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USE OF STEEL GAS THERMAL COATINGS TO INCREASE WEAR RESISTANCE OF PARTS

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Summary. *The process of gas-thermal spraying of coatings made of wire materials has been studied by determining rational regimes to increase the wear resistance of surfaces of vehicle parts. It is determined that the main factors influencing the wear resistance of steel gas-thermal coatings are the cooling rate of steel and the concentration of alloying elements.*

It is shown that in order to obtain wear-resistant sprayed coatings from alloyed structural steels it is necessary to achieve certain conditions of coating formation, namely: heating and spraying temperature of wire, cooling rate of molten particles, and their oxidation state. One of the most probable reasons for increasing wear resistance is the saturation of the melt droplets with alloying elements (primarily chromium) and impurities of introduction (carbon, nitrogen) in the process of melting the wire in the flame. The relatively low flight speed of molten steel particles and the high concentration of propane-containing carbon in the combustion products contribute to the deep saturation of the melt droplets with carbon. It is likely that these circumstances are associated with the process of increasing the wear resistance of coatings obtained by gas-flame and electric arc spraying. An additional factor that increases the wear resistance of the sprayed coating may be the saturation of the melt droplets with carbon in the process of melting and spraying using propane flames.

Studies have suggested that both for the method of gas-flame spraying and for the method of electric arc spraying, there are modes and steels for spraying, which can increase the wear resistance of the coating. On the basis of the conducted researches technologies of strengthening and restoration of details of vehicles by drawing wear-proof coverings are offered.

Key words*: gas-thermal spraying, coating, electric arc spraying, gas-flame spraying, wire materials, wear resistance, strengthening, restoration, alloy structural steels.*

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Statement of the problem. The methods of multifunctional coatings application based on the wire-shaped material spraying have proved to be the most efficient methods of surface reconditioning, strengthening, and protection of wearing surfaces of transportation means (TM) parts of components and assemblies. At the parts of transportation means reconditioning it’s preferable to use gas flame spraying (GFS) and electric arc spraying (EAS) of the wire-shaped material [1–3] to save the time of the spraying process due to the increase of the sprayed particles flying speed by means of gas heating by an uninterrupted power supply [4, 5].

Purpose of the study. The purpose of the study was to investigate the structure of gas thermal coatings made of wire-shaped materials by means of finding the most efficient methods of structure formation process control to achieve the most beneficial physical-mechanical properties of reconditioned surfaces of the parts.

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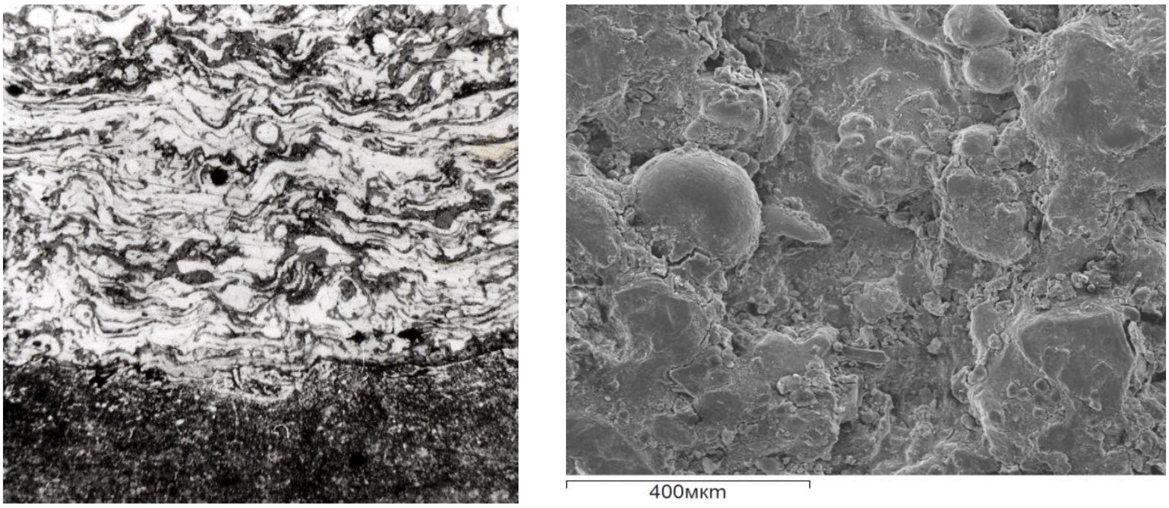
Analysis of the available investigations. Some structural specific features of gas thermal coatings (GTC) obtained by steel wire spraying of martensite (40Kh13) and austenite class (Kh18N10T) by different methods of gas flame spraying (GFS) and electric arc spraying (EAS) have been studied [6] in the following modes:

- mode 1 – spraying of the material melted in a flame body of propane-oxygen flame by a high-speed air stream;
- mode 2 – spraying of the material melted in an electric arc by a jet stream of propane-air mixture flame products rich in propane (deoxidizing atmosphere);
- mode 3 – spraying of the material melted in an electric arc by a jet stream of propane-air mixture flame products rich in the air (oxidizing atmosphere);
- mode 4 – spraying of the material melted in an electric arc by the high-speed air stream.

To increase the coating adhesion with the reconditioned surface made of steel 45 we have used an intermediate layer made of alloy Kh20N80. The flying speed of the sprayed particles was ranging within 100 ... 130 m/c (modes 1, 4) 400 ... 500 m/c (modes 2, 3). The size of particles forming the coating was ranging within 5 ... 40 mkm.

The coatings obtained due to the wire-shaped materials spraying are in their structure similar to gas thermal powder coatings. Nevertheless, in the case of gas thermal spraying of powder materials, some separate particles cannot be enough melted or can be heated to permeating temperatures, but during the spraying of one-piece wires the coating layer is being formed only from the melted particles (otherwise the drops separation from the wire will not occur). It results in larger deformation of particles than in case of powder coatings and less sponginess (fig. 1).



a) X 200

b)

Figure 1. Microstructure (a) and microtopography (b) of electric arc coating from steel 40Kh13

The study of the microstructure was carried out on unetched and etched sections using a light microscope «MeF-3» company «Reichert» (Austria) at a magnification of ×100, ×200, ×500. The surface topography of the coated sample was obtained using a CamScan scanning electron microscope (Oxford Instruments, England) with an X-ray energy dispersive analyzer. The morphology (topography) of the coating surface was studied in the mode of reflected electrons at an accelerating voltage of 10–20 kV. The resolution of this SEM is 70 Å.

The formation of coating is accompanying with the intense impact of flame body on the particles of spraying material and their interaction during the process of coating layer formation on the reconditioned surface of the part. In this case, due to the processes of high-speed crystallization, deformation and drawing inn the layer of formed coating, some oxides are occurring, a part of alloying elements is burning up. Thus, structural state and properties of obtained coatings on the reconditioned surfaces depend on the combination of influence of all parameters of the spray application.

Most of oxides are formed due to the contact of melted particles with air. That is why the impact of spraying air consumption on the amount of oxygen in the coatings obtained in mode 1 by gas flame spraying and in mode 4 by electric arc spraying has been studied. The volume share of the oxides in gas thermal coatings had been studied earlier and the results were described in paper [6, 7].

Under gas-thermal spraying of wires conditions the maximum oxygen content in the coatings was ranging within 1,50 ... 1,70% and it can be obtained at spraying air consumption over 0,35 m^3/min(fig. 2). Further increase of spraying air consumption has not resulted in the oxygen concentration increase. Oxygen content in electric arc coatings is 2,5 ... 3 times higher than in gas flame ones. Moreover, the maximum concentration 3,8% is reached under spraying air consumption conditions of nearly 0,5 m^3/min.

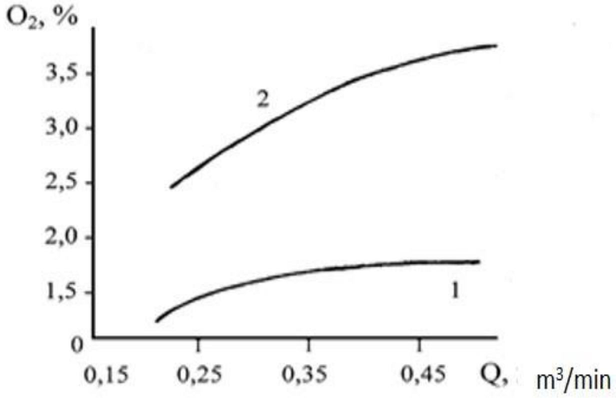


Figure 2. Influence of the flow rate of spraying air on the oxygen content in coatings obtained by gas-flame (1) and electric arc spraying (2)

In the coatings made of steel 40Kh13 obtained both by electric arc spraying and by gas-flame spraying the anomalous large amount of residual austenite has been found (by gas-flame spraying up to 40 vol.%). The normal content of residual austenite in hardened steel 40Kh13 does not exceed 3–5 vol. %.

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It is known [6] that the main factors making impact on the content of residual austenite in hardened steel are the steel quenching rate, alloying elements concentration in austenite phase and also austenite thermal stabilization under self-tempering condtions.

To check the influence of the steel 40Kh13 quenching rate on the austenite content in it the quenching hardening of the wire used for spraying was carried out as an experiment. The isothermal temperature limit of the wire patterns made of steel 40Kh13 under heating for hardening conditions was chosen equal to 1350 K, time of heating – 20 min., cooling was taking place in salt water (15%

NaCl). The phase analysis results of the hardened wire steel 40Kh13 have proved the absence of residual austenite in it while a small amount of chromium carbide $Cr_{23}C_6$ persisted. The values of crystal lattice period for the martensite of the hardened wire was equal to a_α = 0,2873 nm, that was a bit lower the level a_α for the sprayed coatings. Thus, the quenching hardening of the wire steel 40Kh13 has not resulted in residual austenite stabilization in it.

One of the most probable reasons of «austenite effect» taking place in the coatings is the upper layer heating up to the temperature 500-670 K which facilitates the thermal stabilization of austenite and the saturation of the melt drops with alloying elements (first of all with chromium) and impurities (carbon, nitrogen) during the wire melting in the flame. This is proved by the absence of carbides particles $Cr_{23}C_6$ in the coating. One more factor increasing the austenite resistance in the sprayed coating can be the saturation of melt drops with carbon during the process of melting and spraying using propan flame (table 1).

Table 1

The influence of the composition of combustion mixture forming the spray on the carbon and oxygen contents in gas thermal (GAS) coatings from steel 40Kh13

Technique of spraying	Air/propane volume ratio in mixture	Oxygen content in coatings, %	Carbon content in coatings, %
GFS mode 1	(Gas flame) propane/oxygen ratio 1/4	1.3	0.6
EAS mode 2	(EAS) 18	1.4	0.5
EAS mode 3	mode 3 (EAS) 30	2.2	0.4
EAS mode 4	mode 4 (EAS clean air)	3.3 – 3.5	0.4

Relatively low flying speed of melted steel particles and high concentration of propan containing carbon in combustion products contribute to deep saturation of melt drops with carbon. It’s quite possible that a deep content of residual austenite in the coatings obtained by gas flame spraying in connected with these circumstances.

A bit smaller amount of austenite in the coatings obtained by electric arc spraying in the deoxidizing atmosphere (in mode 2) of the spraying torch can be explained by considerably higher flying speed of melted particles which is a specific feature of this way of spraying. In this case the processes of diffusion saturation of melt drops with carbon from the deoxidizing atmosphere of propan-air mixture combustion products have no time to occur (the time of melted drops flight in the combustion products atmosphere is not more than $5 \cdot 10^{-4}$c) and the content of residual austenite in a coating layer is decreasing to $\cong$ 20 об. %.

The increase of oxygen concentration in the mixture was not accompanied with the change of residual austenite content in the coating obtained under super sound speed of melted particles flying conditions (mode 3) and under relatively low speed of melted particles flying conditions (mode 4). In both spraying options the residual austenite content in the coating does not exceed 20 vol. %. Perhaps, such content of residual austenite in steel 40KhN is balanced for the case of complete decomposition of chromium carbides in it and the implementation of typical of GFS cooling conditions of melted steel drops.

To activate the decay process of residual austenite in the gas-flame sprayed coating the tempering was conducted at temperature 520, 620, 720, 770 і 820 K. The holding time of the tempering was 9 min. The X-ray phase analysis data have proved that the decay of stabilized residual austenite of the coating sprayed layer was taking place due to the high pressure at temperature range within 770 ... 820 K. At lower temperature the tempering was not accompanied with the decrease of residual austenite amount in the coating layer. High temperature of the tempering necessary for the sprayed layer austenite decay is caused by the temperature of chromium carbides development in it and after their separation the residual austenite resistance has drastically decreased. The sprayed layer hardness after tempering at 770 K was equal to 2800 MPa.

The sprayed coatings in their initial state had the hardness of 360 ... 380 MPa, microhardness HV_{30} = 2650 MPa, residual austenite content 40 ... 45 vol. % (fig. 3).

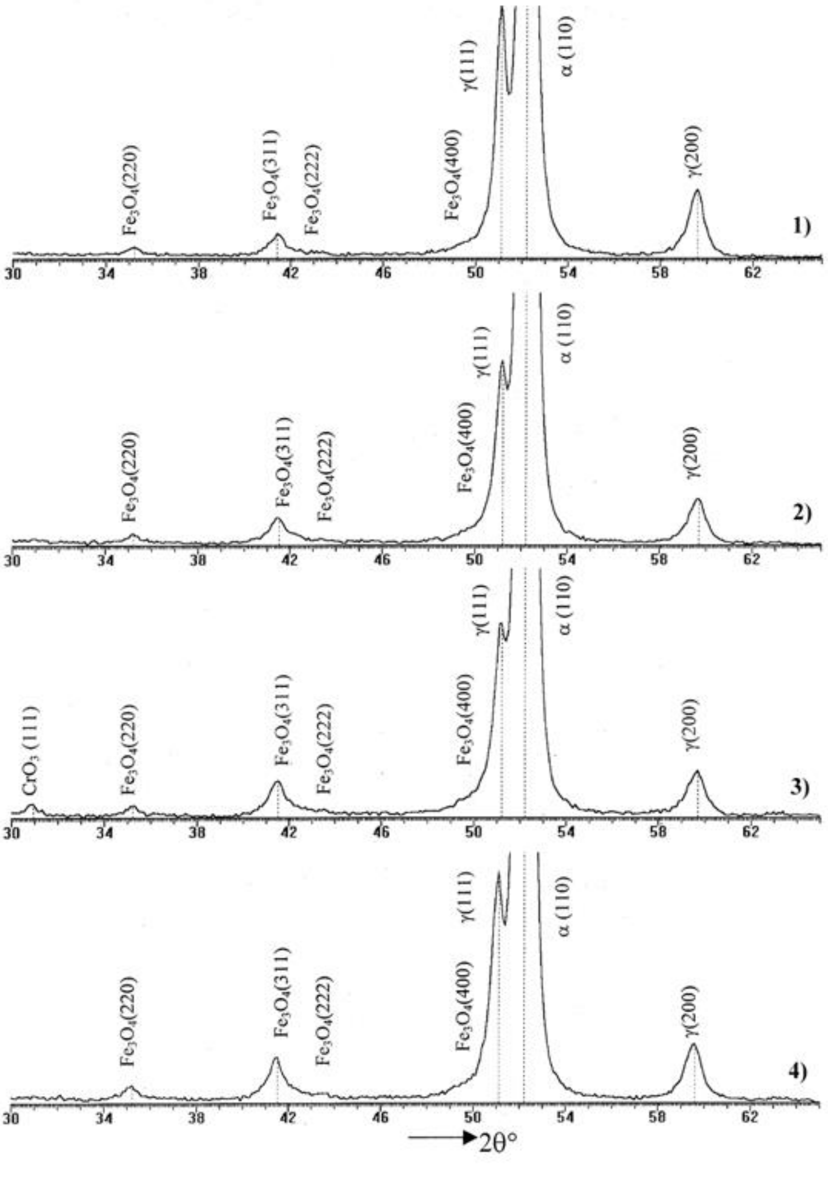


Figure 3. Fragments of X-ray diffraction patterns (CoK_α) from the surface layers of gas-thermal coatings obtained under modes 1-4 (table 1)

One of the main requirements to satisfy the upper layers of the reconditioned parts of tribocouples is plastic property during the initial period of friction to accelerate the process of under working, and also high wear resistance, hardness, adhesion to lubrication during further operation of the assemby. This requirement dealing with steels can be met only in case when two-phase structure was formed in the steels containing metastable austenite of hardness 200–300 HV. In the process of under working as a result of intensive plastic deformation the metastable austenite is transformed into the wear resistant and hard martensite (HV = 700 ... 800) as the deformation $\gamma \rightarrow \alpha$ transformation was taking place.

The conducted investigation made possible to assume that for both the gas-flame spraying method and for electric arc spraing method there are such modes and steels for spraying which allow providing the formation of large amount of metastable austenite in the coatings which will be transformed in martensite during the process of tribocoupling.

In cast steels to obtaine metastable austenite one should apply the special alloy method, complex thermal and thermo mechanical treatment who's conducting is mostly economically inadvisable.

To provide the metastable austenite formation with low temperature of deformation $\gamma \rightarrow \alpha$ transformation (temperature $M_{Д}$) corresponding to the operating temperature of sliding friction units (270–20 K) in the sprayed coating structure, one should reach the determined conditions of the coating formation, namely wire heating temperature (overheating above the point of melting), the temperature of its spraying, speed of melted particles cooling and the degree of their oxidation resulted in the change of alloying constituents concentration.

The experimental study has proved the relation between the temperature value of the beginning of martensite transformation of wire material T_M and the amount of metastable austenite appearing in the formed coating (table 2).

In alloy-treated structural steels, and also in corrosion-resistant steels of martensite class the temperature of the beginning of martensite transformation T_M *is* ranging within 550 ... 700 K (steel group № 1, table 2). Whilst wires made of these steels spraying it was found that the volume content of metastable austenite has reached 24%, if the temperature of wire heating is not higher than 2000 K.

The temperature of martensite transformation T_M in tool (die) steels, and also in structural spring steels is ranging within 420 ... 540 K (steel group № 2, table 2). Whilst wires made of these steels spraying it was found that metastable austenite appeared of amount 15 ... 25 об. % was possible if the sprayed wire was heated to the temperature not higher than 2100K.

In corrosion-resistant and heat resistant steels as well as in Hadfield steel the temperature of martensite transformation T_M ranges from 70 ... 110 K (steel group № 3, table 2). Due to the low temperature of the beginning of martensite transformation T_M, the austenite structure in these steels is characterized by high resistance, hence they are called - «steels of austenite class». For the phase strengthening of the upper layers of steel of austenite class due to the process of martensite transformation a high degree of deformation is required, which is inaccessible at frictional interaction with lubricating material (boundary friction). It was found, that due to the wires spraying made of these steels at the temperatures above 2500 K it is possible to raise the temperature of martensite transformation T_M, the temperature of deformation $\gamma \rightarrow \alpha$ transformation $M_{Д}$ and carry out the destabilization of austenite phase in the formed coatings.

Table 2

Metastable austenite content in gas thermal coatings obtained by spraying various steel grades

Group of steels	Steel grade	Temperature T_M, K	Temperature of heating under spraying, K	Content of austenite in coating, vol%
1	09G2S, 40KhN, 20Kh13, 40Kh13	550–700	1700–2000 2100–2500 > 2600	25–45 17–20 < 6
2	9KhS, Kh12MF, 9Kh12, Kh6VF, 35KhNM, 40KhFVA, 65G	420–540	1700–2100 2200–2500 > 2500	15–25 8–12 < 6
3	08Kh18N10, 12Kh18N10T, 110G13	70–110	1700–2000 2000–2500 > 2500	95–98 90–95 90–95

The austenite stability decrease in the third group steels coatings obtained by the spraying at temperature above 2500 К can be explained in the following way. The chromium and manganese content in steel has made the most important impact on the temperature interval state of martensite transformation. Thus, the manganese content decrease from від 5% to 1% has caused the raise of temperature T_M from 270 to 470 К [8]. As a result, one of the possible ways to increase temperature T_M is lower content of chromium or manganese in the austenite phase of steels due to oxidation under spraying conditions. The change of the coating composition due to the intense oxidation at temperature above 2500 К has made possible to of austenite structure resistance and to raise temperature $M_{Д}$ to the room temperature level.

At wire spraying from steel of the first two groups of steel the preservation of great amount of metastable austenite can be explained in the following way. High speed of steel particles crystallization during the sprayed layer formation and slower speed of its cooling in the interval of martensite and bainite transformations under coating cooling conditions have provided the austenite thermal stabilization. The thermal stabilization is getting more intense if the reconditioned surface of the part is preheated. The increase of metastable austenite contents was being observed at the reconditioned surface of the part heating to 480 К (fig. 4). Further heating of the part was resulted in decrease in strength of the coatings adherence with the reconditioned surface. Preheating of the part prior to the spraying of alloyed wire steels of high temperature T_M has enhanced the effect of austenite stabilization and has made possible to increase the metastable phase volume in the sprayed coatings.

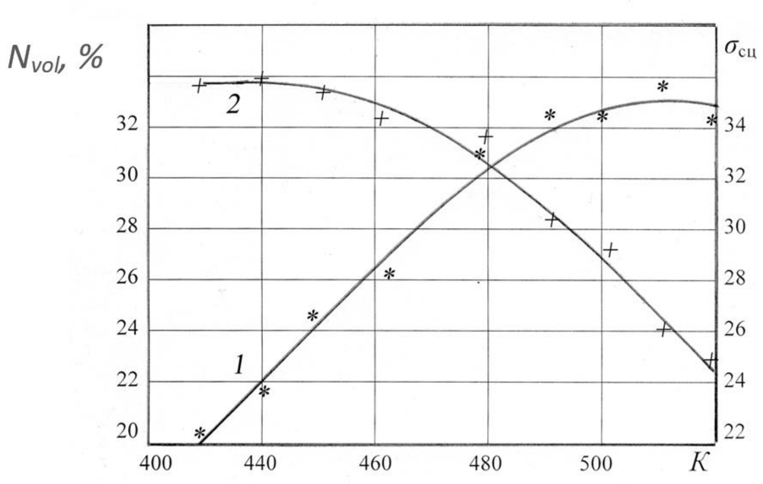
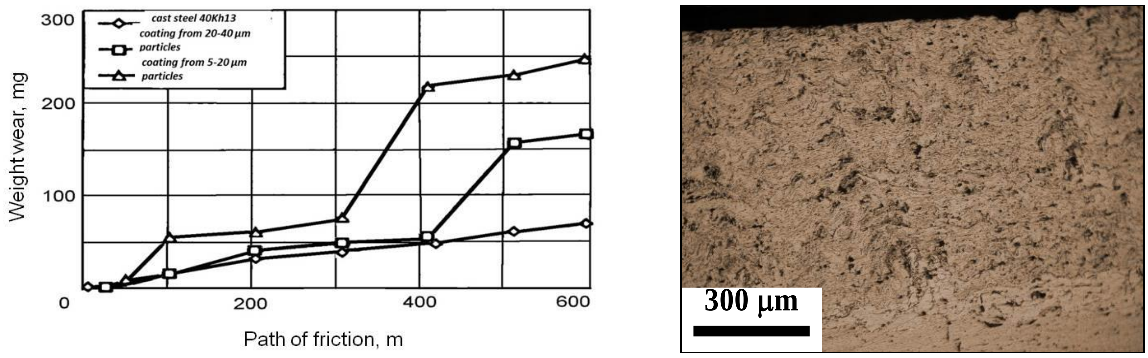


Figure 4. The dependence of the amount of metastable austenite (vol.%) (1) in steel coatings 40KhN and their adhesion (MPa) (2) on the preheating temperature of the surface

Some technological recommendations on parts reconditioning have been developed on the basis of the results of conducted study. Thus, the method of electric arc spraying using steel wire 40Kh13 was chosen to restore the worn out bearing spindles of distributing shafts. Wear resistance of reconditioned surfaces with coatings after the period of wear-in was 40–50% higher than the coating wear resistance sprayed by the same material by gas flame method. The analysis of development and operation testing results has shown that the reconditioned surfaces of distributing shafts with the coatings applied by electric arc spraying had the wear resistance 1,4–1,7 times higher than the coatings obtained due to the gas flame method.

Accelerated tribotechnical tests of specimens with gas thermal coatings (GTC) made of 40Kh13 wire steel and specimens of rolled 40Kh13 steel that had undergone preliminary quenching and high tempering at 970 K for 5 h (HV = 2700 MPa) were carried out on a modernized 2070 SMT-1 machine. In the process of friction without lubrication, the adhesive interaction of the coating material with the counter body occurs, which is accompanied by wear of the mating materials (Fig. 5 a). Analysis of the graphs in fig. 5, a shows that the curve of accumulated weight wear of tempered steel has a characteristic run-in stage and a steady-state wear area with close to linear dependence of weight wear on the friction path. For of GTC coatings, the stages of steady wear are periodically replaced by relatively short-term stages of accelerated wear, i.e. wear of GTC coatings has a pronounced cyclic character (Fig. 5, a).

During spraying, an inhomogeneous structure is formed, formed by the layer-by-layer stacking of molten droplets of the sprayed material (fig. 5, b). Such a structure provides damping of elastic excitations caused by friction. After tribotechnical tests for 9 hours, no noticeable wear of the electric arc coating was revealed.



a

b

Figure 5. Dependence of the weight wear on the friction path for EAS coatings from steel 40Kh13: friction without lubrication, pressure 1.5 MPa, counter body from hardened steel 60 (a) and structure of EAS coating after 9 h testing (b)

Conclusions. It was proved that to provide the formation of metastable austenite with low temperature of deformation $\gamma \rightarrow \alpha$ transformation corresponding to the operating temperature of sliding friction units in the structure of sprayed coatings made of alloy-treated structural, instrumental and corrosion resistant steels, one should reach the determined conditions of the coating formation (heating temperature, the temperature of wire spraying, speed of melted particles cooling and the degree of their oxidation). On the basis of conducted investigation some technologies have been proposed dealing with the parts reconditioning by multifunctional coatings applying where the choice of wire heating method under spraying conditions is made depending on the temperature of the wire material martensite transformation start. In the course of tribotechnical tests, it was found that the wear of sprayed coatings is cyclic. The cyclicity of the weight wear of sprayed coatings is associated with the degradation of their surface layer during friction, which is described in terms of the concepts of physical mesomechanics of solids.

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ВИКОРИСТАННЯ СТАЛЬНИХ ГАЗОТЕРМІЧНИХ ПОКРИТТІВ ДЛЯ ПІДВИЩЕННЯ ЗНОСОСТІЙКОСТІ ДЕТАЛЕЙ

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Резюме. *Досліджено процес газотермічного напилення покриттів із дротяних матеріалів шляхом визначення раціональних режимів для підвищення зносостійкості поверхонь деталей транспортних засобів. Визначено, що основними факторами, які впливають на зносостійкість стальних газотермічних покриттів, є швидкість охолодження сталі та концентрація легуючих елементів. Показано, що для отримання зносостійких напилених покриттів із легованих конструкційних сталей необхідно досягти* *певних умов формування покриття, а саме: температури нагрівання і розпилення дроту, швидкості охолодження розплавлених частинок і ступеня їх окислення. Однією з найбільш ймовірних причин підвищення зносостійкості є насичення крапель розплаву легуючими елементами (перш за все хромом) і домішками впровадження (вуглець, азот) у процесі розплавлення дроту в полум'ї. Відносно низька швидкість польоту розплавлених частинок сталі й висока концентрація пропану, що містить вуглець у продуктах горіння, сприяють глибокому насиченню крапель розплаву вуглецем. Ймовірно, що саме з цими обставинами пов'язаний процес підвищення зносостійкості покриттів, отриманих як газополуменевим напиленням, так і електродуговим напиленням. Додатковим фактором, що збільшує зносостійкість напиленого покриття, може бути насичення крапель розплаву вуглецем у процесі розплавлення й розпилення з використанням полум'я пропану.*

Проведені дослідження дозволили припустити, що як для методу газополуменевого напилення, так як і для методу електродугового напилення існують такі режими й сталі для розпилення, які дозволяють забезпечувати підвищення зносостійкості покриттів. На підставі проведених досліджень запропоновано технології зміцнення та відновлення деталей шляхом нанесення зносостійких покритті.

Ключові слова: *газотермічне напилення, покриття, електродугове напилення, газополуменеве напилення, дротяні матеріали, зносостійкість, зміцнення, відновлення, леговані конструкційні сталі.*

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