 1.2·10^4 W/cm^2: 1 - hardening and tempering according to standard modes, V = 9 mm/s; 2 - hardening and tempering according to standard modes, V = 11 mm/s; 3 - isothermal annealing, V = 9 mm/s; 4 - isothermal annealing, V = 11 mm/s

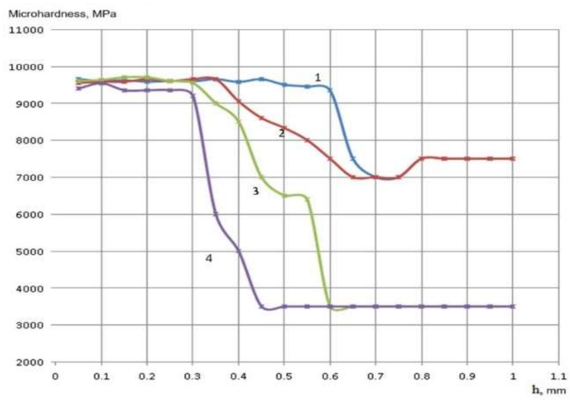

Fig. 7. The effect of preliminary heat treatment on the microhardness of the hardened layer of P18 steel: q = 1.2·10^4 W/cm^2: 1 - hardening and tempering according to standard modes, V = 9 mm/s; 2 - hardening and tempering according to standard modes, V = 11 mm/s; 3 - isothermal annealing, V = 9 mm/s; 4 - isothermal annealing, V = 11 mm/s

Thus, in order to achieve the maximum depth of the hardened layer on high-speed and high-alloy stamping steels, these steels should be subjected to volumetric hardening and tempering under typical conditions before electron beam treatment.

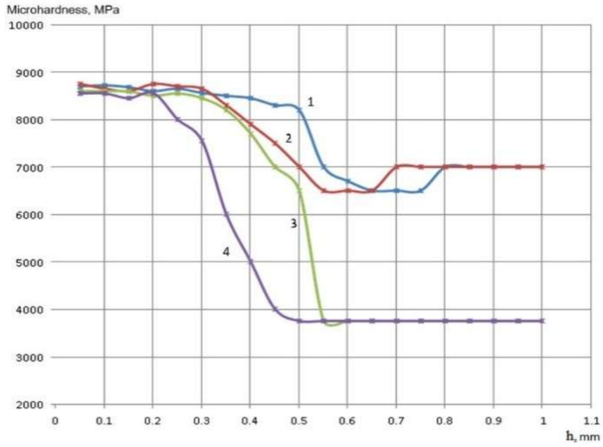

Fig. 8. The effect of preliminary heat treatment on the microhardness of the hardened layer of X12M steel: q = 0.8·10^4 W/cm^2: 1 - hardening and tempering according to standard modes, V = 9 mm/s; 2 - hardening and tempering according to standard modes, V = 11 mm/s; 3 - isothermal annealing, V = 9 mm/s; 4 - isothermal annealing, V = 11 mm/s

Conclusions. 1. Strengthening electron beam treatment of tools made of high-speed and high-alloy stamping steels must be carried out in a solid state in such a way as to obtain a structure in the strengthened layer consisting of high-alloy martensite and excess carbides; Melting of the tool surface is unacceptable, since in this case the hardened layer contains an excessive amount of residual austenite.

2. In order to achieve the maximum depth of the hardened layer on high-speed and high-alloy stamping steels, these steels should be subjected to volumetric hardening and tempering under typical conditions before electron beam treatment.

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Шевченко О.В., Зінченко Д.М. Дослідження закономірностей формування структури інструментальних швидкорізальних сталей при поверхневій електронно-променевій обробці.

Мета дослідження полягала у вивченні режимів електронно-променевого зміцнення на структуру та властивості поверхневих шарів інструментальних швидкорізальних сталей. Експериментальним шляхом було визначено граничні режими електронно-променевого зміцнення, які дозволяють отримати максимальну мікротвердість загартованого шару без оплавлення поверхні, що піддається обробці. За результатами експериментальних досліджень запропоновано комплексний параметр режиму обробки, за яким можна визначити інтенсивність нагрівання та охолодження поверхневого шару інструменту - щільність потужності променя. Цей параметр містить в собі всі інші параметри режиму зміцнювальної обробки: діаметр, потужність, швидкість переміщення променя відносно поверхні інструменту. Встановлено, що максимальної твердості зміцненого шару при електронно-променевій обробці можна досягнути при високотемпературному гартуванні без оплавлення оброблюваної поверхні. Зміцнювальна обробка без оплавлення також забезпечує формування високодисперсної структури по всій глибині зміцненого шару. Оплавлення поверхні інструменту, що піддається зміцнювальній електронно-променевій обробці, слід розглядати як вкрай небажаний варіант обробки. У разі оплавлення поверхневого шару в інструменті із швидкорізальних сталей спостерігається суттєве зменшення мікротвердості. При цьому у поверхневому шарі міститься значна кількість залишкового аустеніту. Гартування із оплавленням, при якому утворюється значна кількість залишкового аустеніту, є основною причиною того, що в поверхневому шарі різко зменшується вміст карбідних фаз. Разом все це призводить до зменшення зносостійкості інструментальних швидкорізальних сталей. У разі гартування з оплавленням також спостерігається погіршення пручання інструменту великим пластичним деформаціям при підвищених температурах в зоні різання. Встановлено, що глибина зміцненого шару суттєвим чином залежить від вихідної структури сталей. Максимальну глибину зміцненого шару в інструментальних швидкорізальних сталях можна отримати у разі їхньої попередньої термічної обробки у вигляді об'ємного гартування та відпуску. В рамках проведених експериментальних досліджень було встановлено діапазон оптимальних значень коефіцієнта перекриття, яким відповідають мінімальні значення ширини зону відпуску.

Ключові слова: *швидкорізальні сталі, термічна обробка, мартенсит, карбіди, аустеніт, мікротвердість.*

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