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PRODUCTION OF PRESS MOULDS BY PLASMA SPRAY FORMING PROCESS

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Summary:

Plasma spray forming process for production of press moulds which are used for manufacture of articles from plastics was developed. The press moulds were produced by plasma spraying of Cu-Al-Fe-alloy powder on surface of a master model. The master models were made from non-metallic materials with heat resistance below 70C (wood, gypsum etc). Double cooling system which provides for a control of surface model temperature and quenching conditions of sprayed material was designed. It made possible on the one hand to support model surface temperature below 70 C and on the other hand to provide for temperature conditions of martensite transformation in Cu-Al-system with a fixation of metastable ductile $\alpha + \beta^1$ -phase. This allowed to decrease residual stresses in sprayed layer (up to 0,5-2,5 MPa), to increase microhardness of the coating material (up to 1200-1800 MPa) and its ductility (σ_B =70-105 MPa, δ =6-12 %). This plasma spray forming process makes possible to spray thick layers (5-20 mm and more) without their cracking and deformation. The process is used for a production of press moulds which are applied in shoes industry, for fabrication of toys, souvenirs etc.

Keywords:

Plasma spray forming, press moulds, Cu-Al-Fe alloy, cooling system, residual stresses, mechanical properties, application.

1. Introduction

Traditional application of the thermal spraying technology is deposition of coatings on surfaces of parts and structures to protect them from wear and corrosion, as well as to restore dimensions after wear. Conditions of

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formation of a thermal spray coating are characterized by deformation and microadhesion of the spray material particles heated and accelerated as a result of their interaction with a high-temperature gas jet. Impingement of the particles on the substrate surface induces pressure in the collision zone, which is conventionally subdivided into two components, i.e. pulse and impact pressure. The value of the pulse pressure can be estimated using a modified Zhukovsky's equation of water hammer, while that of the impact pressure can be estimated, assuming the state of the spray material having the form of a melt, using the Bernulli's equation. The pulse pressure exists for about 10^{-9} s and provides cleaning of the work surface at the point of impact and formation of active centers. Duration of the impact pressure is 10^{-5}-10^{-7} s. It leads to deformation of the spray particle and formation of its physical contact with the surface. During the same period the interatomic bonds providing adhesion of the spray particle with the surface are formed at the interface. The considered phenomenological picture of formation of a thermal spray coating points to the presence of many indicators which coincide with those of such technologies of manufacture of parts and structural materials as hot pressing and rolling of powders. The level of the pressures formed depends also upon the density of the spray material and velocity of particles.

The value of the deformation impact pressure in plasma spraying corresponds to the loads achieved in hot pressing (50-450 MPa), while in detonation spraying it is in excess of the level achieved in pulse hot pressing (500-1500 MPa). This creates technical prerequisites for using thermal spraying as the method for production of free standing components, such as tubes, pipes, crucibles, moulds, dies and other parts [1-6].

The negative point of this technology can be a decrease in strength properties of a material in the as-sprayed state in the case of performing the process in an open atmosphere (in air). The incomplete physical contact between individual particles in the coating, porosity of the layer and oxidation of the surface of the spray particles lead to a decrease in cohesion strength of the layer, which affects the values of tensile strength and impact toughness. Thus, the plasma coating of a copper powder has tensile strength of 70-100 MPa, which is 3-5 times as low as that of a compact material. In the case of a nickel coating these values are 90-130 and 380 MPa, i.e. they are 3-4 times lower [7]. Therefore, one of the basic problems in development of the technology for manufacture of parts involving plasma spraying is that of ensuring the required strength properties of the coating material. The other problem consists in the requirement to decrease the level of residual stresses which grow with an increase in thickness of the sprayed layer.

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Manufacture of parts and different moulds and dies by thermal spraying on a master model is one of the extensively developing applications of this technology. The 0.5-5.0 mm thick metal layer is deposited on the surface of a steel or ceramic model. If necessary, the shell is fitted into a holder and is backed up by a low-melting point metal or epoxy resin.
This work was dedicated to application of plasma spraying for the manufacture of moulds used to make parts of plastic materials.
At present the tooling for plastic injection moulding is mostly manufactured by traditional fitting and machining, which require substantial input of labour of high-skilled machine-tool operators and fitters, sophisticated equipment and expensive tools. Besides, the labour content of the manufacture of the moulding elements proper is 70-90 % of the total labour content of the manufacture of the moulds, and the terms of the manufacture, allowing for the necessity to develop a set of design and technology documents, are up to several months.
The labour productivity can be fundamentally increased and costs of materials and labour, as well as the manufacturing costs of the tooling can be decreased by using a range of thermal spraying methods, and plasma spraying in particular [7]. In their potentialities (precision and complexity of the resulting moulding relief and performance of parts) the spraying methods compete with the methods of galvanoplastics. They are several times superior in productivity and adaptability for industrial production [7].
The necessity of performing tool operations for the manufacture of steel models and single use of the models of heat-resistant self-hardening ceramics are the factors which limit wide practical application of such methods. This determines topicality of development of the process with the ultimate working temperature of the model, T_m, limited to a level of 70 °C. Solution of this problem allows the use of models made from materials of an organic origin, including wood, wide range of thermoplastic materials with the corresponding low values of heat resistance. Also, this makes it possible to use plastics products proper, subject to duplication, as the models.
The characteristic feature of this process is a decrease in residual stresses in the formed metal shell coatings of arbitrary thickness down to values that exclude their showing up in the absence of adhesion to the surface of the model whose heat resistance is below 70 °C.

2. Equipment and materials

The PR-1R plasmatron which uses a mixture of argon and hydrogen as the working gas, and the PM-2M plasmatron using air as the plasma gas were

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employed for plasma spraying. The powder of bronze containing 9 % Al and 3-4 % Fe was chosen as the spray material. As shown by investigation of the phase diagram of the Cu-Al system, conditions of slow cooling lead to formation of a structure consisting of a mixture of the α-phase (Cu_7Al) and products of the $\beta \rightarrow \alpha + \gamma_1$ eutectoid transformation occurring at 565 °C [8]. The α-phase is characterized by high ductility at a low level of strength, whereas the γ-phase ($Cu_{32}Al_{19}$) has high hardness at low ductility. However, under conditions of plasma spraying at high rates of cooling of the molten particles the possibility exists of occurrence of martensitic transformation with suppression of the β-phase eutectoid decomposition and formation of a structure consisting of a mixture of the α-phase providing ductility of the spray material and the β'-phase (Cu_3Al) increasing its strength (Fig 1). This should favour a decrease in the level of residual stresses in the bulk of the deposited layer.

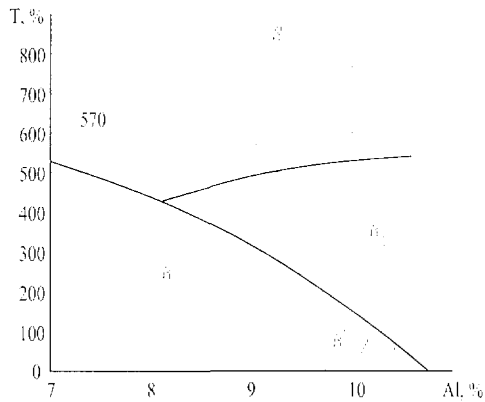

Fig. 1. Sequence of diffusionless transformations leading to formation of metastable phases in the sprayed structures of the Cu-Al system

The master model was made from wood, which limited the temperature at the "substrate-coating" interface to a value of 70 °C. Therefore, the temperature conditions of formation of a coating in this case were limited by the necessity, on the one hand, to ensure the required cooling rates for the spray material (Cu-Al-Fe alloy) and, on the other hand, to avoid heating of the master model to a temperature above 70 °C. The special system for cooling the coating formation zone was developed to solve this problem.

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3. Development of the cooling system and parameters of the plasma spraying technology for the manufacture of parts

The combined binary cooling system was developed to realize the above purpose of the system of cooling the coating formation zone. The system consists of systems for blowing off (cutting off of the plasma jet from the model surface) and spraying of the coolant (Fig. 2) [9]. The object affected by both systems is a dusted plasma jet, and the points of their local effect are the different functional zones (zone of transport of the spray particles within the spraying distance bounds and zone of the spraying spot on the model surface).

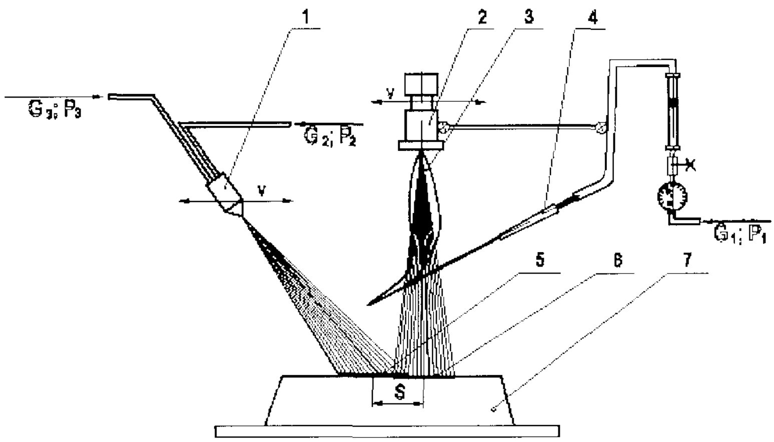

Fig. 2. Schematic of the cooling system: 1 - coolant sprayer; 2 - plasmatron; 3 - dusted plasma jet; 4 - slot nozzle of the blowing off system; 5 - cooling spot; 6 -spraying spot; 7 - model; v, , G_1, G_2,G_3, P_1, P_2, P_3 and S - process parameters of the cooling system

The blowing off system provides a substantial limitation of heating of the model surface due to cutting off of the plasma jet by the gas screen. In practice, this is achieved by intersecting the plasma jet by a properly formed flow of the process gas, e.g. compressed air. The process parameters of the blowing off system are flow rate G_1, pressure P_1, temperature of the process gas, point of its contact with the plasma jet and their relative orientation (attack angle).

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The spraying system is intended for increasing the cooling rate of the spray particles within the spraying spot zone under the effect of a coolant, e.g. a jet of finely dispersed droplets of distilled water. The intensity of the effect of the system is determined by the following parameters: orientation of the cooling spot relative to the spraying spot, S, flow rate G_3 and pressure P_3 of the sprayed water, pressure P_2 and flow rate G_2 of the compressed air that sprays water and velocity v of the plasmatron moving along the surface treated.

The rational operating parameters of the spraying process in the case of using argon-hydrogen mixture (PR-1P plasmatron) and compressed air (PM-2M plasmatron) as the plasma gases and the powder material of the Cu9Al4Fe alloy were determined on the basis of the criterion of achieving the minimum cost of realization of the process allowing for the following indicators: powder utilization factor (PUF), power consumption N, flow rate of the argon-hydrogen mixture G and its composition (H_2, Ar), % (Table 1).

Table 1: Technological parameters of plasma forming process [x)]

Plasmotron type	Power, kW	Amperage, A	Plasma gases: Composition	Plasma gases: Flow rate, $g \cdot s^{-1}$	Productivity, $g \cdot s^{-1}$	Deposition efficiency (PUF)
PR-1R	24,8	420	Ar+20,4 vol. % H_2	0,6	1,27	0,67
PM-2M	35,5	185	Compressed air	2,0	1,2	0,63

[x)] Conditions – powder of Cu9Al4Fe alloy, d_p = 40-50 μm, spraying distance – 0,2 m, model material – wood, with cooling system (CS) application.

Experimental studies, in which the optimization criteria were maximum values of the degree of efficiency of the blowing off system (q_0/q_1) (q_0, q_1 is the heat directed to heating the model by the initial and screened plasma jets, respectively), particles velocities v_p and PUF, allowed determination of the rational operating parameters of the blowing off system. Combinations of the parameters given in Table 2 for the PR-1P plasmatron yield the value of q_0/q_1 = 2.2 and those for the PM-2M plasmatron - 1.8. In this case with the

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plasmatrons in a fixed position T_m is 140-170 and 180-190 °C, respectively, the PUF values are decreased by 3-5 and those of v_p - by 13-15 %.
Further decrease in T_m to 70 °C with a simultaneous decrease in residual stresses in the formed structures is achieved by the effect of the spraying system. In the case of using aluminium bronzes the spraying system hardly deteriorates the strength values and provides the possibility of fixation of the T_m values within a range of 50-100 °C.
It was established that the important parameter of operation of the intensive cooling system was the relative location of the cooling and spraying spots. In the case of coincidence of their centres (S = 0) a sudden decrease in the PUF values (≤ 30 %) and productivity as to spray material, P_s, is observed, and physical-mechanical properties (strength of the coating is decreased from 45-50 to 5-15 MPa) are fundamentally deteriorated. The maximum effect of utilization of the system is achieved in the case if the cooling zone is superimposed on the spraying spot with its peripheral part ($S/\Delta\tau$= 0.5-0.8v, where v is the velocity of movement of the plasmatron and $\Delta\tau$ is the interval of displacement of the spot centres). The process parameter which is not less important is the flow rate of the coolant, G_3, which should be kept at a minimum but sufficient level. The ranges of the effective values of the coolant flow rate G_3 and the cooling spot sizes D_{cool} can be determined from analysis of thermal processes occurring during formation of the "shell".
Thickness of a layer of the shell coating, h, formed in a single pass is estimated on the basis of mass of the spray powder, m, within the spraying spot zone, D_{spray}, travel velocity of the plasmatron, v, productivity P_s and material density ρ.

$$m = \rho \frac{\pi D_{spray}^2}{4} h, \quad (1)$$

$$m = P_s \frac{D_{spray}}{v}, \quad (2)$$

$$h = \frac{4P_s}{\rho \pi D_{spray} v}, \quad (3)$$

At $P_s = 1.3 \cdot 10^{-3}$ kg/s, $D_{spray} = 3.5 \cdot 10^{-2}$ m, $\rho = 7.5 \cdot 10^3$ kg/m^3 and $v = 5 \cdot 10^{-2}$ m/s, the h parameter is equal to $1.3 \cdot 10^{-4}$ m. Assuming the degree of deformation of the spray particles, d_p/h_p, to be equal to 10-20 (where d_p is the diameter of particles of the initial powder material equal to 50 μm and h_p is the height of the deformed particle), the number of particles which determine thickness of the layer, h, is 20-50. If we assume that heating of the model and the coating formed is realized exclusively due to heat of the spray particles, Q_1, since

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heat of the plasma jet is almost completely cut off by the blowing off system, Q_1 can be estimated as:

$$Q = mc\Delta t, \tag{4}$$

or, allowing for dependence (2), as:

$$Q_1 = P_s \frac{D_{spray}}{\upsilon} c\Delta t, \tag{5}$$

where c is the specific heat of the spray material; Δt is the range of temperatures of the cooling particles, $T_{melt} - T_m$. The factor of a low thermal conductivity of the model material of an organic origin (λ = 0.1-0.5 W/(m·°C), limitation of heating of the model (T_m = 70 °C) and an insignificant mass (0.1-0.3 kg) make it possible to neglect the heat flow which cools the formed shell in a direction of the coating-model interface as a very small component, as compared with the cooling effect of the coolant. By considering the spraying process to be a successive deposition of the layer components, h thick, on the substrate with a temperature below 70 °C, the cooling flow Q_2 can be represented by the following relationship:

$$Q_2 = \frac{\Delta T}{\Delta h} \lambda S_{cool} \tau_{cool}, \tag{6}$$

or

$$Q_2 = \frac{\Delta T}{\Delta h} \lambda \frac{\pi D_{cool}^2}{4} \frac{D_{cool}}{\upsilon}, \tag{7}$$

where ΔT is the temperature gradient through thickness of the formed layer, h; λ is the thermal conductivity of the coating material and τ_{cool} is the duration of the coolant effect. On the basis of expressions (5) and (7) we obtain the following relationship of the process parameters investigated:

$$D_{cool} = \sqrt[3]{\frac{4P_s D_{spray} c\Delta t\Delta h}{\Delta T \lambda \pi}}. \tag{8}$$

At c = $0.41 \cdot 10^3$ J/(kg·°C), Δt = 10^3 °C, λ= 83 W/(m·°C), the ΔT dependence of D_{cool} will have the following form:

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$$D_{cool} = 3{,}4 \cdot 10^{-2} \Delta T^{-\frac{1}{3}}. \qquad (9)$$

The acceptable minimum values of ΔT (≤0.01 °C) are determined by the cooling spots $D_{cool} \geq 0.1$ m ($S_{cool} \geq 7.5 \cdot 10^{-3}$ m²).
The coolant flow rate G_3, which provides stabilization of temperature of the model at arbitrary values of T_m ($T_m = T_{melt}-\Delta t$), are determined from the following relationship:

$$G_3 = \frac{P_s c \Delta t}{c_w \Delta t_w + r_w}, \qquad (10)$$

where c_w, r_w and Δt_w are the specific heat, evaporation heat and temperature of heating of water, respectively, or from the Δt dependencies in the following form:

$$G_3 = 2 \cdot 10^{-7} \Delta t. \qquad (11)$$

Excess of the calculated value of the coolant flow rate (see Table 2), as well as incorrect orientation of the cooling spot lead to unjustifiable deterioration of the PUF, strength and ductility values.

Table 2: Conditions of plasma forming process [x)]

Plasmotron type	P_1, MPa	V_s, $m \cdot s^{-1}$	α, grad	P_2, MPa	G_3, $g \cdot s^{-1}$	V_p, $m \cdot s^{-1}$		q_0/q_1	PUF
						Without CS	With CS		
PR-1R	0,12	5,3	45	0,12	0,22	220	190	2,2	-0,05
PM-2M	0,075	4,2	60	0,15	0,35	130	110	1,8	-0,09

[x)] Conditions – powder of Cu9Al4Fe alloy, d_p = 50 µm, h = 0,2 m, T_1 = 150 °C.

Composition of the plasma gases (argon-hydrogen mixture or air) predetermines a different ratio of microhardness, hardness and wear resistance of respective samples (Table 3). This is attributable, in addition to differences in structure and composition of the phases formed, also to a different degree of heating and deformation of particles, different values of porosity, intensity

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of saturation of a structure with intermetallics of the following compositions: $FeCu_2Al_6$, $FeCu_2Al_7$, $FeCu_{10}Al_{12}$, $FeCu_{10}Al_{18}$ and oxides. Inclusions of this type increase values of microhardness and, at the same time, decrease values of strength and hardness as a result of increase in brittleness. A comparatively large number of such inclusions is characteristic of structures formed by the air plasma jet.

Table 3: Properties of plasma sprayed Cu9Al4Fe – alloy

Conditions of plasma spraying		σ_s, MPa	σ_t, MPa	σ_1, MPa	HV_{max}, MPa	HB	$\eta \cdot 10^7$, $kg \cdot m^{-2} \cdot s^{-1}$	δ, %
Plasmatron	CS							
PR-1R	no	8	60-75	25-40	900	80-110	3,6	2-3
PR-1R	yes	<1	80-105	40-55	1800	110-180	6,8	5-10
PM-2M	yes	2,4	70-90	35-40	1700	125-190	7,2	4-8

An increase of 1.8-2.2 times in the ductility values of the initial material favours a decrease of 4-8 times in residual stresses. This allows formation of the aluminium bronze shell parts of any thickness by avoiding buckling at the absence of adhesion to the model surface.

4. Manufacture of press moulds using plasma spray forming process and their practical application

The process developed for the manufacture of press moulds consists of two stages:

1) Production of a shell part with a wall thickness of 5-10 mm by plasma spraying of the Cu-Al-Fe alloy powder on the surface of a master model of an organic origin (e.g. wood) or directly on the surface of a prototype part made from plastics;
2) Production of permanent and split no-flash moulds by backing up the shell part by a metal-polymer composition followed by its polymerization.

Furyl-epoxy resins with a polymerization temperature of 80 °C were used as the binder. Heat resistance of the composition is 250 °C at a thermal conductivity of 12-28 $W \cdot m^{-1} deg^{-1}$ and shrinkage in solidification equal to no more than 1 %. This ensures high service properties of the moulds made by this technology. It is used under conditions of small-series production of similar-type parts with a developed geometry of the surface, such as toys, shoe soles, furniture and wear accessories, pieces of art, souvenirs, etc.

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The term of manufacture of such moulds using plasma spray forming process is no more than 3-7 days, which is much shorter than in the case of using traditional technologies.

Conclusions

1. The use of plasma spray forming process for making tooling for manufacture plastics parts in small-series production of pieces with a complicated profile allows improvement of technical-economic indices of this process, as compared with traditional methods of metal working, galvanoplastics, cold pressing, electric-spark processing and powder metallurgy.
2. The use of the Cu-Al-Fe alloy powders for making shell parts by the method of plasma spraying makes it possible to produce layers with a quenching two-phase (α+β') structure which combines properties of ductility and strength. This allows a substantial decrease in the level of residual stresses in the deposited layer and formation of the shell parts without considerable limitations as to thickness.
3. The developed double system for cooling the coating formation zone makes it possible to control parameters of cooling the spray material and temperature on the master model surface. This permits the use of plasma spraying to deposit layers on the master model surfaces with a heat resistance temperature of up to 70 °C, e.g. made from wood.
4. The best results in the level of service properties of the deposited layer of Cu-Al-Fe alloy were obtained in the case of using a mixture of argon and hydrogen as the plasma gas.
5. The developed technology for making pressmoulds used to manufacture plastics parts consists of stages of plasma spraying of a shell part and backing it by a metal-polymer composition based on the furyl-epoxy binder. The term of manufacture of complicated-profile moulds by using this technology is no longer than 3-7 days. The technology has found application in the manufacture of toys, shoe soles, souvenirs, etc.

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