Migration Letters

Volume: 20, No: S3(2023), pp. 32-39

ISSN: 1741-8984 (Print) ISSN: 1741-8992 (Online)
www.migrationletters.com

Adhesive Strength of Coatings of Military Equipment Parts Obtained by Cold Gas-Dynamic Spraying

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Abstract

The article proposes a model for calculating the adhesive strength of military equipment parts obtained by the method of cold gas-dynamic spraying, without resorting to complex and expensive devices of the non-destructive testing method. This model is based on a system of initial nanocracks, which after 100 nanoseconds turn into mesocracks, and then after being hit by particles of the sprayed substance turn into micron-scale cracks. This process is described by the ratio: Lnm→Lμm→LC=0.17 10-5 M/p (M is the molar mass of the element, p is its density). As a result of spraying due to these cracks, a transition layer is formed, which has adhesive strength. On a concrete example, this model is considered experimentally.

This scientific article was published as part of the implementation of the scientific program of program-targeted financing for 2021-2023 of IRN No. BR1090150221 "Development of technology for protective coatings of surfaces of weapons and military equipment to protect against aggressive environmental factors and operating conditions" (the study is funded by the Science Committee of the Ministry of Science and Higher Education of the Republic of Kazakhstan).

Keywords: *nano crack, meso crack, adhesion, strength, parts, military equipment, gas dynamic spraying, method, model, theory, experiment.*

Introduction

In the process of increasing the adhesive strength of coatings of parts of various technical systems, when a supersonic two-phase flow is directed to a metal substrate, three processes can be observed, which can be carried out both separately and simultaneously in different proportions:

1) solid particles of the flow are reflected from the metal substrate with a change in the structure of the shock wave;

2) solid particles of the flow destroy completely or partially the metal substrate, leading it to erosive wear;

3) the solid particles of the flow are sprayed onto the metal substrate, leading it to the cold gas-dynamic spraying mode [1].

The kinetics of coating formation in the HGDN method depends on the size and velocity of the deposited particles, on their temperature when moving in a supersonic flow, and on the presence of gas (helium or nitrogen) in the flow. These determining factors are given

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increased attention in the technological process of spraying [2, 3]. However, the properties of the sprayed substance are studied only from technological parameters, namely, from the amount of wear, corrosion resistance and others. The near-surface layer, from which the entire deposition process begins (including the HCDN), is currently not fully investigated sufficiently [4]. This is due to the fact that the structure of the surface layer of the metal on which the deposition is applied is not taken into account [5], and the system of initial nano-cracks, along which, basically, the penetration of particles into the sprayed substance occurs [6, 7]. Based on the above, in relation to the details of military equipment, we will perform comprehensive studies of their adhesive strength of coatings obtained with the help of HGDN.

In the period from the beginning of 1980 to the end of 2020, more than 150 patents on HCDN coatings were published [2]. The HGDN technology contributes to the preservation of the fine structure of metals during their plastic deformation. This effect is associated with the memory of powder particles [8-10]. Hardening and repair of parts of military equipment and in industry by the HGDN method is also effective because during ultra-high-speed spraying there are no changes either in the chemical or in the phase state of metals [11, 12]. The disadvantages of the HGDN method include the fact that the parts sprayed with this method should mainly be subjected to thermal or thermal deformation treatment [13-15]. This additional operation in the technological sequence of restoring the operability of the part by the HGDN method of any node or unit of military equipment located in the field is not feasible.

Previously performed studies have established that the length of the nano-crack Lnm is equal to the thickness of the surface layer of the metal R(I) [5]. In addition, the length of a nano crack in a metal is formed not only taking into account the geometry of the crystal lattices, but also depending on the physical properties of the crystals, the characteristics of the types of chemical bonds (ionic, covalent, metallic, etc.); porosity, anisotropy and other properties. The length of the mesoscopic crack is Lμm = 102 Lnm [7]. During the formation of the coating of the HCDN methods, a supersonic two-phase particle flow is directed onto the metal substrate and an impact occurs, leading to an increase in primary nanotracks to LC = 104 Lnm.

The main purpose of the research is to offer an analytical model for calculating the adhesive strength of military equipment parts obtained using the HGDN method, without resorting to complex and expensive devices of the non-destructive testing method.

The main stages of the research. Let's first consider which particles and what size will be used for applying HCDN coatings. At the second stage, the selection of parts of military equipment is carried out, on which the coating will be applied using the HGDN method. Further, a model will be developed, according to which it will be possible to establish the adhesive strength of HDN coatings, which ultimately determines the wear resistance of parts.

Features of the preparation of the material for the formation of the flow of sprayed particles.

The research material was powders made of wires with a diameter of 1.6 mm steel 65X8T2YU (the chemical composition of which is shown in Table 1). The particle size is 40-50 microns.

Table 1 - Chemical composition of steel 65X8T2YU

Steel	The content of elements in steel, %							
	C	Cr	Ti	B	Al	Cu	S	Fe
65X8T2Ю	0.62	5.49	1.81	-	1.14	-	0.014	90.9

Also, a mixture of metals Fe, Cr, Ti, Al, With a similar chemical composition, was prepared for the experiment on a ball mill (Fig. 1) with dimensions of 5, 10, 20 and 30 microns.

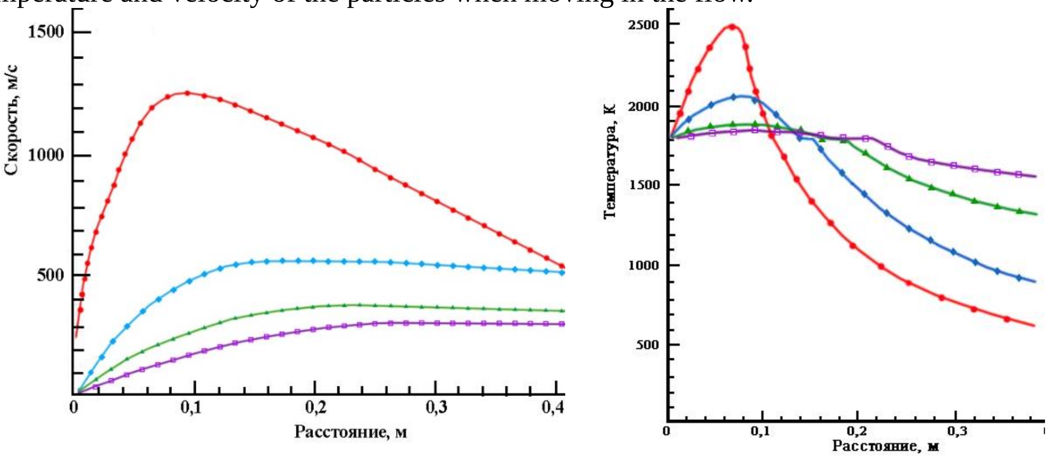
a)

b)

Figure 1 - Ball mill (a); pure metal particles (b)

Granulometric analysis of metal particle images was determined using a SKC-200S sedimentograph.

The quality of the HCDN technological process, as noted above, significantly depends on the speed and temperature during the movement of particles in a supersonic flow. In Fig. 2a, b shows how the distance from the burner nozzle to the sprayed sample affects the temperature and velocity of the particles when moving in the flow.

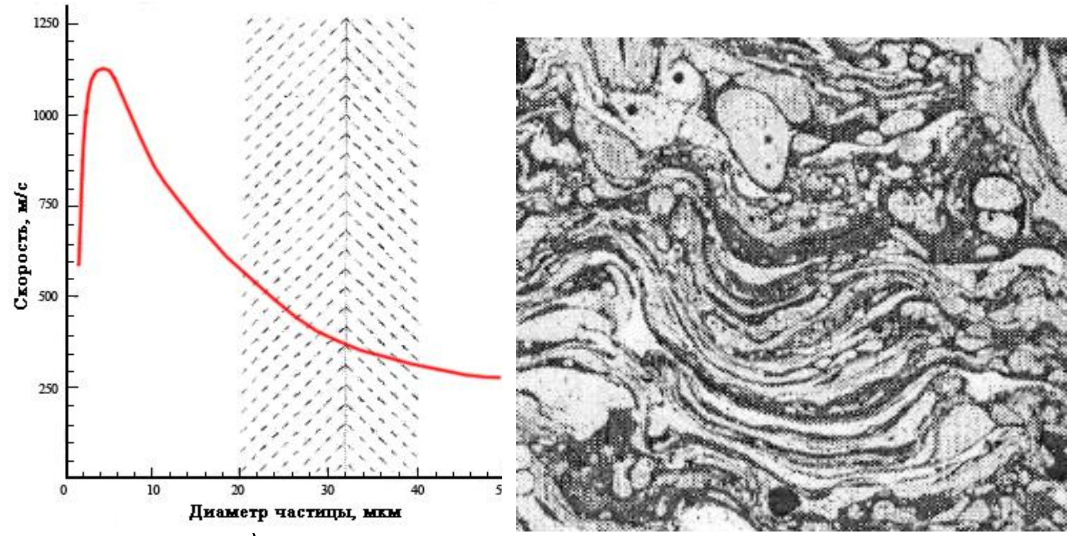


a)

b)

Figure 2 - Change in particle velocity (a), change in particle temperature (b) when moving in a stream

The dependence of the particle velocity on their diameter is shown in Fig. 3a, and the microstructure of the deposition layers is shown in Fig. 3b.



a) б)

Figure 3 - Dependence of particle velocity on their diameter (a); microstructure of deposition layers (b)

Details and samples for spraying. Repair of military equipment is carried out at specialized auto repair plants of the military-industrial complex: Almaty, Semey, Petropavlovsk and Yerementau. For the restoration of worn parts, the main technological methods are surfacing and spraying (including HGDN) of metal coatings. The restoration of military equipment parts can be divided into three component groups [16]:

- parts whose surface is worn out;

- parts that need to be repaired for mechanical and combat damage;

- parts that have been found to have corrosion damage.

Among the metals used are: aluminum alloys (connecting rod inserts), steel 45 (gears of gearboxes), steel 40 L, 45L (front drive axle), as well as steel 20KHN2M, 15KHGN2TA, 20KHGRA, 18KHGTA and ductile cast iron KCH 35-10, KCH 35-12, KCH 35-13 (crankcases of main gears, beams of drive axles) , etc .

As an example, when conducting comprehensive research, consider the gears of gearboxes made of steel 45 (Fig. 4).

a) b)

Figure 4 - Gear subjected to corrosion (a); gear restored with the help of HGDN (b).

A model of coating formation using EGDN. The surface layer of a gear made of 45 R(I) steel, equal to the length of the Lnm nanocrack, is described by the expression [5]:

$$L_{nm} = R(I) = 0{,}17 \cdot 10^{-9} \upsilon \ . \qquad (1)$$

In equation (1), you need to know one parameter – the molar volume of a metal element or compound, which is equal to υ = M / p (M is the molar mass, p is its density). The length of the nanocrack Lnm is equal to the thickness of the surface layer of the metal R(I). The length of the mesoscopic crack is Lμm = 100 Lnm.

In addition, to develop an analytical model, a number of other parameters are needed, which we will use in the future.

It is shown in [6] that the surface energy of the bulk metal γ2 is equal to 3% with an accuracy of:

$$\gamma_2 = 7.8 \cdot 10^{-4} \cdot T_m \ , \qquad (2)$$

where Tm is the melting point of the metal (K).

In the layer R(I), the dimensional effect must be taken into account and therefore the surface energy of the layer R(I) becomes equal to γ1 [7]:

$$\gamma_1 = \gamma_2 (1 - R(I) / R(I) + h) \approx 0{,}3\gamma_2 \ ,. \qquad (3)$$

Equation (3) shows that the surface energy of the layer R(I) is three times less than the surface energy of the main crystal. To separate the layer R(I) from the rest of the crystal, it is necessary to expend energy, which is called the adhesion energy (see Fig. 3) [8]:

$$W_a = \gamma_1 + \gamma_2 - \gamma_{12} \approx \gamma_1 + \gamma_2 = 1.3\gamma_2, \qquad (4)$$

where y12 is the surface energy at the phase interface, which is negligible due to a phase transition of the second kind [9].

Internal voltages σis between phases γ1 and γ2 are determined according to the dependence [8]:

$$\sigma_{is} = \sqrt{W_a \cdot Å / R(I)}, \qquad (5)$$

Let 's take the following relations:

$$T_m = \sum_{i=1}^{n} c_i (T_m)_i, \quad M = \sum_{i=1}^{n} c_i (M)_i, \quad \rho = \sum_{i=1}^{n} c_i (\rho)_i. \qquad (6)$$

Using formulas (1)-(6), we calculate the indicated values, the values of which are presented in Table 2.

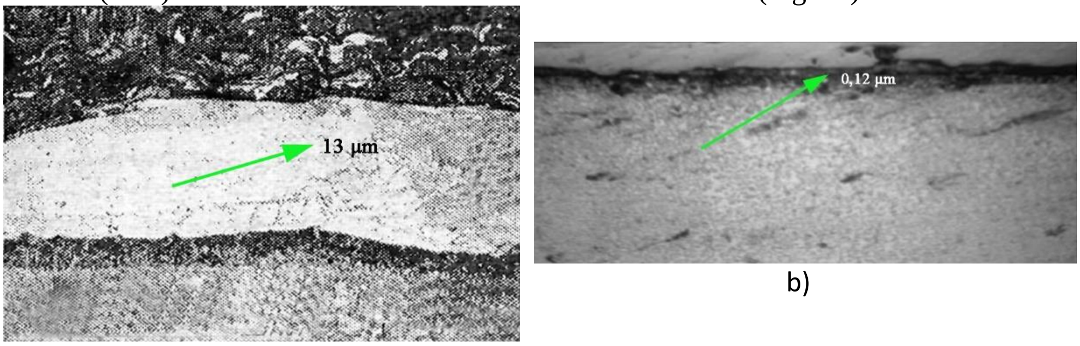
Table 2 - Physical parameters of steel 45 and iron

Steel, alloy	L_{nm} = R(I), nm	L_C, mcm	γ_1, J/m^2	W_a, J/m^2	E, GPa	σ_{is}, MPa
45	1.20	12.0	0.462	1.849	207	17861
Fe	1.21	12.1	0.471	1.884	211	18125

a) b)

Figure 5 - Sample with HCN coating (a); diffusion along the microcrack grid (b)

In this case, a transition layer is formed between the steel and the HCDN coating, measured using the TESCAN MIRA 3 electron microscope at the end of the sample (Fig. 6a). The transition layer between the steel and the coating obtained by the ion-plasma method (IPM) at the HHV-6.6 I1 installation is also shown here (Fig. 6b).



a) b)

Figure 6 - Transition layers: HCDN coatings (a) and IPM coatings (b).

It follows from Fig. 6 that the transition layer of the HCDN coating is two orders of magnitude larger than the transition layer of the EPM coating. This means the growth of primary nanotracks according to the law:

$$L_{nm} \rightarrow L_{\mu m} \rightarrow L_C = 0.17 \cdot 10^{-5}\ M/\rho. \quad (7)$$

To determine the internal stresses of the transition layer (ps) according to the formula (5), the following calculations must be performed:
$W_{пс} = \gamma_{ХГН} + \gamma_{ст} - \gamma_{пс} \approx 2/3(\gamma_{ХГН} + \gamma_{ст})$; $1/E_{пс} = 1/E_{ХГН} + 1/E_{ст}$; $L_C = 12$ mcm.

The results of all calculations are shown in Table 3.

Table 3 - Physical parameters of the transition layer

Layer Parameters	$\gamma_{ХГН}$, J/m^2	$\gamma_{ст}$, J/m^2	$W_{пс}$, J/m^2	$E_{пс}$, GPa	$\sigma_{пс}$, MPa
Transition layer values	1.397	1.386	1.855	209	179

In accordance with Table 3, it follows from the value of σps that the hardness of the transition layer of the Nps is ≈ 180 MPa. To determine the nano-hardness of the obtained HCDN coatings, we used the Ntegra probe laboratory with a Berkovich indenter.

For the HCDN coating, this value turned out to be equal to HCGN ≈ 21000 MPa, which is two orders of magnitude greater than the Nps of the transition layer. Steel 45 has a tensile strength of σB ≈ 600 MPa, which is 35 times less than the NHGDN of the HGDN coating. Consequently, the completed technological process of hardening the gear allows you to increase its service life.

The value of σps should be called the adhesive strength of the HCDN coating.

Based on the above reasoning, the adhesive strength value is determined by equations (1) – (7), taking into account the chemical composition of the components of the sprayed coating and the composition of the substance on which this coating is sprayed, that is, it is necessary to know the composition of the adhesive and substrate.

The adhesive strength of bronze coatings obtained on steel 45 by deformation cladding averaged 15 MPa [17], which is 10 times less than the HCDN coating.

Conclusion

In this article, for the first time, the structure of the surface layer of metal is considered, due to primary nano-cracks, through which the diffusion of the deposited components occurs in the technological process of applying the HGDN method. Primary nano cracks of a metal reflect its atomic structure and after 100 nanoseconds they turn into meso cracks, forming a surface layer. To destroy this layer, it is necessary to perform the work of adhesion.

In order to determine the adhesive strength of the coating applied with WHERE, it is possible to use an analytical model in accordance with the experimentally determined properties of the coatings and their base on which the coatings are deposited.

References

1. Alkhimov A.P., Klinkov S.V., Kosarev V.F., Fomin V.M. Cold gas dynamic spraying. Theory and practice. - M.: FIZMATLIT, 2009. - 536 p.
2. Kozlov I.A., Leshchev K.A., Nikiforov A.A., Demin S.A. Cold gas-dynamic coating spraying (review) // Proceedings of VIAM, 2020, №8(90). – Pp. 77-93.
3. Spasenko A.A., Cheverikin V.V., Petrovsky P.V. Influence of hot isostatic pressing on the structure and properties of VT6 alloy products obtained by cold gas-dynamic spraying // Metallology and heat treatment of Metals, 2021, No. 2. – pp. 26-29.
4. Panin V.E., Sergeev V.P., Panin A.V. Nanostructuring of surface layers of structural materials and application of nanostructured coatings // Tomsk: TPU Publishing House, 2010. - 254 p.
5. Yurov V.M. Thickness of the surface layer of atomically smooth crystals // Physico-chemical aspects of studying clusters, nanostructures and nanomaterials. 2019. issue 11. pp. 389-397.
6. Vettegren V.I., Ponomarev A.V., Mamalimov R.I., Shcherbakov I.P. Nanotracks in the destruction of oligoclase // Physics of the Earth, 2021, No. 6. - pp. 87-92.
7. Yurov V.M., Goncharenko V.I., Oleshko V.S. Investigation of primary nanotracks of atomically smooth metals // Letters in ZhTF, 2023, volume 49, vol. 8. pp. 35-38.
8. Pradhan S., Ghosh S., Barman T., Sahoo P. Tribological Behavior of Al-SiC Metal Matrix Composite Under Dry // Aqueous and Alkaline Medium. Silicon, 2017, V. 9. - P. 923-931.
9. Croteau J., Griffiths S., Rossell M., Leinenbach C., Kenel C., Jansen V., Seidman D.N., Dunand D., Vo N. Microstructure and mechanical properties of Al-Mg-Zr alloys processed by selective laser melting // Acta Materialia, 2018, V. 153. - P. 35-44.
10. Cao K., Yu M., Liang C., Chen H. Quantitative determination of SiC particles distribution of cold sprayed Al5056/SiC composite coatings // Surf Eng., 2020, V. 36. - P. 1040-1048.
11. Sova A., Grigoriev S., Okunkova A., Smurov I. Potential of cold gas dynamic spray as additive manufacturing technology // International Journal of Advanced Manufacturing Technology, 2013, V. 69. – P. 2269-2278.
12. Rokni M., Widener C., Crawford G. Microstructural evolution of 7075 Al gas atomised powder and high-pressure cold sprayed deposition // Surf Coat Technol., 2014, V. 251. - P. 254-263.

13. Raoelison R.N., Verdy C., Liao H. Cold gas dynamic spray additive manufacturing today: Deposit possibilities, technological solutions and viable applications: Materials and Design, 2017, Vol. 133. - P. 266-287.

14. Assadi H., Gдrtner F., Klassen T., Kreye H. Comment on «Adiabatic shear instability is not necessary for adhesion in cold spray» // Scripta Materialia, 2019, V. 162. - P. 512-514.

15. Khomutov M., Spasenko A., Sova A., Petrovskiy P., Cheverikin V., Travyanov A., Smurov I. Structure and properties of AA7075-sic composite parts produced by cold spray additive manufacturing // The International Journal of Advanced Manufacturing Technology, 2021, Vol. 116. - P. 847-861.

16. Tarasenko P.N. Repair of military vehicles. - Minsk: BNTU, 2015. – 252 p.

17. Levantsevich M.A., Maksimchenko N.N., Bely A.N., Dema R.R., Kadoshnikov V.I., Nefediev S.P., Kharchsyash M.V. Adhesive strength of coatings formed by deformation cladding with a flexible tool // Hardening technologies and coatings, 2016, No. 6. – pp. 12-18.