Temperature effect on nanostructured wear-resistant coating on the surface of a band-saw cutting tool

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Abstract. The article presents the results of study of temperature effect on microstructural and thermophysical properties of developed nanostructured wear-resistant coating with high strength characteristics, resistance to shock and vibration loads on the surface of metal saw band for industrial instrumental and high-speed steel treatment. Studies are shown on the example of one of the cutting on band-cutting machines, using closed band saws as cutting tools made of spring-spring steels with obtained carbide cutting edges. It is known that the operating conditions of a band saw include such characteristics as increased vibration resistance, resistance to alternating and dynamic loads, as well as increased wear resistance. This article presents the results of the thermal effect on the characteristics of the developed wear-resistant nanostructured coating on the surface of the cutting edge of a band saw tooth for metalworking.

1. Introduction

It is known that at present it is necessary to create a band saw with higher characteristics of high-speed cutting, such as increased vibration resistance, resistance to alternating and dynamic loads, as well as increased wear resistance. One of the proposed ways to solve this problem is to use the same material as a tooth and a saw blade when applying a wear-resistant carbide nanostructured coating to the surface of the cutting edge of the tooth. It is known that the creation of a layered nanocomposite of high-hard refractory phases $\text{Al}_2\text{O}_3$, $\text{TiC}$, $\text{TiN}$, (Ti, Zr) (C, N), $\text{TiB}_2$ is one of the recognized directions for solving the problem of thermomechanical wear of metalworking tools [1-3].

The principal factors of affecting band-sawing processing of metals and alloys include cutting force, cutting geometry, cutting heat, local stress-strain and chip thickness formation uniformity [4]. These complex factors have an important influence on band saw blade and tooth cutter wear, surface roughness of cutting materials, production precision and cutting efficiency in high-speed sawing process of metals and alloys.

It is known that the metal cutting is a coupled thermo-mechanical process [5]. In the process of cutting metal with a band saw, intense heat generation occurs as a result of plastic deformation and friction at the interface between the band saw tooth and the workpiece. The high speed sawing process results in an increase in temperature and normal stress on the band saw blade and at the tooth / chip interface, leading to wear on the saw band and damage to the workpiece material. There are various mechanisms for the wear of the saw band surface and material, but it is generally known that an
increase in temperature leads to progressive wear of the saw band. The thermomechanical heat flux during high-speed sawing creates thermal stresses in the band saw. These thermal stresses are more likely to result in band fatigue, saw tooth failure, wear, and tear and consequent failure.

In ultra-speed steel sawing process at velocity greater than 80 m/min, the WC tool-edge will achieve transient higher temperature 400°C [5]. In order to solve the problem under high temperature, the edge anti-wear TiN coating for adaptive coating-layer range was applied to reduce the cutting temperature raising [5]. With a correct analysis of the operating conditions of band saws for high-speed metal cutting the wear-resistant protective coating by AC magnetron sputtering can be developed. Plasma-based magnetron sputtering allows spraying thin functional films and is currently the most optimal technology for obtaining coatings on band saws in terms of adhesion and the resulting structure of the nanostructured coating.

Spectral emissivity describes the ability of material surface to emit radiation on a certain wavelength in relation to the radiation of a blackbody. The definition is the ratio between the radiant energy emitted from an actual object and that emitted from a blackbody at the same wavelength and temperature. It is known that the observed emissivity of the measured metals increases with increasing roughness [6, 7]. Numerous experiments confirm that both surface oxidation and surface roughness affect spectral emissivity with surface oxidation having a more dominant effect [6, 7]. The effect is more significant when the measured temperature is low. The infrared IR radiation technique is useful method for evaluation of thermal emissivity values of materials and coating in 8-12 micrometer wavelength range.

In this paper, the temperature effect on the microstructural and spectrophysical properties of nanostructured wear-resistant coating on the surface of a band-saw cutting tool are discussed.

2. Materials and equipment
The following equipment was used for research: a JET band saw (testing of the obtained saws under conditions close to the factory ones). A Falcon 500 microhardness tester was used to test the microhardness according to a preliminary analysis of wear resistance. A magnetron radio-frequency deposition unit. Q150T ES RF was applied for the coating process. A JEOL JSM-7500F scanning electron microscope was used to study the microstructure of the coatings. A Perkin-Elmer Spectrum Two FTIR spectrometer was used to analyze the composition of the coatings. A digital electric cooker IKA C-Mag HS7 was taken for heat treatment of the samples. To estimate the emissivity by averaging over the results of three independent measurements, a UT303D digital thermometer was used. The Smart Sensor ST9450 thermal imager with an operating wavelength range of 8–14 µm was used to monitor the temperature fields on the surface of test samples.

3. Analysis of experimental data
To apply nanostructured and wear-resistant coatings by magnetron sputtering on the surface of band saw the sequential technological cycle is used: 1) pre-cleaning the surface of a standard saw band with isopropyl alcohol, the surface of a new, not worn-in saw (as supplied); 2) argon plasma ion etching of the commercial band saw surface with low-temperature argon plasma to improve the adhesion of the applied protective coating; 3) magnetron-plasma spraying of a nanostructured film of metal or alloy on the surface of band saw.

Processing the surface of the industrial band saw teeth and blade surface with low-temperature argon plasma makes it easy to clean the surface of the product from organic dirt and grease residues. At the same time, argon ion-plasma etching occurs with surface ablation of the band saw tooth cutters material. This process which makes it possible to change the microstructural properties of band saw surface, increase the roughness, which will improve the adhesion between the surface of the band saw tooth cutters and their metal blade and the applied protective material. With the magnetron-plasma spraying, nanostructured metal thin-layer films of the desired chemical composition and thickness are deposited in vertical direction upright cutting surface of band saw. For the deposition of nanostructured coatings 100 nm thick on the surface of the cutting edge of band saw a Q150T ES RF
magnetron sputtering unit with appropriate metal targets was used. The following values of magnetron sputtering currents were used at weak discharge (2×10⁻⁴ Pa): 50 mA for chromium, 80 mA for Kh15N60 nichrome, 120 mA for Ti6Al4VW alloy. With the method of obtaining a preliminary coating, no thermal heating of the band saw is observed, due to which there are no residual stresses on the surface of the gear cutter and along the interface between the band saw and the coating.

The produced metal and alloys films were not modified by annealing, but according to IR spectroscopy data, oxide phases were present in them in a small amount due to the used method of magnetron sputtering at weak discharge (10⁻³ Pa) in argon plasma with air oxygen impurities.

The microstructure of the obtained metal coatings on the saw teeth was studied by scanning electron microscope and shown in Figure 1.

![Figure 1](image)

**Figure 1.** Microstructure of the obtained coatings a - nichrome Kh15N60; b - Ti6Al4VW alloy; c – chrome.

According to electron microscopy data, it can be seen that the fabricated coatings contain clusters of nanoparticles 10–30 nm in size and the size of clusters of nanoparticles in different coatings is different. Table 1 presents data on the weighted average calculated size of nanoparticles in the applied nanostructured coatings. The data was obtained using the Gwyddion 2.54 program.

|          | chromium | Kh15N60 | Ti6Al4V |
|----------|----------|---------|---------|
| size (nm)| 11±3     | 25±6    | 14±4    |

It can be assumed that, in accordance with the well-known Hall-Petch equation [9], the size of the nanoparticles in the films of the deposited metal and alloy films is close to the transition from the forward Hall-Petch law to the reverse one [10, 11]. Thus, a high microhardness can be expected from the obtained nanostructured coatings. For chromium coating it can be expected, that size of produced nanoparticles is smaller than transition from Hall-Petch region to inverse Hall-Petch range [12].

The Rockwell microhardness of the obtained samples of coating on the band saw teeth surface was measured on a Falkon 500 microhardness tester and microhardness values were taken as averages over the results of 10 measurements (Table 2).

**Table 2.** Rockwell microhardness of samples of the initial material of saw teeth and with applied nanostructured coatings.

| saw tooth material | chromium | Kh15N60 | Ti6Al4V |
|--------------------|----------|---------|---------|
| 54±2               | 55±4     | 62±2    | 71±2    |

From the data in Table 2, it follows that, with the exception of the chromium film, the nanostructured alloy coatings were used noticeably increase the hardness of the working surfaces of the HSS saw teeth. In the case of a chromium film, it can be assumed that the small size of chromium nanoparticles, characteristic of the region with the manifestation of the inverse Hall-Petch effect, leads to the formation of an amorphous film coating with low microhardness. In the case of the prepared
coating of the Ti6Al4V alloy, the obtained considerable microhardness result is rather unexpected. Nevertheless, it was recently shown in [13] that the Ti6Al4V alloy nanostructured by laser sintering has a nanohardness of 7.43 GPa.

Thus, the obtained results show that the developed single-layer nanostructured coatings noticeably increase the hardness of the working surfaces of high-speed steel band saw.

Further, the results of a study for the effect of oxidative annealing in air on the characteristics of a wear-resistant nanostructured metal coating for a band saw were considered. A high-speed (50°C / minute) thermal annealing was carried out with a holding time of 2 minutes at the temperature points of interest for samples of saw teeth with and without coatings in the temperature range from 50 to 300°C with a step of 50°C. At each temperature, after 2 minutes of heating for 20-30 seconds, a threefold determination of the heat emission coefficient (Figure 2) was carried out in the direction of the normal to the saw tooth fixed horizontally on the ceramic heating surface of the electric stove.

A systematic increase in the observed characteristics of thermal emission in the mid-IR range is associated with the formation of films of metal oxides, both on the surface of metal wear-resistant coatings and on the surface of the material of the saw teeth. Also, an increase in the roughness of the surface oxide films formed during thermal action leads to an increase in the emission characteristics of the developed coatings with increasing temperature. The microstructure of the obtained film oxide coatings from an alloy of nichrome grade X15N60 on the saw teeth was investigated using a scanning electron microscope at high magnification and is shown in Figure 3.

The microstructure of the samples of the obtained protective coatings after thermal air-oxidative annealing in air shows a pronounced change in the microstructure with an observed increase in roughness in comparison with the protective metal coatings applied by magnetron sputtering. This occurs both due to the oxidation of metal nanoparticles according to the obtained IR spectroscopic data and due to the effect of recrystallization of the formed oxide phases. In all cases studied by us, the
samples of the obtained oxidative coatings have a pronounced nanostructure with a nanoparticle size from 20 to 45 nm.

During thermal oxidative annealing of saw teeth made of a high-speed alloy with an approximate composition of WC-15% Co, the oxidation products will be tungsten trioxide (WO$_3$) with a small proportion of cobalt tungstate (CoWO$_3$) [14]. During thermal oxidative annealing of nichrome grade Kh15N60 (so-called ferronichrome with an approximate elemental content of Ni - 60%, Cr - 15%, Fe - 25%), the products of low-temperature oxidation are most likely to be metal oxides of the following compositions: NiO, Cr$_2$O$_3$, Co$_3$O$_4$, Fe$_3$O$_4$ and Fe$_2$O$_3$.

It is known that during thermal oxidation of titanium alloys, according to X-ray photoelectron spectroscopy data [15], films of amorphous oxide of three types of titanium oxide phases TiO, Ti$_2$O$_3$, and TiO$_2$ are formed on the surface. Under our conditions of prolonged thermo-oxidative annealing, the expected main phase in the obtained coatings is TiO$_2$. It is known that the main crystalline phases of TiO$_2$ are the phases of tetragonal anatase and rutile. At low-temperature oxidation up to 400 °C, the anatase phase predominates [16]. Based on the used thermal annealing conditions, it can be assumed that the nanostructured oxide film obtained by thermal oxidation of the Ti6Al4V film consists of rutile nanoparticles interspersed with highly hard Al$_2$O$_3$ nanoparticles.

In the case of a chromium film, the main product of its surface thermal oxidation is chromia Cr$_2$O$_3$, which is formed at low intensity at low temperatures, thereby indicating the heat resistance of the studied chromium nanofilm.

4. Conclusion
Samples of nanostructured wear-resistant coatings with high strength characteristics, resistance to shock and vibration loads on the surface of carbide cutting teeth and a metal band saw for industrial high-speed tool steel cutting machines were manufactured and studied.

The results of studying the effect of temperature in the range of 100-300°C on the microstructural and spectrophysical properties of the developed wear-resistant coatings showed that during the formation of surface oxide films, the microstructure and surface roughness of protective coatings change. Also, the thermal emission characteristics in the thermal IR range for the developed wear-resistant nanostructured coatings, especially ferronichrome Kh15N60 and Ti6Al4V alloys, on the surface of the cutting edge of the teeth of a band saw for industrial metalworking, also sharply increase.

5. References
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