EFFECT OF MAGNETIC FIELD ON THE SURFACE STRUCTURE OF HIGH-SPEED STEELS

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Abstract – Today, High-Speed Steels (HSS) occupy a special place in the manufacture of cutting tools in the machining of machine parts. Their good heat resistance, strength, and improved wear resistance make them an important material in the production of cutting tools. The paper analyzes the effect of applying a magnetic field on High-Speed Steel samples used to manufacture metal cutting turning tools for machining operations. To investigate the effect of the magnetic field on the strength of HSS tool materials, experimental data on the surface layer structure of samples during magnetization are presented. In this case, the influence of the magnetic field on the film formation at the chip-tool interface, which is important for reducing the wear of the cutting tool, was investigated. Experiments were conducted with samples heated to different temperatures at 400°C, 500°C, 600°C, 700°C, and 800°C. Samples were analyzed on a Dron 2.0 diffractometer using filtered copper radiation (SiK_{a1}). Moreover, turning tests in diverse cutting modes were conducted using an AISI T1 HSS solid tool before and after magnetic treatment. HSS tool used after magnetic treatment performed 1.5-2 times better tool life in machining AISI 1025 and AISI 1045 workpieces. The results of the experiments showed that under the influence of the magnetic field, there were significant changes in the phases on the surface of the HSS samples.

Keywords: Magnetization, Radiograph, Phase, Diffraction lines, Plastic deformation.

1. Introduction

Currently, mechanical processing in the production industry has a significant impact on the development rate of mechanical engineering. Therefore, increasing the productivity, accuracy, and quality of machined parts has great importance in manufacturing. Increasing productivity, improving the accuracy and quality of machining, in turn, is related to the problem of increasing the wear resistance of cutting tools, which is the most important and relevant problem in the science of metal cutting [1-4]. As it is known, in mechanical engineering, one of the popular materials used in cutting tool manufacturing is high-speed steels (HSS), and increasing their wear resistance is one of the important tasks. This task can be solved by creating new tool materials with higher operational characteristics of existing HSS tools [4-6].

HSS tools are used in different areas in machining operations, such as turning, hard turning, milling, drilling, broaching and etc. In all the methods of machining operations, using HSS tools is mainly tool wear (tool life) [7-9].

Many different methods of increasing the wear resistance of HSS cutting tools are known, such as nitriding, cyanidation, cold treatment, cutting or magnetic field treatment of the tool, application of various lubricating and cooling media, etc. [10-12]. However, the higher costs of carrying out most of these processes, the complexity of the process, and the need for specialists can cause inconveniences in their application. Therefore, the need for research to reduce these shortcomings or increase the service life of HSS tools by developing new methods remains relevant.

Among the above-mentioned methods, the application of a magnetic field in the cutting process using various methods occupies a special place and

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is becoming an increasingly relevant area of research today. In particular, the research on increasing the wear resistance of high-speed cutting tools using a magnetic field has been conducted by many authors [13, 14]. Mardonov et al. studied the effect of a permanent magnetic field on water-based cutting fluid in turning AISI 4045. They used an HSS cutting tool to investigate the influence of magnetically treated cutting fluids on chip formation. They investigated that the magnetic field has a positive effect on cutting fluids, and using magnetically treated tools can improve the machining process [14]. The results obtained by the works [13, 14] show that the application of different magnetic fields in the mechanical processing of metals improves the wear resistance of metal cutting tools. The application of a magnetic field in metal cutting zone has various approaches, as can be seen in Figure 1.

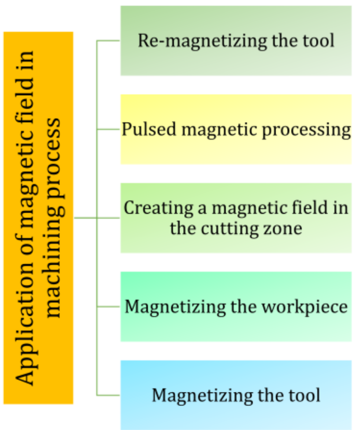


Figure 1: Methods of using a magnetic field in the machining process

Miliukova et al. [15] and Chen et al. [16] studied the change in the properties of different alloys under the effect of a pulsed magnetic field. Miliukova et al. investigated that magnetically pulsed treated HSS tools' microhardness improved noticeably when they are preheated up to 350^{0}C. In the studies of Chen et al., WC-TiC-Co inserts magnetized wuth a pulsed magnetic field showed better results in machining tests. Toshov et al. [17] studied the effect of magnetic pulse treatment and radiation on the carbide tools' wear resistance. They found that magnetic treatment of samples improves the wear resistance of the materials by two times compared to non-magnetized samples.

Literature analysis shows that by magnetic treatment of different steels, it is possible to achieve an increase in their wear resistance up to 1.5÷2 times. Moreover, studies on applying a magnetic field in the metal cutting zone show that under the effect of a magnetic field wear resistance of HSS machining tools increases, and this increase depends on the magnetic field strength. Authors explain this by the change in cutting temperature due to the strengthening of the tool's surface layer [18-22]. Moreover, this phenomenon is explained by the decrease in the friction coefficient between the friction surfaces (chip-tool interface) and the appearance of small particles as an additional lubricating effect [23].

Studies on re-magnetization and pulsed magnetic treatment of cutting tools believe that the improvement of the operational characteristics of high-speed steels occurs as a result of surface strengthening under the influence of the re-magnetization process [24-26].

In the works [27-31], experimental data obtained from the application of a magnetic field during the simultaneous action of lubricating and cooling fluids are presented. Results show that the application of a magnetic field can change some characteristics of the lubricating and cooling fluids; as a result, tool wear decreased. According to many authors, the magnetic treatment of metal cutting tools is one of the promising directions to increase the wear resistance of metal cutting tools.

The authors [32-35] believe that metals have a thin oxide film on their surface layer. The external environment interacts with the surface layer of the metal, forming thin films. In the application of a magnetic field, due to the diffusion of metal and oxygen atoms, the thickness of these layers increases. It is known that metal surfaces have diverse imperfections for various reasons. These imperfections in the surface of a real crystal determine its reactivity. Then the oxidation of metals occurs according to the following equation:

$$M_e + \frac{1}{2}O_2 \leftrightarrow M_eO_2 \tag{1}$$

These oxide films have different thicknesses. The thickness of thin films is up to 400 angstroms (A). Such films appear mainly in dry air at room temperature. Similar films on the metal surface are invisible. The thickness of the medium-thick films is about 400-5000 A, they appear when heated in air to approximately 400°C in iron compounds. Thick films with a thickness of more than 5000 A are usually visible to the naked eye. They can appear when heated at approximately 400°C in open-air conditions.

Experiments show that the formation rate of oxide films depends on temperature, i.e., the higher the temperature, the greater the oxidation rate. The change in oxidation rate and its temperature dependence can be expressed by the following equation:

$$u = \frac{dy}{d\tau} = A \cdot l^{-\frac{Q}{RT}} \tag{2}$$

where,
A and Q - constants;
R - gas constant;
T - basis of natural logarithms;

l- absolute temperature;
y - film thickness;
τ - time.

As it is known, plastic deformation occurs in the metal cutting process, and it leads to a significant influence of the magnetic field on the process of changing the chemical composition and structure of the tool's upper layer. It is one of the current tasks to determine the impact of magnetization on tool materials on the change in their surface structure in the absence of plastic deformation.

The main objective of this study is to determine the influence of the electromagnetic field on the surface structure of the HSS tools. Intensity of the oxidation process, structure, and the chemical composition of the surface layers of HSS tools are studied. Magnetized and non-magnetized HSS samples are investigated according to the above-stated parameters.

Results of the research can be applied to the metal cutting process directly after the magnetization of the tool made of HSS.

2. Methods

In the experimental study, tool sample sizes of 20x20x20 mm were prepared. The HSS tool made of the AISI T1 brand was chosen as the tool material. Chemical composition of the material is shown in Table 1, and the mechanical properties of the material at T=20°C are shown in Table 2. The hardness shown in Table 2 is for the material after heat treatment. These samples were made from a single rod, and for each temperature, adjacent ones located on the rod were selected. Turning tests were also conducted using an AISI T1 solid cutting tool, and workpiece materials were AISI 1025 and AISI 1045.

Table 1. Chemical composition of AISI T1, in %

C	Si	Mn	Ni	S	P	Cr	Mo	W	V	Co	Cu
0.73-0.83	0.2-0.5	0.2-0.5	<0.6	<0.03	<0.03	3.8-4.4	<1	17-18.5	1-1.4	<0.5	<0.25

Table 2. Mechanical properties of AISI T1 at T=20°C

Short-term strength limit, σ_B, MPa	**Yield strength for residual deformation, σ_T, MPa**	**Relative elongation at rupture, σ_5, %**	**Relative narrowing, Ψ, %**	**Toughness, kJ/m²**	**Hardness, HRC**
840	510	8	10	190	62-66

The polishing of these patterns was carried out under the same conditions. The samples were heated in an SNOL-12/1200 electric furnace. The temperature fluctuations in the furnace were within ±5°C. During the oxidation of the samples, they were kept in the furnace for one hour, and the studied magnetized and non-magnetized samples were placed in the furnace simultaneously using a special device.

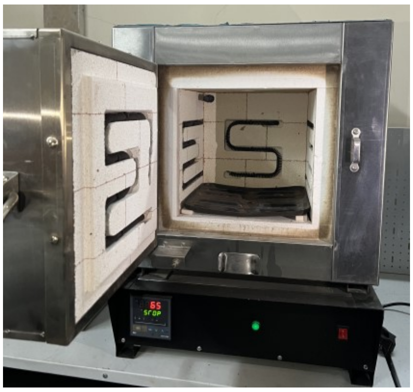


Figure 2: SNOL 12/1200 ceramic chamber universal laboratory electric furnace

In all experiments, the free entry of air into the furnace through a special opening was ensured. The main goal of heating magnetized and non-magnetized samples made of HSS tool material was to investigate the influence of the magnetic field on HSS tool oxidation state at various temperatures. Experiments were conducted at temperatures of 400°C, 500°C, 600°C, 700°C, and 800°C. To further test this phenomenon, a 10% solution of potassium permanganate was used as a strong oxidizing agent. To conduct this test, two magnetized and non-magnetized samples were simultaneously immersed in a potassium permanganate solution and held for 24 hours. After removal from the solution, the samples were dried under the same conditions. X-ray diffraction of the samples was performed on a Dron-2.0 diffractometer using filtered copper radiation ($SiK_{\alpha 1}$). The study of the chemical composition of the surface layers of the cutting tool was carried out on a scanning microanalyzer with an electronic probe of the "M5-46" comeca type. The microanalyzer operated at V=20 kW and J=20 NA. As a standard, Fe=100% K_{a1} was used; W = 100% $K_{\alpha 1}$; Cr = 100% $K_{\alpha 1}$; V = 100% $K_{\alpha 1}$.

2.1 Magnetization Setup

Magnetization of the samples was carried out using a coil (Fig. 3) powered by a rectifier assembled from diodes, with the winding wire diameter is d=0.8mm.

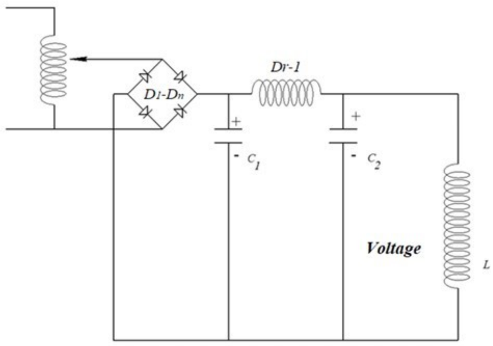


Figure 3: Diagram of a rectifier assembled from 4 D245 diodes

During the magnetization process, U=220 volts was applied to the coil, and the current was I=3.75 amperes. In all experiments, the sample was magnetized for 3 minutes. Magnetic field strength was 3000 oersted (Oe) in the magnetic treatment process of the samples. The residual magnetic induction on the samples was determined using the ballistic method. To assess the reproducibility of these experiments, variation coefficients were calculated. For this, the results of experiments repeated 3÷4 times were selected.

3. Results and Discussions

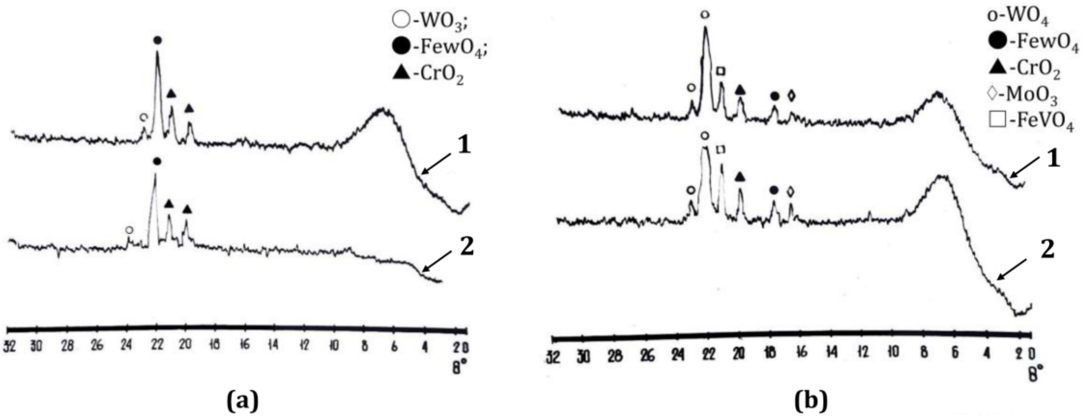
3.1 Surface Analysis

To study the structural change of the polished surface, radiographs (diffractograms) of the samples were taken. The peaks on the X-ray taken from the samples made of high-speed steel AISI T1 correspond to WO_3; $FeWO_4$; $FeVO_4$; Fe_2O_3; $FeMoO_4$; CrO_2; and MoO_3. Diffraction maxima with interplanar distances d=1.57; 1.6; 1.66; 1.68; 1.84; 1.95; 2.01; 2.18; 2.63 A correspond to the WO_3 phase, while d = 1.47; 1.708; 2.047; 2.47; 2.476 A correspond to the $FeWO^4$ phase. Diffraction maxima with distances d=2.15; 2.55; 2.79; 2.85 A correspond to the $FeVO_4$ phase, and with distances d = 2.74; 3.6 A correspond to the Fe_2O_3 phase. Further, the maximum with distances d = 2.88 corresponds to $FeMoO_4$, and with distances d = 2.128; 2.207 A correspond to the CrO_2 phase, and d = 2.88 A corresponds to the MoO_3 phase.

Analysis of the radiographs shows that the structure of the surface layer of the polished samples depends on the temperature. As the temperature changes, the height of the peaks also changes, and even new peaks appear. This indicates a change in the surface layer structure of the samples. In the diagrams (Fig. 4), the detector rotation angle (θ) is shown horizontally, and the height of the diffraction maxima of various compounds (intensity, Imp [impulse/second]) is shown vertically.

Fig. 4, a shows the X-ray diffraction patterns of magnetized and non-magnetized samples heated at t=400°C. From the figure, it can be seen that the diffraction maxima of $FeWO_4$ and CrO_2 decrease in the magnetized sample compared to the non-magnetized one. With increasing temperature up to t=500°C, conversely, an increase in the diffraction lines of $FeWO_4$; $FeVO_4$; CrO_2; MoO_3 is indicated in the magnetized samples (Fig. 4, b). Moreover, a noticeable increase in the MoO_3 phase occurred. At a temperature of t=600°C (Fig. 4, c), while WO_3, $FeWO_4$, and $FeVO_4$ phases decreased noticeably, peaks corresponding to $FeMoO_4$ increased in the magnetized sample. When the sample is heated at t=700°C (Fig. 4, d), the radiographs look completely different. It can be seen from the figure that new peaks appeared (WO_3; $FeVO_4$), and others ($FeWO_4$) disappeared. This indicates that at this temperature, the influence of the magnetic field is more noticeable, i.e., a sharp change in the surface layer structure occurred. Increasing the heating temperature to 800°C (Fig. 4, e) to stabilize the diffraction maxima, i.e., the peak values in the non-magnetized sample compared to the magnetized sample are relatively the same. Since the changes in the surface structure of the samples during the magnetic treatment period are explained by the appearance of oxide films. It was interesting to test this phenomenon in an aqueous solution of potassium permanganate.

The results obtained in this case also show changes in the diffraction maxima when the sample is pre-magnetized (Fig. 4, f).



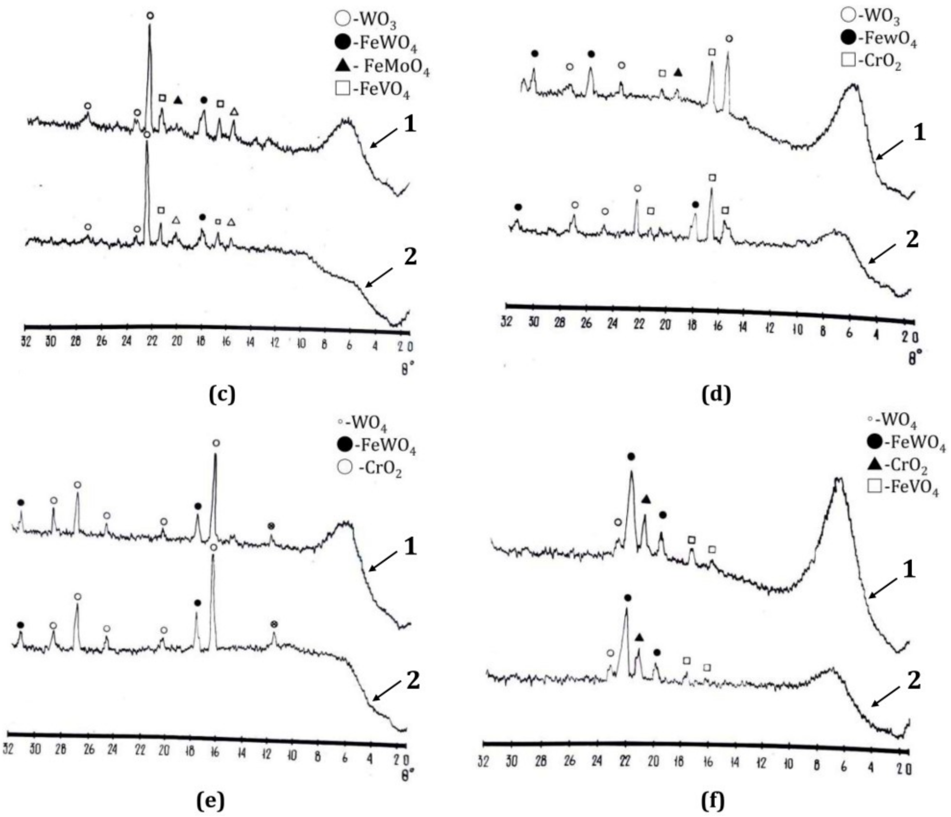


Figure 4: Radiographs. a) t=400⁰C, b) t=500⁰C, c) t=600⁰C, d) t=700⁰C, e) t=800⁰C, f) X-ray of samples held in potassium permanganate solution. 1-non magnetized sample, 2-magnetized sample

The results obtained (according to the effect of the magnetic field on the wear resistance of HSS turning tool) from the experimental analysis can be applied only for finishing and semi-finishing machining operations.

The application of the magnetic field on HSS cutting tools must be carried out depending on the required accuracy and surface cleanliness of the workpiece.

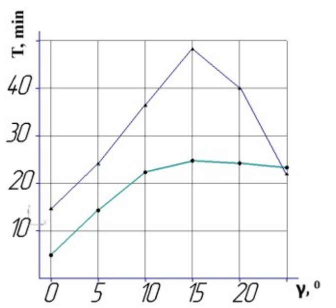


Figure 5: The effect of the rake angle and magnetization on the tool life when machining AISI 1025, V=146m/min, S=0.11mm/rev 1 - non-magnetized tool; 2 - magnetized tool.

3.2 Tool Life

Experimental data, presented in Fig.5 to Fig. 9, show that the HSS tool life increases by 1.5-2 times when they are magnetized. Machining tests were conducted using a HSS AISI T1 solid cutting tool under various cutting conditions.

The study demonstrates the absence of any negative side effects of the magnetic field's influence on the tool. The studies also demonstrate that the effect of the magnetic field depends on the workpiece material being machined.

The effect when treating paramagnetic materials is relatively low compared to the treatment of ferromagnetic materials.

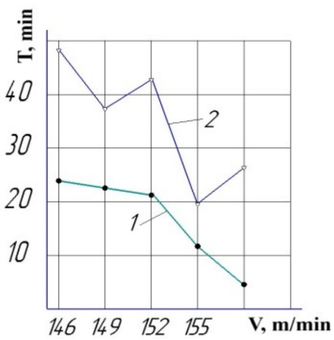


Figure 6: The effect of cutting speed and tool magnetization on the tool life when machining AISI 1025. Feed rate is 0.11 mm/rev. 1 - non-magnetized tool; 2 - magnetized tool.

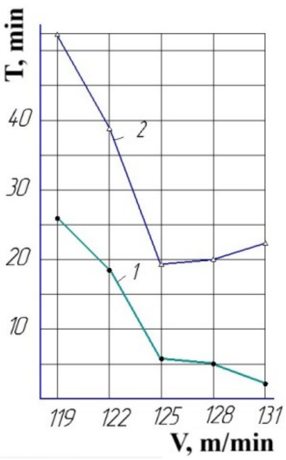


Figure 7: Influence of cutting speed and tool magnetization on the tool life when machining AISI 1025. Feed rate is 0.15 mm/rev. 1 - non-magnetized tool; 2 - magnetized tool.

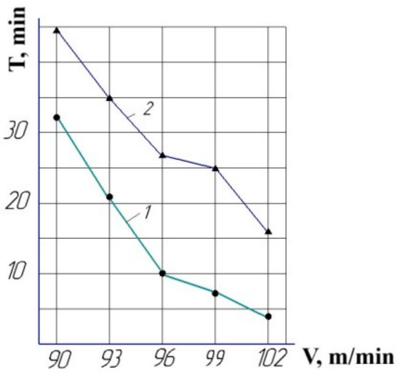


Figure 8: The effect of cutting speed and tool magnetization on the tool life when machining AISI 1025, with a feed rate of 0.2 mm/rev. 1 - non-magnetized tool; 2 - magnetized tool.

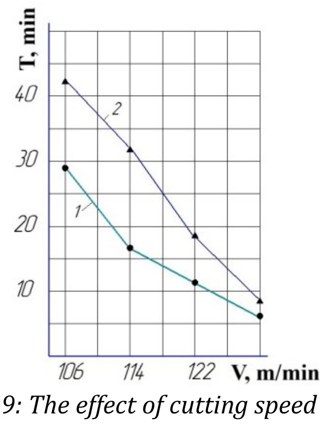


Figure 9: The effect of cutting speed and tool magnetization on the tool life when machining AISI 1045. Feed rate is S=0.2 mm/rev, tool rake angle γ=15°. 1 - non-magnetized tool; 2 - magnetized tool.

Data on the influence of the magnetic field on the oxidation of tool materials are presented in Fig. 10. Comparison of these data shows that when processed in a magnetic field (b), these materials oxidize more intensively than before magnetization (a).

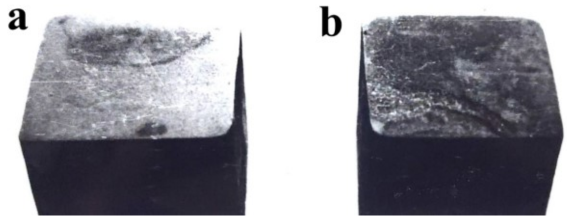


Figure 10: Photograph of samples made of HSS AISI T1 in a 10% potassium permanganate solution. a) before magnetization, b) after magnetization

In the machining materials such as AISI 1025 and AISI 1045, it is advisable to cut with magnetized tools using relatively low feed rates. Moreover, when turning off these materials, the optimal value of the tool rake angle is γ=15° is advisable. In the machining of steel alloys such as 30XGSNA steel and the VT3-1 titanium alloys (GOST 19807-91), it is necessary to consider that the maximum effect from the magnetization of HSS tools is achieved by regulating the cutting speed, the rake angle γ, and the feed rate.

4. Conclusions

Based on the conducted research work and analysis of the obtained experimental data, the following main conclusions can be drawn:

1. In the first, the reasons for the influence of magnetic field on the resistance of samples were determined: it was established that under the influence of magnetization of samples made of HSS, the intensity of their oxidation, the structure, and the chemical composition of the surface layers changed, as a result, it affects the friction coefficients of pairs made of these materials.

2. It has been established that during the Magnetic treatment of HSS samples, changes in the chemical composition occur in their contact and non-contact surfaces. In the surface layer of the sample, up to a depth of 600 µm, the percentage of tungsten increases and the percentage of iron decreases, and above 600 µm, conversely, the tungsten content decreases and the percentage of iron increases.

3. Based on the obtained radiographs, it can be assumed that the change in the wear resistance of high-speed cutting tools during their preliminary magnetization is influenced to a certain extent by changes in their surface layer structure before the cutting process.

4. Turning tests conducted in different cutting conditions prove that magnetically treated AISI T1 HSS tools performed better tool life (1.5-2 times higher) compared to a non-magnetized tool. It is also obtained that the magnetized tool showed better results in higher cutting speeds.

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