for the wrought metal the standard level of *KCV* amounts to 182–312 J/cm^2.

The obtained results of investigation of peculiarities of formation of structure and properties of high-alloy steel show the high level and isotropy of physical and mechanical properties of cast metal of the model ingot after the successive circumferential ESS LM without post high-temperature heat treatment, usually used after the electroslag welding. This shows the challenges in application of the described method for the enlargement of ingots of high-alloy steels and alloys.

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EFFICIENCY OF THE USE OF PROTECTIVE EXTENSION IN PLASMA SPRAYING

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It was established that the use of the protective extension provides a 25 % increase in average velocity of spraying particles, improves heating of the particles, and decreases the required specific energy of the spraying process by 20 % due to increase in size of the high-temperature zone of the plasma jet. The content of oxides in coatings deposited by using the extension is 10 % lower, the content of pores in them is 4 times lower, and the coating to substrate adhesion strength is 20 % higher.

Keywords: *plasma spraying, plasma jet, extension, properties of coatings, material utilisation factor, experimental design*

In deposition of coatings by the plasma jet in open atmosphere, formation of a coating is affected by an admixture of ambient gases to the jet. The initial region of the jet measured from the plasmatron nozzle with diameter d_0 to boundary I–I is characterised by the constant values of velocity u_0 and temperature of the flow, as well as by their equality to the initial values up to x_0 (Figure 1) [1]. In addition, the ionisation and dissociation energies are intensively released in the initial region of the plasma jet. Efflux of the electric current, additional release of the energy and turbulisation of the flow caused by the processes of large- and small-scale shunting of the arc take place sometimes. Static pressure in the initial region is not equal to zero because of electromagnetic compression of the ionised gas in the electric arc. That is why, depending on the shape of the outlet part of the nozzle, the jet dramatically expands near its exit section. The mixing zone, where a radial transfer of impulse and energy takes place, and where parameters of the plasma jet continuously change from their initial values to the values characteristic of the ambient atmosphere, forms in the peripheral region of the jet starting from the exit section of the nozzle. Therefore, the transition region of the jet, and then the basic one, forms outside the initial region to boundary T–T. The temperature and velocity of the plasma jet decrease as a result of its dilution with cold air, this deteriorating heating of the spraying material. The spraying material actively interacts with the atmosphere components (O_2, N_2) already in the initial region. For example, for standard plasmatron UMP-4 the concentration of argon in the jet at a distance of $(2–3)d_0$ is 50 %, and in the zone where the spraying particles interact with the workpiece surface at a distance of 70–100 mm ($(10–15)d_0$) the concentration of argon is 20 %. This leads to formation of oxide and nitride inclusions in the coatings, that deteriorate properties of the latter (porosity, cracking, exfoliation) [2, 3].

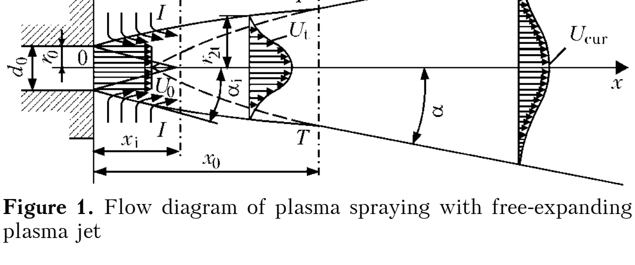

Figure 1. Flow diagram of plasma spraying with free-expanding plasma jet

To prevent the processes causing admixture of the atmosphere components to the jet, plasma spraying is performed in normal-pressure shielding atmosphere (APS), in rarefied controlled atmosphere (VPS), under a layer of liquid (WPS) and in increased-pressure

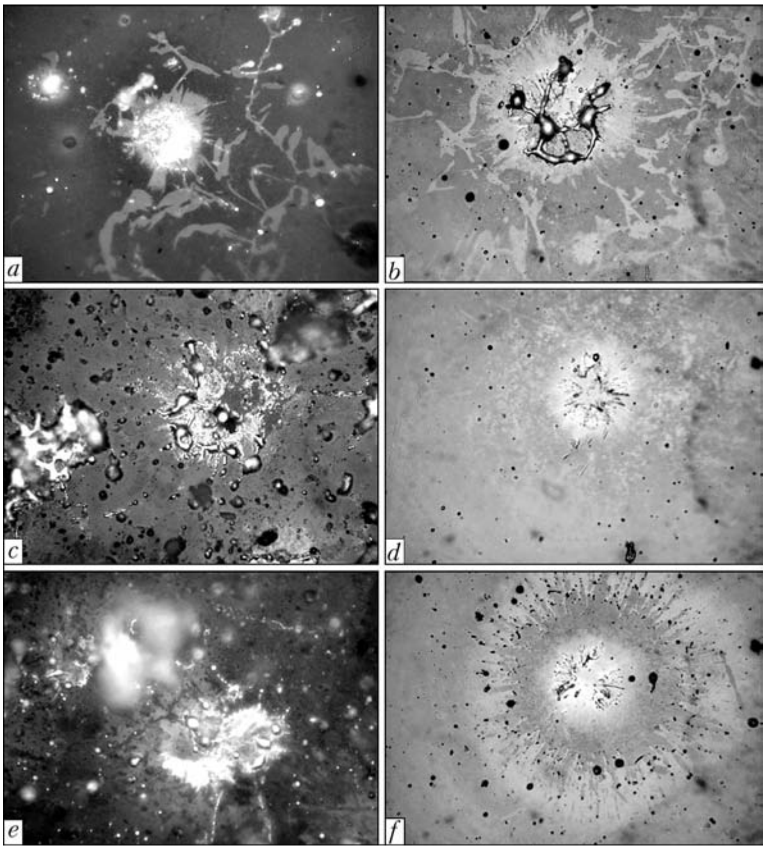

Figure 2. Splats of particles of powder PT-NA-01 sprayed by the plasma arc method without (*a*, *c*, *e*) and with extension (*b*, *d*, *f*) at currents of 300 (*a*, *b*), 400 (*c*, *d*) and 500 (*e*, *f*) A

controlled atmosphere (HPPS) [3–6], as well as by using systems with local shielding [3, 7–10].

The following tasks can be achieved by using the system of local shielding of the plasma spraying zone:

- increase in size of the high-temperature zone of the plasma jet (by restricting admixture of an ambient cold gas) and concentration of the spraying material in the central part, which leads to more efficient heating of the spraying material and more rational utilisation of the plasma jet energy;
- mitigation of the oxidation process caused by reaction of the spraying material with active components of the ambient atmosphere (O_2, N_2).

The purpose of this study was to evaluate the efficiency of the use of the protective extension in plasma spraying and its effect on improvement of the quality of coatings by upgrading heating and accelerating of the powder particles during spraying, as well as the protection of the spraying material from the ambient atmosphere (O_2, N_2).

The effect of the protective system on properties of the coatings was evaluated in the experiments on plasma arc spraying with and without the protective extension by using plasma spraying unit UPU-8M and a thermoreactive powder of the PT-NA-01 grade (95 wt.% Ni–5 wt.% Al) with a particle size of +40 – –60 μm [11].

The efficiency of heating of the particles was determined by evaluating their appearance after solidification in collision with the surface of a glass plate (splat-test). Spraying was carried out with and without the extension at different specific energies of the process

$$\varepsilon = \frac{UI\eta}{V_{\rm p.g}},$$

where U is the voltage, V; I is the current, A; η is the efficiency of the plasmatron; and $V_{\rm p.g}$ is the flow rate of the plasma gas, m^3/h.

The value of ε was varied by varying the current (300, 400 and 500 A). The plasma gas was argon with a flow rate of 1.38 m^3/h. Arc voltage was 30 V, and efficiency of the plasmatron was 53 % at a current of 300 A, 48 % at 400 A, and 47 % at 500 A (which was determined by using software CASPSP [12]). Under these conditions the specific energy of spraying was varied from 3.5 to 4.2 and to 5.2 $kW{\cdot}h/m^3$.

Spraying was performed on glass plates measuring 50 × 30 × 3 mm. As seen from the appearance of the splats sprayed without the extension (Figure 2), at a current of 300 A the particles did not melt and rebounded from the surface, and at 400 A melting of the particles was incomplete (the shell melted, and the nucleus remained solid; increase in the amount of the incompletely melted particles in a coating leads to formation of coarse pores). At a current of 500 A the particles fully melted. In spraying with the extension, the particles fully melted already at a current of 400 A.

Therefore, the application of the extension allowed decreasing the required specific energy of the spraying

Table 1. Matrix of fractional (2^{4-1}) factorial experimental design

Experiment No.	I, A	$V_{p.g}$, m^3/h	H, mm	Ar/N_2
1	+	+	+	+
2	+	+	−	−
3	+	−	+	−
4	+	−	−	+
5	−	+	+	−
6	−	+	−	+
7	−	−	+	+
8	−	−	−	−
9	0	0	0	0

Table 2. Boundary values of factors of plasma spraying of powder PT-NA-01

Level	I, A	$V_{p.g}$, m^3/h	H, mm	Ar/N_2
+	500	1.50	160	0.7
−	400	1.26	100	1
0	450	1.38	130	0.85

process using powder Ni–5Al from 5.2 to 4.2 kW·h/m^3 (by 20 %), this being a result of increasing the size of the high-temperature zone of the plasma jet.

Measurement of the velocity of the spraying particles in the plasma jet at a distance of 140 mm from the exit section of the nozzle by using instrument ISSO-1 showed that in spraying of powder PT-NA-01 with the extension the velocity of the particles was about 120 m/s, this being 25 % higher than the velocity of the particles in spraying without the extension (95 m/s).

Optimisation of the spraying parameters was performed by the method of mathematical experimental design [13], and the optimisation parameter was a material utilisation factor (MUF), which was determined in spraying on a flat surface (250 × 250 × × 1.2 mm) for each spraying variant (with and without the extension).

Weight of a sprayed coating and spraying powder was evaluated by using the KERN balance EMB 200-2 with a measurement accuracy of ±0.01 g.

Table 1 presents the matrix of the fractional (2^{4-1}) factorial experimental design for evaluation of MUF. Current, plasma gas flow rate, plasma gas composition and spraying distance which have the most substantial effect on the spraying process, were chosen as variable factors [14]. In addition to the variable spraying factors, the following factors were chosen as the constant ones: powder consumption — 32 g/min, spraying time — 15 s, and transporting gas flow rate — 0.21 m^3/h.

The limits of variation of the factors were chosen on the basis of the experience of spraying using the said powder and characteristics of the spraying equipment. The boundary values of the factors are given in Table 2.

Table 3 gives the values of MUF in plasma arc spraying with and without the extension.

The regression equation was derived from the results of the experiment under conditions without the extension (Table 3) for the dependence of MUF on the spraying factors:

$$\mathrm{MUF}\ (\%) = 48.1 + 0.045I - 6.46V_{p.g} - 2.08H + \\ + 1.8(\mathrm{Ar}/\mathrm{N}_2).$$

Parameters of spraying with the extension at a maximal value of MUF by using powder PT-NA-01 were determined in a similar way. In this case the regression equation for the dependence of MUF on the spraying factors has the following form:

$$\mathrm{MUF}\ (\%) = 72.9 - 0.148I - 5.1V_{p.g} - 0.16H + \\ + 92.5(\mathrm{Ar}/\mathrm{N}_2).$$

As established as a result of analysis of the experimental results (Table 3), without the use of the extension the highest value of MUF was achieved in mode 6, which provides the maximal amount of the melted spraying particles and the lowest amount of the overheated particles, the presence of which leads to losses for evaporation and splashing of the particles melt.

Table 3. Values of MUF in spraying of powder PT-NA-01 with and without extension

Experiment No.	I, A	$V_{p.g}$, m^3/h	H, mm	Ar/N_2	MUF without extension, %	MUF with extension, %
1	500	1.5	100	1	48	51
2	500	1.26	160	1	43	58
3	400	1.5	160	1	34	64
4	400	1.26	100	1	56	74
5	500	1.5	160	0.7	38	28
6	500	1.26	100	0.7	72	62
7	400	1.5	100	0.7	41	61
8	400	1.26	160	0.7	52	59
9	450	1.38	130	0.85	60	70

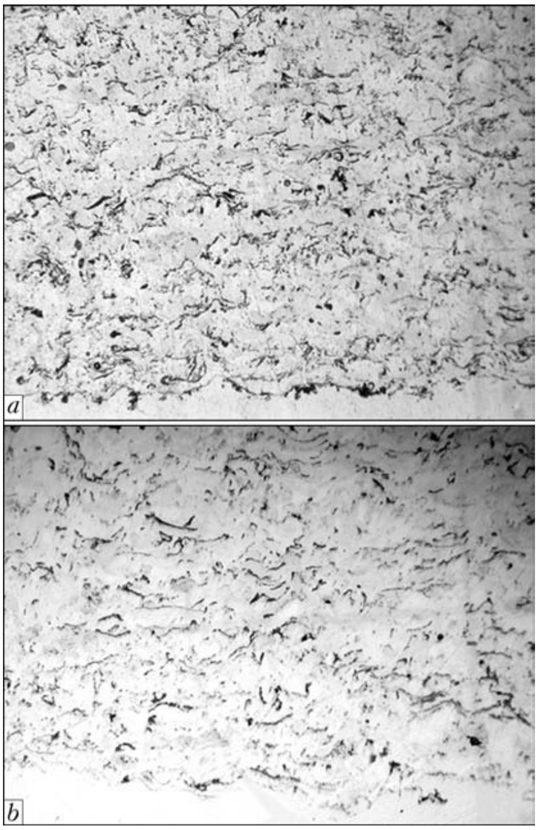

Figure 3. Microstructures (×200) of coatings sprayed by using powder PT-AN-01 without (mode 6, MUF = 72 %) (*a*) and with extension (mode 4, MUF = 74 %) (*b*)

By using the extension, the maximal value of MUF was obtained in mode 4, which differed from mode 6 in a lower current (400 instead of 500 A) and in a composition of the plasma gas (pure argon instead of the Ar/N_2 mixture), this coinciding with the results of the above-described splat-test. This decrease in the specific energy of the spraying process for achieving the maximal value of MUF in the case of using the extension is attributable to increase in size of the high-temperature zone of the jet and in velocity of the particles.

The average value of MUF in spraying with the extension by using the Ar/N_2 mixture increased but insignificantly (from 51 to 53 %), whereas in the case of using argon as a plasma gas the average value of MUF in spraying with the extension grew from 45 to 62 %, compared to the average values of MUF achieved in spraying without the extension. This is related to the fact that in spraying without the extension the low-enthalpy (in case of argon used as a plasma gas) plasma is diluted with air, which leads to dramatic lowering of its temperature and decrease in size of the high-temperature zone. The use of the extension and the addition of N_2 as a high-enthalpy plasma gas make it possible to provide an extended high-temperature zone.

Figure 3 shows microstructures of the coatings sprayed with and without the extension by using powder PT-AN-01 at the parameters with the maximal value of MUF. Structure of the coatings consisted of the molten particles in the form of lamellae. In addition to pores, oxides uniformly distributed across the coating and being lighter in colour, compared to the pores, were located along the boundaries of the particles. This made it possible to distinguish them and evaluate the degree of oxidation of the coating material.

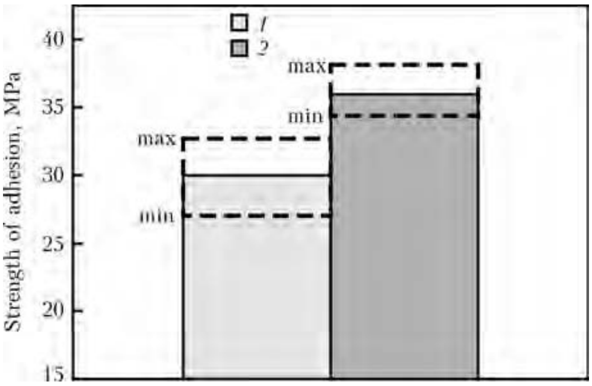

Figure 4. Strength of adhesion of coatings produced by spraying without (*2*) and with (*1*) extension by using powder PT-NA-01

Analysis of structures of the coatings produced in modes with the maximal value of MUF allows a conclusion of the correspondence of the chosen spraying parameters to the process of deposition of coatings from the completely melted powder particles, which, upon colliding with the surface, form lamellae.

The coatings produced by spraying without the extension had porosity of 0.4 % and oxide content of 5 %. In case of using the extension, porosity of the coatings was 0.1 %, and oxide content was 4.5 %.

The coating to substrate adhesion strength was evaluated by the glue method according to GOST-14760–69 and ASTM C 633–79 by using tensile testing machine R-50 (maximal load — 50 kN). Spraying of four specimens at the spraying parameters with the maximal value of MUF was carried out simultaneously for each variant. Thickness of the coatings was 0.25 ± ± 0.03 mm.

Adhesion strength of the coatings sprayed without the extension was 30 ± 3.3, and that with the extension was 36 ± 2.8 MPa. The coatings produced with and without the extension differed in the character of fracture. The coatings sprayed without the extension fractured along the interface with the substrate, whereas the coatings sprayed with the extension fractured in the glue, this evidencing the really higher strength of adhesion of the coatings to the substrate, compared to the fixed value. Therefore, in spraying with the extension the coating to substrate adhesion strength increased not less than by 20 % (Figure 4).

CONCLUSION

The use of the protective extension increases the average velocity of spraying particles of powder PT-NA-01 by 25 %, improves heating of the powder particles, and decreases the required specific energy of the spraying process by 20 % due to increase in size of the high-temperature zone of the plasma jet. The coatings produced by spraying with the extension contain 10 % less oxides (5.0 and 4.5 %, respectively), they have lower porosity (decreased from 0.4 to 0.1 %), and their strength of adhesion to the substrate grows by 20 % (from 30 ± 3.3 to 36 ± 2.8 MPa).

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