Problems of Tribology, *V. 26, No4/102-2021,28-33*

Problems of Tribology
Website: http://tribology.khnu.km.ua/index.php/ProbTrib
E-mail: tribosenator@gmail.com

DOI: https://doi.org/10.31891/2079-1372-2021-102-4-28-33

Dependence of the elastic modulus of powder coatings on their porosity in electrical contact hardening

O. Lopata[1*], I. Smirnov[1], A. Zinkovskii[2], L. Lopata[2]

[1]National Technical University of Ukraine "Igor Sikorsky, Polytechnic Institute", Kyiv
[2]G. S. Pisarenko Institute for Problems of Strength of the National Academy of Sciences of Ukraine, Kiev
**E-mail: beryuza @ukr.net*

Received: 28 September 2021: Revised: 27 Octobert: Accept: 13December 2021

Abstract

The relationship between the elastic modulus and the porosity of powder coatings has been investigated for different methods of their deposition. Porosity is the main means of assessing the quality of coatings and depends on the techniques for their production. A decrease in the elastic modulus of coatings after gas flame spraying is due to the presence of porosity to 30%, and after electric arc spraying – to 20%. The electric contact method of forming coatings makes it possible to reduce porosity to 5-6% and so to bring the value of the elastic modulus of coatings closer to that of compact materials.

Key words: electric contact method for forming coatings, powder coatings, porosity, elastic modulus, mechanical properties, adhesion strength.

Introduction

Porosity is an inherent feature for many types of powder coatings and is considered to be of their second (after adhesion strength), but in some cases, of the first order property. It is the main means of assessing the quality of coatings, especially corrosion-resistant and wear-resistant coatings, where its presence is undesirable. The porosity of coatings and its relationship with their mechanical properties, in particular with the elastic modulus (E), has long attracted the attention of researchers. Investigation of the mechanical properties of materials with coatings is one of the most important stages of researches, because this allows one not only to objectively interpret the behavior of parts during operation, but also to effectively control the resource of their service through influencing the composition, structure and, naturally, the conditions of obtaining them.

State of the problem

A significant decrease in the porosity of coatings can be achieved by thermal hardening. However, it should be noted that in some cases the volumetric heat treatment of coatings is undesirable, since it deteriorates their physical and mechanical properties [1].

Required compaction of coatings can be achieved using chromium and aluminum-containing phosphate binders as well as polymeric and other materials [2-3]. For the same purposes, chemical heat treatment (CHT) is used. Nitriding and carbiding of coatings are carried out in molten salts or gaseous media, while boriding and siliciding – in various plasters [4]. When the temperature of such processes is low (usually below 600°C), CHT can affect the adhesion strength of coatings mainly due to partial relaxation of stresses in the coating.

In order to increase the coating density, methods of subsequent processing of coatings have become widespread such as overflow in a furnace or with an open flame of a gas burner, as well as impregnation with plastics or molten metals.

The current methods of coating processing have a number of disadvantages: as a rule, during the overflow the pores are closed only at the outer surface of the coating while in the subsurface layers they preserve. Similar effect is provided by filling them with molten metal or plastic mass: no through filling of the pores occurs. The above picture leads to the fact that during the operation of gas-thermal coatings under the conditions of contact interactions in the process of wear, the pores become open. Thus, there appear channels through which the chemically active medium directly flows to the steel base surface. Ultimately, the processes of local corrosion damage are actively developing up to the part failure.

An increase in the density of the sprayed coatings is facilitated by an increase in the intensity of the mechanical-thermal interaction between particles of the powder and the base during both formation of coatings and subsequent mechanical-thermal treatment. The use of mechanical-thermal treatment of as-formed coatings (for example, deposited by gas thermal spraying) makes it possible to increase the coating density in parallel with maximal preservation of the original structure and properties of the powder [5].

To obtain coatings with low residual porosity, various procedures are widely used, including hot processing of powder layers by pressure.

In order to improve the quality of gas thermal coatings, the mechanic-thermal formation (MTF) of porous layers has been used immediately after deposition. As a result, the density of the coatings increased significantly and the porosity decreased (Table 1) [1].

A significant decrease in porosity after MTF in comparison with the effect of gas-flame treatment is due to the positive role of the mechanical factor, which under high temperatures determines the development of plastic deformations that contribute to the "healing" of pores [1].

The interaction of materials in the solid phase is activated not only by temperature, but also by pressure [6]. Herein, for its marked acceleration at high temperatures, rather low pressures are required to initiate the directed motion of structural defects [7, 8].

Table 1

Effect of subsequent treatment on porosity of coatings

Material of coating	Initial porosity, %	Porosity after treatment, %	
		Melting with a gas burner	MTF (Electric contact treatment)
BrAZh9-4	18	2	0.07
SNGN-35	7	1.30	0.10
3V16K	6	1.45	0.08
VK-52	8	1.35	0.07

Hence, the use of MTF is a more effective method of increasing the density of coatings than heat treatment. It can be carried out in the same technological chain with the coating deposition, just along the layer of as-formed coating by rolling in rolls, rollers [7], using heating with the flame of an additional burner.

According to the reviewed literature and patent information, among the large number of current mechanic-thermal methods of hardening parts with powder and compact materials, the advantage should be given to electric contact ones [8-11], because they allow one: to obtain practically non-porous coatings; more than 150 MPa; to preserve the original properties of the coating materials, to improve the properties of the base material, to achieve the minimum zone of thermal influence of current on the part (0.1 ... 0.3 mm) thanks to the short duration of heating pulses, and to increase the thickness of coatings by 3 ... 6 times. Moreover, they are characterized by high productivity along with low energy consumption and do not require any protective atmosphere, light radiation or gas release.

The electric contact method of hardening (formation of coatings) is carried out under pressure with direct transmission of electric current [12] and refers to pulse technologies, which are based on the principles of synchronous combination of pulsed modes of mechanical and electrical energy. It is a type of hot pressing. Unlike the conventional powder metallurgy technology, a direct passage of an electric current through the contact activates and accelerates the processes that determine properties of sintered materials. Powder under the influence of electric heating becomes plastic in a short time and easily deforms. The dominant processes in the electric impulse method of forming coatings are those that occur during both hot pressing and pressure welding. The degree of participation of either of the processes is different and depends on temperature, pressure, and material properties.

The purpose of the study

In order to confirm the efficiency of the electric contact method for forming powder coatings (electric contact processing) with reduced porosity, the task was set: to investigate the relationship between the elastic modulus and the porosity of powder coatings.

Investigation of dependence of the elastic modulus on the porosity of powder coatings in the electric contact method

In practice, porosity is most often determined by the planimetric method of metallographic analysis. The measurement of the elastic modulus of materials is performed by both dynamic and static methods [13]. Analysis of the literature data on the elastic characteristics of coatings showed that the ratio of the values of the dynamic and static moduli can vary in a wide range: from 1 to 10 [13]. Taking into account that the method for determining the adhesion and cohesive strength of the coating assumes the statistical application of tensile forces, it is obvious that the use of the elastic modulus measured under applied load will make it possible to more objectively evaluate the stress-strain state of the coating and, consequently, its limit characteristics.

In paper [14], dependence of the elastic modulus on the porosity has been shown. The first was determined by calculation using the Kashin procedure [15]. A steel base was chosen as an object of research for glass-ceramic and cermet coatings. The value of the elastic modulus for a monolithic material was higher ($7.8.10^4$ MPa) than for a porous one ($6.2.10^4$ MPa) at a porosity of 10% and (7.10^4 MPa) at a porosity of 5%. The elastic modulus of cermet coatings with a porosity of 5% was $21.5.10^4$ MPa, which is 20% higher than that of the corresponding steel coatings (18.10^4 MPa).

It has been noted [16] that porosity of ceramic coatings exhibits the strongest effect on the elastic modulus. For inorganic glasses, the experimental results are presented in the form of the dependence [17]:

$$E = E_0(1-\alpha_E P)\,, \qquad (1)$$

where E is the elastic modulus;
E_0 is the elastic modulus of non-porous material;
α_E is a constant obtained by calculation for spherical closed porosity;
P is the porosity.

The literature review has shown that there are predominantly data on the dependence of the elastic modulus on porosity for compact materials, but not for coatings. In particular, for sprayed zirconium boride-copper coatings no relationship between the elastic modulus and the density of the thermal gas coating was found [16]. Most researchers consider porosity and elastic modulus as independent characteristics, and thus do not establish any relationship between them. From the experimental results [17] follows a stable dependence of the elastic modulus on porosity, close to a linear one, for glass-0ceramic coatings on austenitic steel Kh18N10T.

In order to reveal elastic modulus-porosity relationship for sprayed coatings in the case of electric contact hardening, we used standard samples.

The values of the modulus of elasticity for samples with porosity from 0 to 30% were obtained by calculation according to the method described in [18], where the dependence of the physical and mechanical properties of compact materials on porosity has been studied. A number of properties was shown to decrease monotonically with increasing porosity and to be described by a generalized function:

$$æ = æ_0\,(1 - P)^{m}, \qquad (2)$$

where æ is a numerical characteristic of properties for a porous body;
$æ_0$ is the same for a non-porous body;
P is the porosity, fractions of units; m is a constant exponent.

Yu. Kharlamov [19] has developed a volumetric model of a thermal gas coating in the form of monolayers of cylindrical monoparticles:

$$æ = æ_0\, f\,(F)\,, \qquad (3)$$

where F is the shape factor for particles forming the coating, which serves as a criterion for the relationship of the porosity with the relative adhesive and cohesive bond strength.

In general, the distribution of the E_0 values is close to normal. The most probable value is E_P = 2.104 MPa with a standard deviation of $0.86.10^4$ MPa. For compact zinc E = 9.10^4 MPa [19]. The decrease in the elastic modulus for a coating obtained by electric arc spraying may be due to the presence of 20% pores and its layered structure (Table 2, Fig. 2). Coating material: powder of hard alloy PG-12N-01 (base Ni, 8 ... 14% Cr, 1.7 ... 2.5 V; 1.2 ... 3.2 Si; 1.2 ... 3.2 Fe; 0.3 ... 0.6 C); flux-cored wire PP FMI-2; charge FKhB (50% Cr; 20% B, 7% Al, 3% Ti, 20% Fe) + Al.

Table 2

Dependence of mechanical properties of coatings (in particular, elastic modulus) on porosity

Method	Material	Elastic modulus E·10^{-5}, MPa						
		Base Steel 45	Porosity of coating, %					
			5	10	15	20	25	30
Gas flame spraying	PG-12N-01	2	-	-	3.2	2.7	2.5	2.2
Electric arc spraying	PP FMI-2	2	-	-	0.8	0.75	0.70	0.60
Electric contact	PP FMI-2	2	1.35	-	-	-	-	-

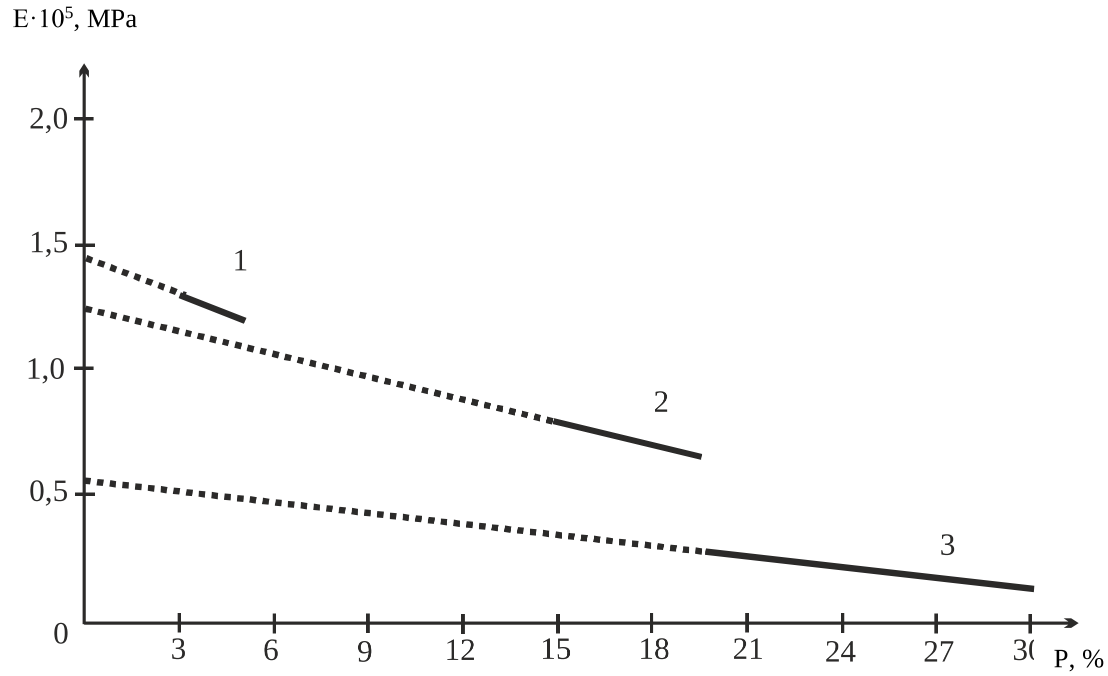

Fig. 1. Relationship between porosity and elastic modulus of coatings: 1 – coating obtained by the electric contact method; 2 – coating obtained by electric arc spraying; 3 – coating obtained by the gas flame method

Conditions of the electric contact method for forming coatings: voltage 3 ... 6 V; current 8 ... 12 kA; load on the electrode 10 ... 30 MPa; current pulse time 0.02 ... 0.04 s; pause time 0.02 ... 0.04 s.

Conditions of the electric arc spraying: voltage 18 ... 35 V; current 50 ... 600 A; the nozzle-surface distance 50 ... 200 mm; compressed air pressure 0.4 ... 0.5 MPa; compressed gas (air) consumption 60 ... 150 m^3/h.

Conclusions

The decrease in the elastic modulus of coatings is due to the presence of porosity (up to 30% after gas flame spraying and up to 20% after electric arc spraying). The electric contact method of forming coatings (electric contact method of processing coatings) makes it possible to reduce the porosity to 5-6% and to bring the value of the elastic modulus closer to that of compact materials.

References

1. Kirshenbaum V.Ya. Mechanic-thermal formation of friction surfaces. M.: Mashinostroenie, 1987. 232 p.

2. Kupriyanov I.L., Korotkina M.N, Ivashko V.S. et al. Study of protective properties of metallic and metal-polymer coatings / Protection of metals. 1986. Vol. 22. No. 4. P. 507-509.

3. Kupriyanov I.L., Ivashko V.S., Sakhadze V.M. et al. Metal-polymer coatings for protection of agricultural machinery from corrosion. Tractors and agricultural machines. 1985. No. 10. P. 38-40.

4. Kuznetsov V.V., Klyshko I.N. Application of enamel frits for melting of sprayed coatings / Technological processes and equipment for hardening of machine parts, tools, and technological equipment: Proc. of scientific and technical conf. Minsk: BelNIINTI.

5. Korobov Yu.S. Calculation of the parameters of motion, heating and oxidation of particles in electric arc metallization. /Welding production. 1998. No. 3. P. 9-13.

6. Kudinov V.V. Plasma coatings. Moscow: Nauka, 1977. 184 p.

7. Ergashev M., Matyakubov B. Features of obtaining hardened coatings by the electric contact method / Automatic welding. 1986. No. 5. P. 49 - 51.

8. Engineering of the surface of transport mas0chine parts: current state, perspectives. Newsletter / Collection of Science Practices of Transport University and Transport Academy of Ukraine. Iss. 4, Kyiv, RVV NTU, 2000. P. 3-14.

9. Routes to improvement of methods for engineering the surface of transport machine parts. Metody obliczeniowe i badawcze w rozwoju pojazdow samochodowych i maszyn roboczych samojezdnych, 2000. P. 20-23.

10. Electric contact hardening as a method of engineering the surface of parts of transport equipment when prepared and restored. Newsletter / Collection of Science Practices of Transport University and Transport Academy of Ukraine. Iss. 4, Kyiv, RVV NTU. 2000. P. 3-6.

11. Electrical contact hardening as a mechanical-thermal method of surface quality control. Collection: Materials, technologies and equipment for restoration of machine parts. Minsk: UP Technoprint, Novopolotsk, PSU. 2003. P. 252-254.

12. Yaroshevich V.K., Genkin Ya.S., Vereshchagin V.A. Electric contact hardening. Minsk: Science and Technology, 1982. P. 256.

13. Lyashenko B.A., Rishin V.V., Astakhov E.A., Sharivker S.Yu. Investigation of the adhesion strength of detonation-sprayed coatings / Problems of strength. 1972.

14. Race Roy W. Effects of inhomogeneous porosity on elastic properties of ceramic properties of ceramics. J. Amer. Ceram. Soc. Discussion and Notes. 1975. Vol. 58. No. 9-10. P. 458-459.

15. Hasselman D.P.H., Fulrath R.M. Effect of small fraction of spherical porosity on elastic modulus of glass. J. Amer. Ceram. Soc. Discussion and Notes. 1964. Vol. 47. No. 1. P. 52-53.

16. Loskutov V.S., Dekhtyar L.I. Mechanical properties of plasma-sprayed coatings from zirconium boride, copper and their compositions. Powder metallurgy. Kyiv. 1985. No. 7. P. 78-81.

17. Antonova E.A., Burkova L.I. Residual thermal stresses in sintered coatings. Anticorrosion coatings. L.: Nauka. 1983. P. 4-42.

18. Skorokhod V.V. Powder materials based on refractory metals and compounds. Kyiv: Tekhnika, 1982. 167 p.

19. Kharlamov Yu.A. Prediction of the porosity of powder coatings. Powder metallurgy. 1990. No. 12. P. 36-41.

Лопата А.В., Смирнов І.В., Зіньківський А.П., Лопата Л.А. Залежність модуля пружності порошкових покриттів від їх пористості при електроконтактному методі

Досліджено зв'язок між модулем пружності та пористістю порошкових покриттів при різних методах їх нанесення. Пористість є основним засобом оцінки якості покриттів та залежить від технології їх отримання. Зниження модуля пружності покриттів при газополум'яному напиленні обумовлено наявністю пористості до 30%, а при електродуговому напиленні – до 20%. Електроконтактне припікання покриття дозволяє знизити пористість до 5-6% і наблизити значення модуля пружності покриттів до модуля пружності компактних матеріалів.

Ключові слова: електроконтактний метод формування покриттів, порошкові покриття, пористість модуль пружності, механічні властивості, адгезійна міцність