DOI 10.1007/s10891-022-02637-1
Journal of Engineering Physics and Thermophysics, Vol. 95, No. 7, November, 2022

WEAR-RESISTANT DETONATION COATINGS BASED ON CHROMIUM CARBIDE FOR GAS TURBINES

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UDC 534.222.2+621.693.79

A systematic study of detonation deposition of wear-resistant coatings made of composite powders based on chromium carbide used to harden parts operating at temperatures up to 870°C is carried out. An integrated analysis of the characteristics of coatings produced from powders of Russian and foreign manufacturers was carried out. A composite in the form of mechanical mixture and powders obtained by cladding and the Spray–Dry method are considered. Using a numerical code, the acceleration and heating of particles of the sprayed powder are calculated and the optimal spraying modes are determined. The hardness, porosity, wear resistance, and bond strength of the resulting coatings were considered. A comparative characterization of residual stresses has been carried out. The influence of the spraying distance in the range from 50 to 400 mm and of the inclination angle of the treated surface up to 60° has been studied.

It is shown that in the case of dual-fuel mixture spraying, the density and wear resistance of coating increase and residual tensile stresses are completely eliminated. The adhesion of the resulting coatings exceeds 150 MPa, and the abrasive resistance of the best coating is characterized by a specific wear of about 3 mm^3/1000 rpm according to the ASTM G65 standard, which is 5 times higher than the resistance of the alloys used for the manufacture of gas turbine parts.

Keywords: *detonation spraying, wear-resistant coatings, chromium carbide, microstructure, adhesion, residual stresses.*

Introduction. Modern industry has a wide arsenal of technologies for applying protective and functional coatings. These are surfacing technologies [1], and various gas-thermal technologies [2], including cold gas-dynamical spraying [3], and gas-jet deposition [4], and many other technologies and methods. The technology of detonation spraying (DS) [5] has existed for more than 60 years and is widely used in industry for applying coatings for a wide range of purposes [6–8]. Along with other gas-thermal spraying technologies (plasma, high velocity oxygen fuel (HVOF), gas flame, etc.), detonation spraying is used to apply wear-resistant coatings to gas turbine parts. In this case, coatings made of cermet composites based on carbides provide the highest wear resistance. The coatings obtained by the method of detonation spraying on the basis of chromium carbide with nickel bond are used to increase the wear resistance of the parts of aircraft engines operating at temperatures up to 870°C [6, 7, 9].

The technology and equipment of detonation spraying are being constantly improved — a suspension detonation spraying was implanted at the M. A. Lavrentiev Institute of Hydrodynamics of the Siberian Branch of the Russian Academy of Sciences [10]. Moreover, the detonation of dual- and multifuel gas mixtures [11, 12] are of interest for detonation spraying, because in recent years, instead of the traditional single-fuel D-Gun process, the dual-fuel Super D-Gun process is used [13, 14], and the number of parts with coatings in aircraft engines has increased many times [15]. A new generation of equipment — computerized detonation complex CCDS2000 has been developed and is being introduced actively [16]. Simultaneously with experimental studies, theoretical models of detonation spraying were developed with the creation of computer codes for calculating the process in the barrel of a detonation installation [17–19].

In connection with the expansion of the technological capabilities of detonation spraying and the appearance of new powders based on chromium carbide, a comprehensive study of the properties of wear-resistant coatings for parts of gas turbines with optimization of the technological parameters of spraying becomes a crucial problem.

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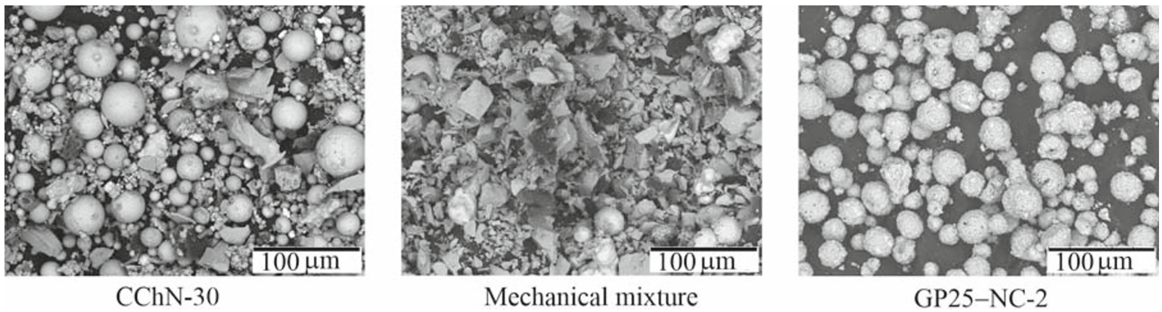


Fig. 1. Morphology of composite powders based on chromium carbide.

Description of Experiments. ***Applied materials.*** The experiments were carried out on the detonation complex CCDS2000 developed at the M. A. Lavrentiev Institute of Hydrodynamics, Siberian Branch of the Russian Academy of Sciences [16]. The complex allows one to implement both the single-fuel (acetylene–oxygen) D-Gun process, used at domestic enterprises, and the more efficient dual-fuel Super D-Gun process [13] used by Praxair abroad for hardening parts of aircraft engines. Technical gases used were: nitrogen, oxygen, acetylene, and propane for the dual-fuel technology.

As the main material for detonation spraying, used at domestic aircraft enterprises, we selected chromium carbide powder clad with 30% nickel CChN-30 [Cr_3C_2/Ni (70/30)] with a fractional composition <64 μm produced by Limited Corporation Rosnamis (the city of Taganrog). For comparison we used a mechanical mixture of chromium carbide with nichrome in the ratio Cr_3C_2/NiCr (75/25) with a fractional composition <64 μm used for plasma spraying, and an agglomerated powder of chromium carbide with nichrome Cr_3C_2/NiCr (75/25), hereinafter referred to as GP25–NC-2, with a fractional composition of 15–45 μm from the Chinese manufacturer LUOYANG GOLDEN EGRET GEOTOOLS CO., LTD; it is an analog of the CRC-300/1375VM powder sprayed by Praxair on parts of foreign aircraft engines. The morphology of the listed powders is presented in Fig. 1.

Composite powder based on chromium carbide is produced by cladding carbide particles with a metal binder. However, as can be seen from the comparison of the CChN-30 powder supplied by the Limited Corporation Rosnamis with a mechanical mixture Cr_3C_2/NiCr (75/25) in Fig. 1, the CChN-30 powder, along with clad carbides, has also "balls" of pure nickel and "crystals" of unclad carbide. The powder produced using the Spray-Dry technology (Fig. 1, GP25–NC-2) differs fundamentally in morphology as it consists of homogeneous agglomerates with visible pores between micron-sized particles of clad carbide.

Methods for analyzing the characteristics of coatings. To determine the powder utilization factor (PUF) in detonation spraying the coating is applied to a preweighed sample. During the experiment, N shots are produced, after which the sample is again weighed, and the mass of sprayed coating M is determined. The powder utilization factor is calculated using the formula PUF = M/M_0, where M_0 is the mass of powder injected into the barrel for spraying the coating.

The protective properties of the coating depend largely on its density. In the presence of defects and pores in the coating, its wear resistance is significantly reduced. The porosity of coatings was determined on transverse sections of coatings prepared using a STRUERS Tegramin-20 grinding and polishing station by contrast analysis of coating images obtained on an OLYMPUS GX-51 metallographic microscope using the Olympus Stream Essentials 1.9.1 image processing program. The average value is calculated from the measurements on five frames of one section.

When developing wear-resistant coatings, microhardness is considered as a parameter that correlates with wear resistance, which was measured using a Vickers hardness tester EMCO-Test DuraScan-50 with a load of 300 g ($HV_{0.3}$) at nine points on the transverse sections of coatings. Furthermore, the Vickers hardness was measured with a load of 5 kg ($HV_{5.0}$) at five points on the frontal surface. Such a measurement is carried out to certify the spraying mode in industrial practice.

Abrasive resistance was tested according to the ASTM G65 standard following the procedure ASTM G65(B) (2000 revolutions of AFs 50–70 quartz sand abrasive at 130 N of pressing the sample to the disk). For comparison, a sample of the Inc 617 alloy, used in gas turbines, was tested.

During the deposition process, residual stresses can accumulate in the coating, which, in the case of intense stretching, can cause cracking of the coating or its delamination both during deposition of a coating and during its operation; therefore, to ensure high reliability and durability of a wear-resistant coating, compressive character of residual stresses is

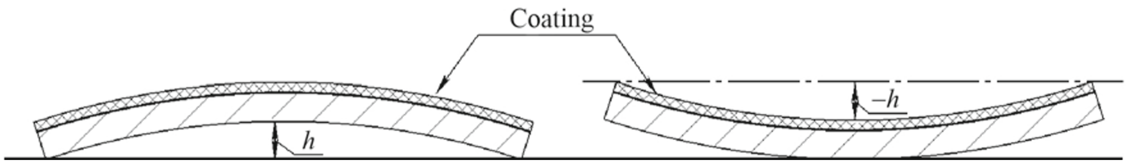


Fig. 2. Scheme of characterization of residual stresses in the coating.

preferable. To characterize the residual stresses in the coating, the Almen method [20, 21] was used, in which the bending of a standardized plate (Almen Strip) is analyzed. Under tensile stress, a coated plate is sagging, and under compressive stress it buckles. A coating layer of 100 ± 20 μm was sprayed on Almen Strip N1, after which the sagging deflection was measured to compare the level of stresses *h* (Fig. 2). To estimate the residual stresses in real products in this way, a coating about 300 μm thick was applied to an Inc 617 plate.

The strength of the bond of the coating with the substrate (adhesion) was measured by the adhesive method (ASTM C633 standard). The tests were carried out with Ultra Bond 100 adhesive on a Zwick Roell Z100 tensile tester. If the adhesion of the coating exceeded the strength of the adhesive (≈80 MPa), the measurement was carried out by the pin method [22]. A coating about 1 mm thick was applied to samples with pins 1.7 ± 0.5 mm in diameter, and the average value of the bond strength was calculated from the results of three tests: adhesion, if the rupture goes along the coating–substrate interface, or cohesion, if the rupture is along the coating.

Optimization of Spraying Modes. In our study, we consider two variants of the technology: the obsolete single-fuel D-Gun process still used at domestic enterprises, and the dual-fuel Super D-Gun process used abroad.

To optimize the modes of spraying, the LIH code [19] was used, in which the temperature *T* and the speed of powder particles *V* at the exit from the barrel are calculated, which determine the conditions for the formation of the coating. By varying the length and diameter of the barrel, the composition and magnitude of the explosive mixture charge (EMCh), as well as the position of powder injection into the barrel, it is possible to achieve maximum acceleration of powder particles with heating to a partially or completely molten state, which determines obtaining the highest density and strength of the coating [8], and the corresponding parameters are considered optimal for obtaining the best functional characteristics of the coating. The scheme of the formulation of the problem and its implementation in the experiment is presented in Fig. 3.

When sputtering composites based on carbides, it is necessary to exclude decarbidization of the powder material. To do this, one needs such a ratio of fuel and oxidizer, in which there is no oxygen in the detonation products. This is achieved if the number of oxygen atoms in relation to carbon atoms in the initial detonating mixture satisfies the ratio $O/C \leq 1$. In the single-fuel D-Gun process, this condition is satisfied by the acetylene–oxygen mixture $C_2H_2 + O_2$. However, due to the excessively high temperature of the detonation products of this mixture, equal to 4516 K [8], it must be diluted with nitrogen in order to prevent overheating of the powder particles, which is enough to heat up to the melting temperature of the binder material: up to 1726 K in the case of nickel or up to 1673 K in the case of nichrome. With allowance for these requirements, calculations to optimize the spraying mode were performed for currently industrially operating CCDS2000 installations equipped with a barrel with a diameter of 20 mm and a length of 1100 mm with a combustion chamber of 700 mm (Fig. 3).

Calculations for composites based on chromium carbide showed that in the detonation products of an undiluted mixture of $C_2H_2 + O_2$ the binder (nickel) is completely melted even in the largest particles (about 60 μm), and the bulk of the powder (particles of size less than 40 μm) flies out of the barrel in the form of superheated drops with a temperature of about 2500 K. As the heating of small particles decreases due to the dilution with nitrogen, the large particles in the powder of a wide fraction will be unmelted. In a mixture diluted with nitrogen by 20% ($O_2 + C_2H_2 + 0.5N_2$) the particles, of size more than 40 microns, which determine more than 50% of the mass of domestic powders and at least 90% of the mass of powders of foreign manufacturers, are melted without significant overheating.

With variation of the value of the explosive mixture charge (EMC) in calculations, the maximum acceleration of the powder particle is obtained when the combustion chamber is filled with an explosive mixture by (85 ± 5%). The calculated speeds *V* and temperatures *T* of particles at the exit from the barrel for the mode with the filling of the combustions chamber by 90% with the mixture $C_2H_2 + O_2 + 0.5N_2$ are presented in Table 1, and this ND (Nitrogen Diluted) mode was chose as the optimal one for deposition using the single-fuel technology in the experiments. The bulk of the particles fly out of the barrel (from 40 μm and below) almost in a state of melting. Only large particles (from 50 to 60 μm), which fall on

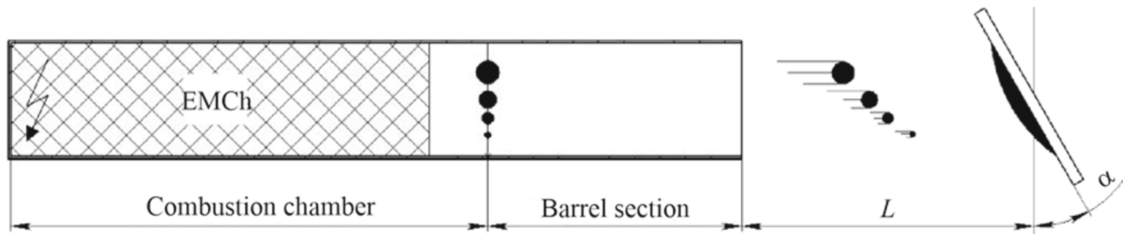


Fig. 3. Scheme of the experiment on detonation spraying.

TABLE 1. Velocities and Temperatures of CChN-30 Particles at the Exit from the Barrel

Particles, μm	Dilution with nitrogen (ND)		Dilution with propane (PD)	
	T, K	*V*, m/s	*T*, K	*V*, m/s
15	1898	634	1930	762
25	1760	536	1704	649
40	1658	442	1474	530
60	1403	352	1285	439

the substrate in the solid state, are substantially undercooled. The amount of the binder (from 20 to 30%) and its material (nickel/nichrome), corresponding to the selected powders, do not significantly affect either the heating of the particles of their acceleration in this mode.

In the Super D-Gun process, the acetylene–oxygen mixture is diluted not with nitrogen, but with a second, less active than acetylene, gas fuel: propylene, propane, etc. [13]. This makes it possible to lower the temperature of the detonation products without losing their dynamic head [8] and to prevent overheating of the powder without loss of particle velocity. When such a process is implemented in CCDS2000, the density, hardness, and wear resistance of the coating reach extremely high values [14].

Propane was used as a diluent fuel and, as the calculation showed, for composites based on chromium carbide, the bulk of the powder (particles smaller than 40 μm) is heated to the melting of the binder by the detonation products of an equimolar mixture diluted by 10.5% propane (O_2 + $0.7C_2H_2$ + $0.2C_3H_8$) in a barrel 1100 mm long with injection at a distance of 400 mm. In this case, the particle velocities increase by 100 m/s (Table 1), and the dynamic effect on the substrate (impact energy) increases almost one and a half times. This mode [hereinafter, the propane diluted (PD) mode] was chosen as the optimal one for the detonation spraying by the dual-fuel technology.

The Results of the Study of the Properties of Coatings. ***Influence of spray distance and angle of inclination of substrates.*** For a comparative analysis of the properties of coatings on the detonation complex CCDS2000, samples were obtained in optimal deposition modes.

When processing parts in industrial conditions, both the spray distance *L* and the slope of the treated surface relative to the direction of the flow of sprayed particles can vary (Fig. 3). The influence of these parameters was studied with variation of *L* from the 50 to 400 mm and of the inclination angle α from 0 to 60^{o} at a distance of 200 mm. The general laws governing the behavior of the powders under study are characterized by the results obtained by deposition of the CChN-30 powder in the nitrogen diluted mode.

To measure the powder utilization factor, samples with coatings weighing at least 2 g were sprayed, and, with a weighing accuracy of 10 mg, the measurement error did not exceed 5%, and the statistical dosing error for the CCDS2000 did not exceed 1%. The graph of the powder utilization factor versus *L* is shown in Fig. 4.

Due to the wide fractional composition (<64 μm) of CChN-30, subcooled large particles ricochet without being retained in the coating, while the superheated fine fraction increases losses by sputtering on collision with the substrate. As a result, the value of the powder utilization factor approaches 45% only at a short distance and stabilizes in the range from 150 to 250 mm at a level of 41–38%, after which the losses increase due to the cooling of the powder, and the powder utilization factor falls below 30% (Fig. 4).

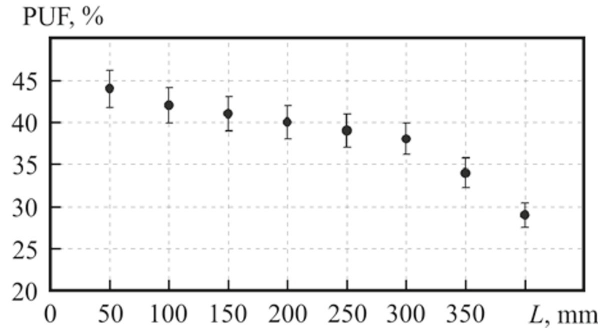


Fig. 4. Dependence of PUF of the CChN-30 powder on the spraying distance.

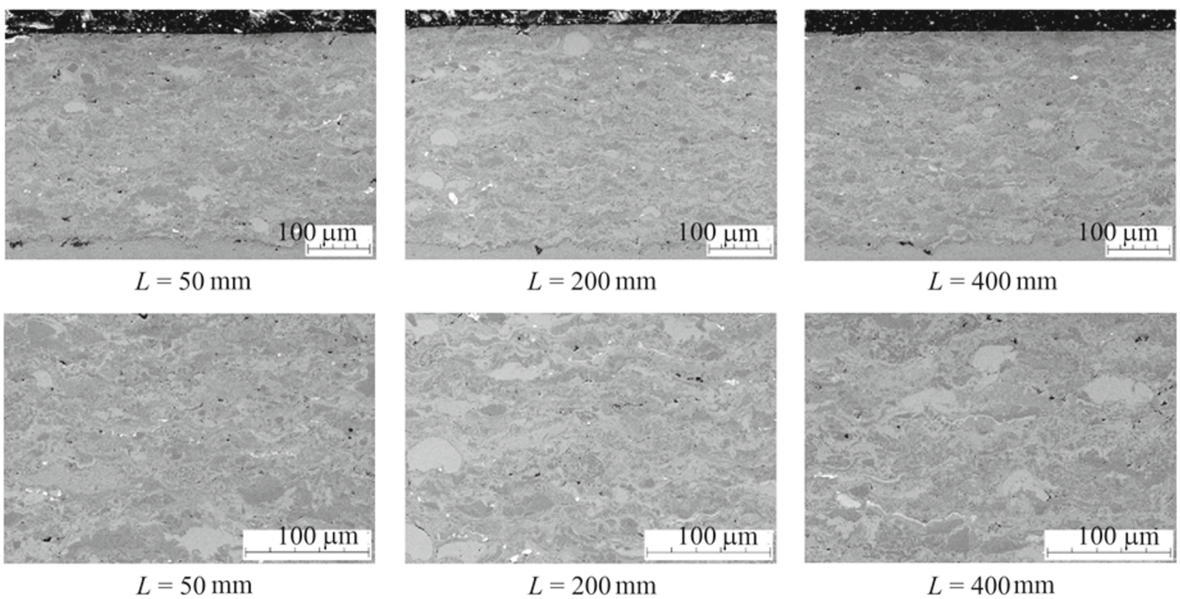


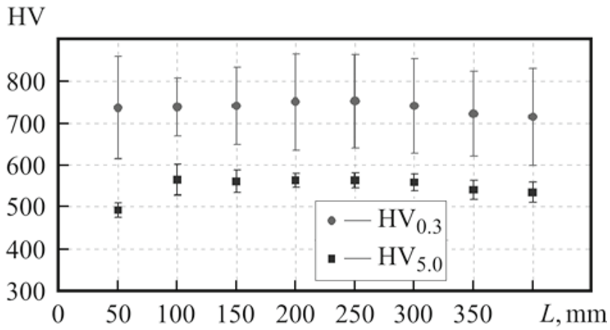
Fig. 5. Microstructure of the CChN-30 coating at different spraying distances.

The evolution of the coating microstructure with change in the deposition distance is illustrated by the photographs in Fig. 5.

Over the entire range of deposition distances, a CChN-30 forms a dense coating with porosity not exceeding 1.0%. In this case, in a fairly homogenous structure of a composite from carbides of about 10 μm in size with thin (micron) metal veins, large (tens of μm) fragments of pure metal (nickel) are clearly distinguishable, formed from the above-mentioned metal impurity in the original powder. As the distance increases, the content of these fragments decreases. Well-heated cobalt balls at the exit from the barrel at a short distance are flattened several times due to strong deformation upon impact with the substrate (Fig. 5, $L = 50$ mm). With increasing distance due to cooling and solidification primarily of large particles, their content decreases and at a distance only individual particles are incorporated into the coating without significant deformation (Fig. 5, $L = 400$ mm).

The results of measuring the coating hardness at different deposition distances are shown in Fig. 6.

Average value of microhardness at a maximum of about 750 $HV_{0.3}$ changes little in the range from 50 to 300 mm, following which it begins to decrease and drops to almost 700 $HV_{0.3}$ at a distance of 400 mm. Due to the fact that the size of the indentation in these measurements was comparable with the size of large metal inclusions, the spread of the measured microhardness values reached ±150 HV. At a load of 5 kg, the effect of inhomogeneity is leveled, the spread is reduced by a factor of three, and the average value is reduced by more than 150 HV. Moreover, for this parameter in the range of 150–250 mm, the hardness extremum is clearly expressed with a value of about 600 $HV_{0.3}$.



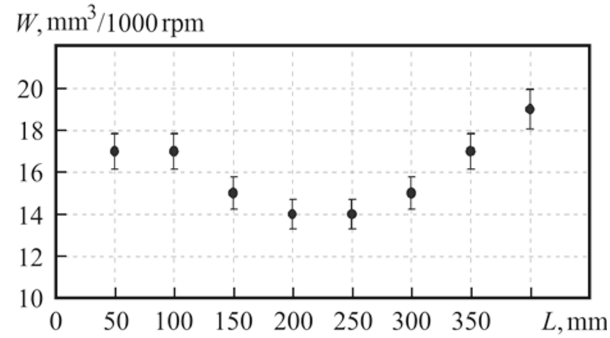


Fig. 6. Dependence of the hardness (HV units) of the CChN-30 coating on the spraying distance.

Fig. 7. Dependence of the wear of the CChN-30 coating on the spraying distance.

A clear correlation is observed between the hardness and wear resistance of the coating. The results of tests for abrasion resistance are presented in Fig. 7. The measurement error of coating wear was about 10%.

Minimum wear value W = 5.3 mm^3/100 rpm in the range of 200–250 mm corresponds to a maximum hardness value of 560 HV$_{5.0}$. The main reason for increased wear at short distances is the inhomogeneity of the coating with large fragments of the metal bond. Some decrease in wear resistance with a corresponding drop in hardness at short distances is most likely due to the drop in the strength of the coating due to the loss of speed and cooling of the particles as they escape from the detonation products into the environment.

When predicting the service life of a wear-resistant coating operating under mechanical loads, along with wear resistance it is necessary to take into account the level of residual stresses in the coating. In detonation coatings, as in any coatings obtained by thermal spraying, residual tensile stresses accumulate due to the shrinkage of the molten material during its cooling. These stresses are neutralized as a result of a kind of shot-blasting ("pinning effect") of the already deposited material with particles that continue to form the overall coating layer. Depending on the intensity of the pinning effect, the tensile stress is partially or completely compensated, and at high intensity, a coating with compressive stress is formed. The main role in pinning is played by solid ricocheting particles, and the intensity of the effect depend both on the velocity of particles and on their fraction determined by the powder utilization factor. The final state of the formed coating can be characterized using the Almen test.

The results of characterization of residual stresses in coatings for various spraying distance are shown in Fig. 8. The accuracy of measurement of the plate bend was ±20 μm.

One can notice a clear correlation between the dependences in Figs. 5 and 8. At a short distance (50 mm) at a relatively large powder utilization factor, the pinning effect is not enough to compensate tensile stresses, and a deflection is recorded for the coated plate (negative value of h). As the distance increases, the powder utilization factor decreases, and the number of ricocheting particles increases, which enhances the pinning effect. With an increase in the pinning effect, the stretching is more and more compensated, and from 150 mm it is transformed into compression, which causes the camber of plate (positive value of h), which increases as the powder utilization factor falls.

During the formation of a coating, the accumulation of tensile residual stresses is extremely undesirable; these stresses not only shorten the service life, but can cause destruction and delamination during the building up of the coating layer in the process of spraying. A moderate level of compression, not exceeding the strength of the coating material, increases the fatigue strength of the coating with a possible increase in its service life. The average level of residual stresses can be estimated by the formula [21]

$$\sigma = \frac{4E_0\delta_0^2 h}{3\delta(1-\nu_0)(4h^2+l^2)}, \tag{1}$$

where E_0, δ_0, ν_0, and l are the Young′s modulus, thickness, Poisson′s ratio, and the length of the Almen plate, δ is the thickness of the coating, and h is the deflection arrow of the Almen plate (see Fig. 2). The positive value of h corresponds to compressive stresses, and the negative one — to tensile stresses. Accordingly, the compressive stresses in the coating have a

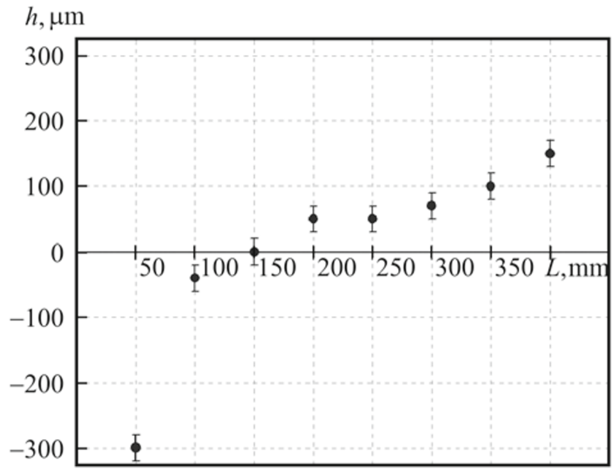


Fig. 8. Dependence of the sagging deflection on the spraying distance for the CChN-30 powder.

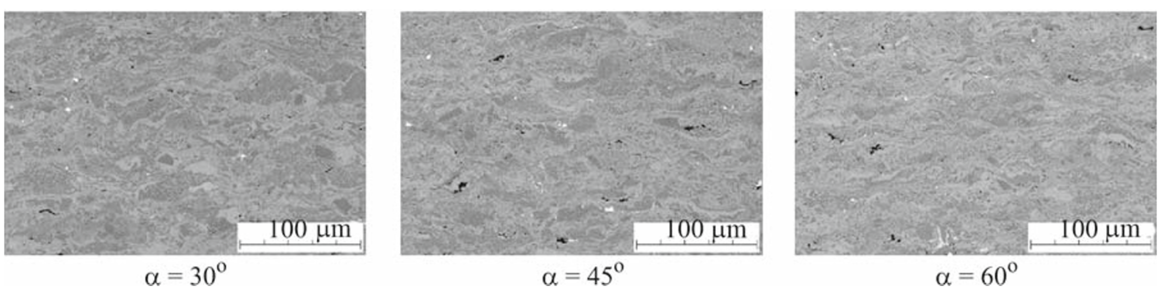


Fig. 9. Microstructure of the coating from CChN-30 at different values of α at a distance of 200 mm.

TABLE 2. Parameters of CChN-30 Coatings at Different Values of α (ND mode, L = 200 mm)

α, deg	PUF, %	Porosity, %	$HV_{0.3}/HV_{5.0}$	W, mm^3/1000 rpm	h, µm	σ, MPa
0^o	40	0.5	750/553	5.3	50	19
15^o	39	0.6	748/553	5.3	50	19
30^o	33	0.6	742/544	5.5	50	19
45^o	27	0.4	736/538	6.1	0	0
60^o	22	0.4	710/521	6.6	0	0

positive sign in formula (1), while the tensile stresses have a negative sign. For Almen Strip N1 $E_0 = 2\cdot10^5$ MPa (SAE 1070 steel), δ_0 = 0.75 µm, ν_0 = 0.3, l = 76 mm, and δ = 0.1 mm. The value of residual stresses calculated by formula (1) for the results presented in Fig. 8 varies from –111 MPa (tensile stresses) to +56 MPa (compressive stresses).

Based on the results obtained, to study the effect of the angle of inclination and compare the parameters of coatings from different powders a distance of 200 mm was chosen, near which the most wear-resistant coating with moderate compressive stresses is formed at a still high powder utilization factor. The results on the influence of the angle of inclination are summerized in Table 2, and the corresponding microstructures are shown in Fig. 9.

At α = 15^o, no noticeable change in the coating parameters was found. The microstructure at α = 15^o also does not differ from that observed at α = 0^o (Fig. 5, L = 200 mm). Changes become noticeable starting from α = 30^o, where the

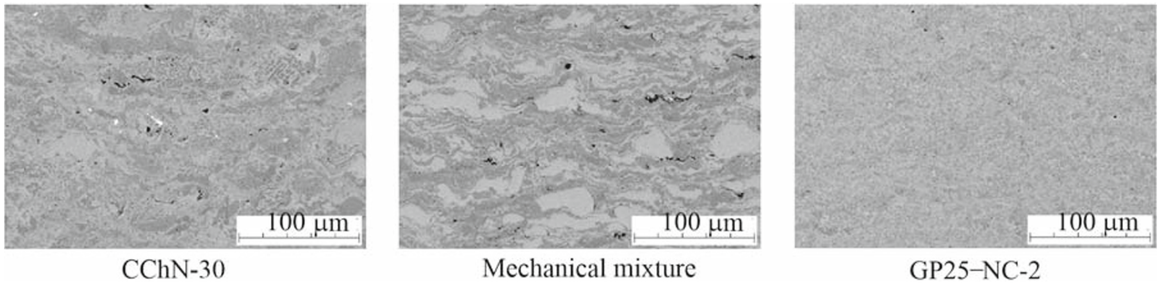


Fig. 10. Microstructure of coatings from different powders (ND mode, L = 200 mm).

TABLE 3. Parameters of Coatings Deposited in the ND Mode at a Distance of 200 mm

Powder	PUF, %	Porosity, %	$HV_{0.3}/HV_{5.0}$	W, mm^3/1000 rpm	h, μm	σ, MPa
CChN-30	40	0.6	750/533	5.3	50	19
Mechanical mixture	27	1.0	641/476	5.4	250	93
GP25–NC-2	45	0.3	924/690	3.2	−100	−37

powder utilization factor drops to 33%, while the uniformity of the coating improves. Apparently, during a grazing fall, the metal drops partially splatter and "smear," forming fragments already in the form of relatively thin lamellae. With a further increase in the angle, these tendencies intensify and at $\alpha = 60^o$ the powder utilization factor is equal to 22%. However, despite the doubling of the rebound, the compression in the coating decreases to zero, since the pinning effect in this case decreases due to the strong decrease in the normal component of the particle–substrate collision velocity. The hardness of the coating almost does not change, and the porosity decreases even slightly with increasing slope. Wear resistance changes insignificantly with slope, only at $\alpha = 60^o$ it decreases by 25%.

When carrying out testing using the adhesive method, in the entire range of variation of L and α samples were torn along the adhesive connection with a result of (85 ± 5) MPa. In measurements by the pin method, a cohesive rupture (along the coating) was recorded [22] with an average value of about 180 MPa. Spread of measured values over the entire range of variation of L and α did not exceed ±30 MPa, which allows one to speak of a bond strength of at least 150 MPa.

Influence of powder manufacturing technology. Comparison of coating parameters for various coating powders sprayed in the ND mode at a distance of 200 mm are presented in Table 3.

When spraying a mechanical mixture, the loss of powder increases sharply — the powder utilization factor decreases by one and the half times, and homogeneous GP25–NC-2 agglomerates from clad particles are sprayed more efficiently — the powder utilization factor increases. Photos for comparison of the microstructure of the coatings are shown in Fig. 10.

The structure of the coating from a mechanical mixture is formed from carbides interspersed with large fragments of a metal binder, in contrast to the microstructure of a coating from CChN-30, where only individual large fragments of pure metal are found along the carbides bounded by binder veinlets. The agglomerated powder GP25–NC-2 produces a dense coating with a uniform structure of small carbides bound by thin veins in a metal binder. Its porosity is less than 0.5%, twice the porosity of the coating from CChN-30, and about 10% porosity for the coating from the mechanical mixture. Because of the inhomogeneity and high porosity, the hardness of the mechanical mixture coating is 100 HV lower than that of the CChN-30 coating, while the microhardness of the homogeneous dense coating of GP25–NC-2 is higher than that of the CChN-30 coating by 200 HV. Such a relationship between the specific features of the microstructure and hardness of coatings determines the corresponding relationship of wear resistances. The abrasive resistance of the coating from GP25–NC-2 is more than one and a half times higher than the resistance of the coating from CChN-30 and higher than the resistance of the coating from mechanical mixture.

A clear correlation is seen between the powder utilization factor and the nature of the residual stresses in the coating. Due to the rebound of more than 70%, the tension in the coating during the deposition of a mechanical mixture is leveled due to the intense pinning effect, and the resulting coating has a high level of residual compressive stress. At a higher powder

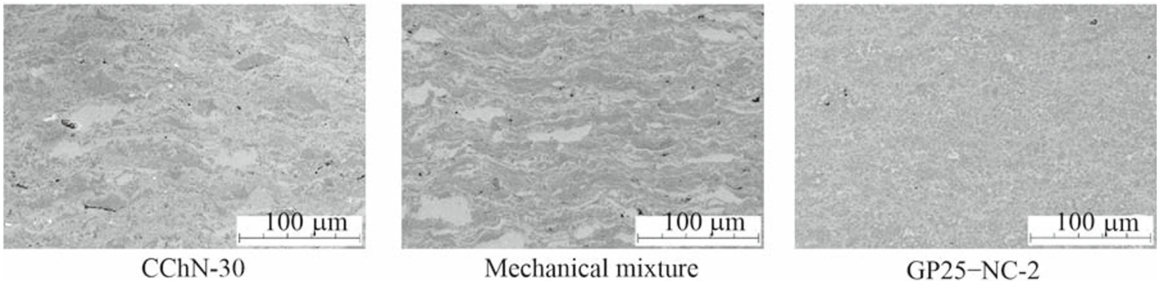


Fig. 11. Microstructure of coatings from different powders (PD mode; L = 200 mm).

TABLE 4. Parameters of Coatings Deposited in the PD Mode at a Distance of 200 mm

Powder	PUF, %	Pores, %	$HV_{0.3}/HV_{5.0}$	W, mm/1000 rpm	h, μm	σ, MPa
KXH-30	40	0.5	758/540	5.1	200	74
Mechanical mixture	26	0.8	735/515	5.0	800	297
GP25–NC-2	44	0.12	955/751	3.1	0	0

utilization factor, in the CChN-30 coating the level of compression is noticeably lower, and at a rebound of only 55% of the powder, the intensity of the pinning effect is no longer sufficient to compensate for the tension in the GP25–NC-2 coating.

During pin tests, the coatings made of GP25–NC-2 had a cohesive rupture, and the specific tensile strength exceeded 150 MPa, as in the case of CChN-30, only in the mechanical mixture the bond strength decreased to 120 MPa due to the large inhomogeneity of the coating.

Influence of the spraying mode. As calculations showed, in the dual-fuel mode (PD), the particle velocity at the exit from the barrel increases, and the energy of particle impact on the substrate increases by a factor of one and a half (Table 1). The results of sputtering in the propane diluted mode at a distance of 200 mm are illustrated by photographs of the microstructure in Fig. 11.

In the propane diluted mode, large metal particles colliding with the substrate at a higher speed are deformed more strongly and are even fragmented, which is clearly reflected in the microstructure of the coating from the mechanical mixture and CChN-30. The defectiveness of the GP25–NC-2 coating decreases and the pores shrink. In general, the density of coatings of all materials increases and the porosity of the GP25–NC-2 coating falls below 0.2%. Comparison of coating parameters for various powders sprayed in the propane diluted mode at a distance of 200 mm is presented in Table 4.

Despite the increase in the particle velocity, the loss of powder does not increase and the powder utilization factor remains practically unchanged. In this case, due to the 1.5-fold increase in the impact energy, the pinning effect is enhanced, and the compressive stresses are leveled in the GP25–NC-2 coating as well. Hardness increases markedly in the mechanical mixture coating, apparently due to the greater deformation and fragmentation of the binder. At the same time, the wear resistance of all coatings practically does not change.

To estimate the residual stresses by formula (1) on plates made of the Inc 617 heat-resistant alloy, the following values were taken: $E_0 = 1.12\cdot10^5$ MPa (Inc 617), $\delta_0 = 2.0$ mm, $\nu_0 = 0.32$, $l = 76$ mm, and $\delta = 0.3$ mm. According to the results of processing the tests, the relationship between the residual stresses in coatings from different powders and for different spraying modes did not change qualitatively, and the values of σ in coating 300 μm thick are comparable with the values indicated in Table 4. When testing the abrasion resistance of Inc 617 heat-resistant alloy, the value $W = 23$ mm^3/1000 rpm was obtained. Thus, the best detonation coatings (with $W \approx 3$ mm^3/1000 rpm) make it possible to increase the wear resistance of Inc 617 products by almost 7 times.

In pin tests of bond strength, cohesive failure was still recorded, and the specific braking force exceeded 150 MPa for all materials, including the mechanical mixture.

Conclusions. For the first time, a systematic study of the application of wear-resistant coatings from composite powders based on chromium carbide by means of the detonation method to harden parts of aircraft equipment and power gas turbines has been carried out. A comprehensive analysis of the characteristics of coatings obtained from powders of Russian and foreign manufacturers was performed. The hardness, porosity, wear resistance, and bond strength of the resulting coatings were measured. Comparative characterization of residual stresses is carried out. To optimize the regimes, the acceleration and heating of particles of the spray powder were calculated using a numerical code, and the optimal regimes for single-fuel and dual-fuel technologies were determined.

The influence of the spraying distance and the slope of the treated surface has been studied. According to the results of experiments, in order to obtain the best quality of the coating, it is possible to recommend spraying at a distance of 200 to 250 mm with a surface slope of up to 45^{o}.

It is shown that when using the dual mixture spraying, the coating density improves and residual stresses are completely leveled. It has been established that as regards the wear resistance, mechanical mixture coating practically do not differ from coatings made of clad powder, and are characterized by specific wear of about 5 mm^3/1000 rpm according to the ASTM G65 standard, however, in terms of the efficiency of using the powder, the mechanical mixture is one and a half times inferior to the clad CChN-30 one. The efficiency of using the spray-dry powder is even better (by 10%). The coating from it is more homogenous and in terms of wear resistance it is 60% superior to coatings from a mechanical mixture and CChN-30. In pin tests, coatings of all materials show a cohesive rupture at a specific load of more than 150 MPa, which gives grounds to consider the adhesion of coatings to be at least 150 MPa.

The main disadvantages of the powders used at domestic enterprises are an excessively wide fraction and the presence of individual particles of a binder of large agglomerates, which cause a significant inhomogeneity of the resulting coatings, which is one of the reasons for heir lower wear resistance in comparison with coatings from homogeneous powders used abroad. However, when sprayed under optimized conditions, the bond strength of all chromium carbide hard alloy detonation coatings exceeds 150 MPa and the abrasion resistance of coated Inc 617 alloy parts increases by more than 5 times, and spraying using two fuels allows the formation of coatings without tensile stresses.

Acknowledgment. This work was supported by a grant from the Ministry of Science and Higher Education of the Russian Federation (Project No. 075-15-2020-781).

NOTATION

E_0, Young′s modulus; h, sagging deflection of the Almen plate, μm; l, length of the Almen plate; W, specific wear of the material, mm^3/100 rpm; α, angle of inclination of the treated surface, deg; δ_0, thickness of the Almen plate; δ, coating thickness, μm; σ, residual compressive-tensile stresses, MPa; ν_0, Poisson ratio.

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