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Use of structural anomalies in steel gas-thermal coatings during increased wear-out

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Abstract

The structure of gas-thermal coatings made of wire materials has been studied by determining the most efficient methods of controlling the process of structure formation to achieve the highest physical and mechanical properties of renewable surfaces of vehicle parts.

The effect of formation of anomaly amount of residual austenite in sprayed steel coatings was established. Technologies of application of the “austenitic effect” is suggested here to increase a coating wear-resistance. It is determined that the main factors influencing the content of residual austenite in hardened steel are the cooling rate of steel, the concentration of alloying elements in the austenitic phase, as well as thermal stabilization of austenite during self-tempering.

It is shown that to ensure the formation in the structure of sprayed coatings of alloy structural, tool and corrosion-resistant steels of metastable austenite, which has a low flow temperature of deformation gamma-alpha transformation, which corresponds to the operating temperatures of sliding friction units, it is necessary to achieve certain coating conditions. wire spraying, cooling rate of molten particles and the degree of their oxidation). One of the most probable reasons for the appearance of the "austenitic effect" in coatings is the heating of the surface layer to a temperature that promotes thermal stabilization of austenite, as well as saturation of melt droplets with alloying elements (primarily chromium) and impurities (carbon, nitrogen) in flames. 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 a high content of residual austenite in the coatings obtained by gas-flame spraying. An additional factor that increases the resistance of austenite in the sprayed coating may be the saturation of the droplets of the melt with carbon during melting and spraying using a propane flame.

The studies under discussion 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 that allow the formation of large amounts of metastable austenite in coatings, which in the process of tribocoupling will turn into martensite.On the basis of the carried-out researches technologies of restoration of details of vehicles by drawing multipurpose coverings in which the choice of a method of heating of a wire at spraying is carried out depending on temperature of the beginning of martensitic transformation of a wire material are offered.

Key words: electric arc spraying, gas flame spraying, wear resistance, residual austenite, resurfacing, gas thermal coating

State of the matter

The mehods of multifunctional coatings application based on the wire-shaped materail 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 materail [2] to save time of the spraying process due to the increase of the sprayed particles flying speed by means of gas heating by an uninterrapted power supply [3].

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 transportation means parts.

Research procedure

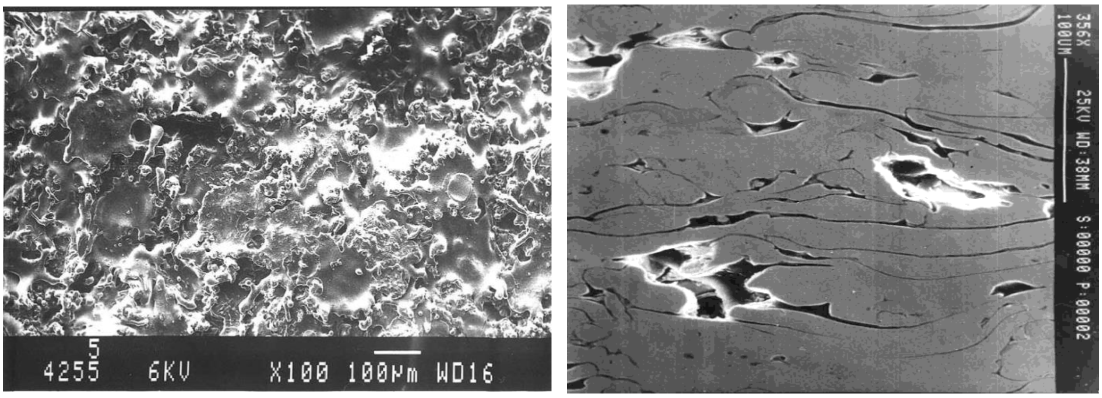
Some structural specific features of gas thermal coatings (GTC) obtained by steel wire spraying of martensite (40Kh13) and austenite class (Kh18N10T) by different methods of gas flame spraying (GFS) and electric arc spraying (EAS) have been studied [3] in the following modes:

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

Results of their study and their discussion

The coatings obtained due to the wire-shaped materials spraying are in their structure similar to gas thermal powder coatings. Nevertheless, in case of gas thermal spraying of powder materials some separate particles can not be enough melted or can be heated to premelting 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) b)

Fig. 1. Microtopography (a) and microstructure (b) of steel gas-thermal coating

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 crystalization, deformation and drawing innthe 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 [3].

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 concdentration 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.

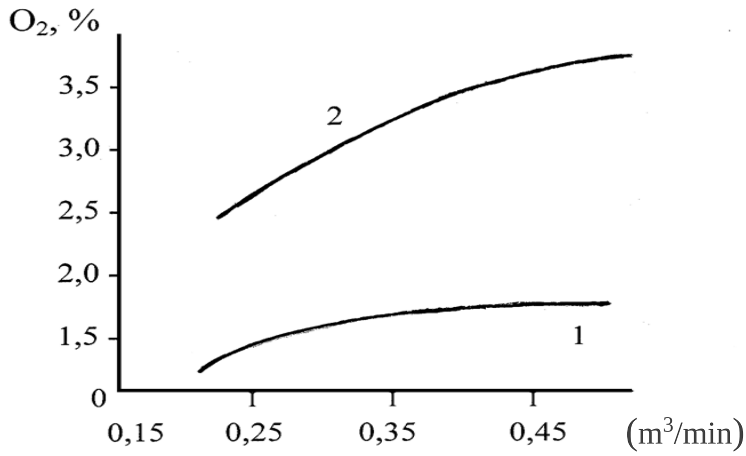


Fig. 2. The effect of the spraying air consumption on the amount of oxygen in the coatings obtained by gas-flame spraying in mode 1 (1) and electric arc spraying in mode 4 (2)

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 sprayedcoating can be the saturation of melt drops with carbon during the process of melting and spraying using propan flame (table 1).

Table 1

The effect of the composition of the combustible mixture, forming a torch in gas-flame and electric arc spraying on the content of carbon and oxygen in the coatings of steel 40Kh13

Spraying mode	Oxygen-propan volume ratio in the mixture	Oxygen content in the coating, %	Carbon content in the coating, %
GFS mode 1	Propan-oxygen mixture, ratio 1/4	1,3	0,6-0,7
EAS mode 2	Propan-air mixture, ratio1/18	1,4	0,5
mode 3	Propan-air mixture, ratio1/30	2,2	0,4
mode 4	Pure air	3,3-3,5	0,3-0,4

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 coattings 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
≅ 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 i 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).

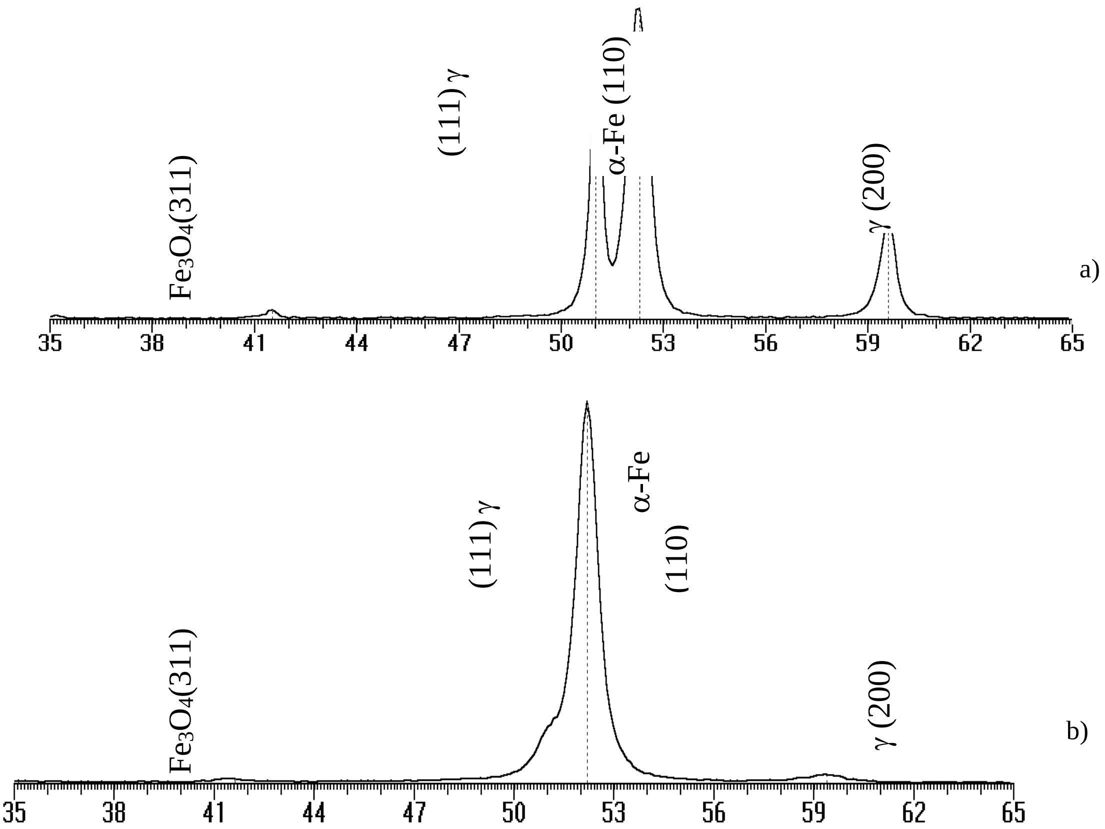


Fig. 3. Fragments of X-ray diffraction patterns from the surface layers of coatings after gas-flame (a) and electric arc spraying (b)

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 underworking, 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 inthe steels containing metastable austenite of hardness 200 - 300 HV. In the process of underworking 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 spraying method there are such modes and steels for spraying which allow to provide 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 thermomechanical treatment whose 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 oxydation 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 corossion-resistant steels of martensite class the temperature of the beginning of martensite transformation T_M *is* ranging within 550 ... 700 K (steel group №1, tabl. 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, tabl. 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 2100 K.

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, tabl. 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 steels 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

The content of metastable austenite in the coatings obtained by spraying of different grades of steel

№ of steel group	Steel grade	Temperature of martensite transformation T_M, K	Temperature of heating at spraying, K	Austenite content in the coating, vol.%
1	09GC, 40KhN, 20Kh13, 40Kh13	550…700	1700…2000 2100…2500 > 2600	17…25 7…15 < 6
2	9KhC, Kh12MF 9Kh12, Kh6VF, 35KhNM, 40KhFVA, 65G	420…540	1700…2100 2200…2500 > 2500	15…25 8…12 < 6
3	08Kh18N10T 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 K can be explained in the folowing way. The chromium and manganese content in steel has made the most important impact on the tempearture interval state of martensite transformation. Thus, the mangenese content decrease from від 5% to 1% has caused the raise of temperature T_M from 270 to 470 K [5]. As a result, one of the possible ways to increase temperature T_M is lower content of chromium or mangenese 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 K has made possible to of austenite structure resistance and to raise temperature $M_Д$ to the roomtemperature 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 folowing way. High speed of steel particles crystalization 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 of metastable austenite contens was being obsderved at the reconditioned surface of the part heating to 480 K (fig. 4). Further heating of the part was resulted in decresae in strength of the coatings adherence with the reconditioned surface. Preheating of the part prior to the sparying of alloyed wire steels of high tempearture T_M has enhanced the effect of austenite stabilization and has made possible to increase the meatstable phase volume in the sprayed coatings.

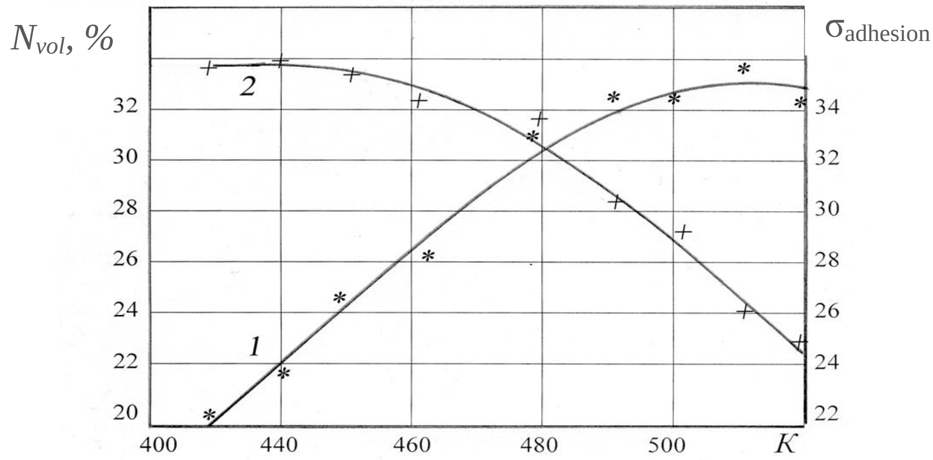


Fig. 4. The dependence of the amount of metastable austenite (vol.%) (1) in steel coatings 2Kh18N10T and 40KhN and their adhesion (MPa) (2) on the preheating temperature of the recoverable surface

Practical use of the study results

Some technological recommendations on transportation means 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 of transport means 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.

Conclusions

The effect of anomalously great amount of residual austenite (20 - 40 vol.%) formation in gas thermal coatings of sprayed steels of martensite class has been determined.

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 oxydation).

On the basis of conducted investigation some technologies have been proposed dealing with the parts of transportation means 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.

Referenses

1. Belocerkovskij M.A. Tekhnologii aktivirovannogo gazoplamennogo napyleniya antifrikcionnyh pokrytij. Mn.: Tekhnoprint. 2004. 200 s.

2. Sharov V.M. Metallizacionnye pokrytiya. Kiev: Budivel' nik. 1981. 80 s.

3. Belocerkovskij M.A., Pryadko A.S. Aktivirovannoe gazoplamennoe i elektrodugovoe napylenie pokrytij provolochnymi materialami. Uprochnyayushchie tekhnologii i pokrytiya, 2006. №12.

4. Popova L.E., Popov A.A. Diagrammy prevrashcheniya austenita v stalyah i beta-rastvorah v splavah titana. Spravochnik. M.: Metallurgiya, 1991. 501 s.

5. Gulyaev A.P. Metallovedenie. M.: Metallurgiya 1977. 648 s.

Лопата В.М., Черновол М.І., Солових Є.К., Дудан О.В. Використання структурних аномалій в стальних газотермічних покриттях при підвищенні їх зносостійкості

Досліджена структури газотермических покриттів із дротяних матеріалів шляхом визначення раціональних методів керування процесом структуроутворення для досягнення найбільш високих фізико-механічних властивостей відновлюємих поверхонь деталей транспортних засобів. Встановлено ефект утворення аномально великої кількості залишкового аустеніту при напиленні покриттів із сталевих дротів. Запропоновано технології використання «аустенітного ефекту» для підвищення зносостійкості покриттів.. Визначено, що основними факторами, що впливають на вміст залишкового аустеніту в загартованій сталі, є швидкість охолодження сталі, концентрація легуючих елементів в аустенітній фазі, а також термічна стабілізація аустеніту при самовідпуску.

Показано, що для забезпечення формування в структурі напилених покриттів з легованих конструкційних, інструментальних та корозійностійких сталей метастабільного аустеніту, що має низьку температуру протікання деформаційного гама-альфа перетворення, яка відповідає температурам експлуатації вузлів тертя ковзання, необхідно досягнення певних умов формування покриття (температури нагріву і розпилення дроту, швидкості охолодження розплавлених частинок і ступеню їх окислення). Однією з найбільш ймовірних причин появи «аустенітного ефекту» в покриттях є розігрівання поверхневого шару до температури, що сприяє термічній стабілізації аустеніту, а також насиченню крапель розплаву легуючими елементами (перш за все хромом) і домішками впровадження (вуглець, азот) в процесі розплавлення дроту в полум'ї. Відносно низька швидкість польоту розплавлених частинок стали і висока концентрація пропану, що містить вуглець в продуктах горіння, сприяють глибокого насиченню крапель розплаву вуглецем. Ймовірно, що саме з цими обставинами пов'язаний високий вміст залишкового аустеніту в покриттях, отриманих газополуменевим напиленням. Додатковим фактором, що збільшує стійкість аустеніту в напиленому покритті може бути насичення крапель розплаву вуглецем в процесі розплавлення і 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 і сталі для розпилення які дозволяють забезпечувати формування в покриттях великої кількості метастабільного аустеніту, який в процесі роботи трибоспряження перейде в мартенсит. .На підставі проведених досліджень запропоновані технології відновлення деталей засобів транспорту шляхом нанесення багатофункціональних покриттів, в яких вибір методу нагріву дроту при розпиленні здійснюється в залежності від температури початку мартенситного перетворення матеріалу дроту.

Ключові слова: електродугове напилення, газополуменеве напилення, зносостійкість, залишковий аустеніт, відновлення, газотермічні покриття