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Mathematical modelling of heat exchange between the coating sprayed by explosion and the surface

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Abstract. A huge drawback of classical electro-impulse metallization is that only internal cylindrical surfaces of components may be metallized up to 120 mm diameter. In order to eliminate this drawback, a special diverter, which permits to form coatings both on the internal and external profiles and plane surfaces, has been developed. One of the most important properties of any coating is adhesion. The most significant factor, which influences the adhesion of the obtained coating, is the temperature of contact at the coated surface. It is impossible to experimentally measure the temperature of contact, therefore, calculations were carried out with a mathematical model. The obtained results reveal that the interaction of the sprayed coating with the coated surface is close to 100%. Therefore the adhesion of coatings, sprayed by directional electro-impulse metallization method, is several times higher compared with the coatings obtained by plasma and electric arc spray methods.

Key words: explosion spraying, coatings, temperature, mathematical modelling, surface hardening.

1. INTRODUCTION

At present, renewing parts as well as manufacturing new machines, various coatings are widely used [1–4]. Thermal spraying is a family of coating deposition processes in which molten, semi-molten or solid particles are deposited onto a substrate. The microstructure of the coatings depends on their solidification and sintering. The processes use hot gas, flame or plasma to accelerate the particles and to heat them up. Obtained coatings have a lamellar microstructure, which determines many properties of the coatings. Optimization of coating properties for a given specification needs careful control of the operational spray parameters [5–11].

Practice has shown that coatings, obtained by the plasma spraying (adhesion strength 10–15 MPa) or gas-explosion spraying (adhesion strength 5–25 MPa) cannot be widely used when renewing or manufacturing heavily loaded parts. The adhesion strength of coatings, obtained by gaseous detonation spraying, may vary from 10 to 160 MPa. However, this method is not suitable for obtaining coatings, the thickness of which is 0.3 mm and more, since in such case the adhesion strength is strongly reduced and even the coating may be detached from the coated surface [6–10,12,13].

High-velocity arc spraying technique is a widely used traditional spraying technology [14–16], which utilizes an electric arc as a heat source to melt wires into droplets, which are sprayed onto the substrate by high-velocity compressed air. For higher velocity and better atomizing of melted droplets, these coatings have low porosity, dense structure and high bond strength [17].

However, recently research efforts have been mainly focused on the electro-thermal explosion spraying mechanism (EES) [1,16,18]. The EES is a technique for material deposition and is used widely by virtue of its ability to make coatings with compact microstructure, high microhardness, low porosity and metallurgical bonding [19,20]. The EES technique is characterized by the duration of the process between 1 and 10 ms, the plasma temperature about 10^4 K, the speed of spraying droplets up to 3–4.5 km s^{-1}, the average cooling rate of particles up to 10^9 K s^{-1} and specific energy of more than 1 MJ kg^{-1} [18,21]. Among coatings, obtained by the electro-thermal explosion spraying methods, the coatings, obtained by the electro-thermal wire explosion spraying (EWES) method, are least investigated [22].

2. EXPERIMENTAL

By coating with the EWES technique the conducting material is melted and overheated to boiling by an electric shock of 5 to 30 kV and by the power of 10^{11} to 10^{12} A/m^2. In 10^{-7} to 10^{-5} s a certain part of the conductor is evaporated, the rest is sprayed out as micrometer-sized droplets at the boiling temperature. Due to the very short duration of this process and the inertia of the conductor material, a thermal blow-out occurs. This blow-out leads to a high increase of pressure, which accelerates the droplets to a velocity up to 500–600 m/s. The obtained aerosol, a mixture of vapour and droplets, reaches the surface, which is to be coated and the vapour condenses, while the droplets cohere with the surface and a metal coating is formed. Due to high dynamics of the explained process, the droplets are heated up to tens of thousands degrees. This extreme heating cannot be obtained by plasma, other material coating methods or by processing with concentrated energy. After the burst of the conductor, the accelerated droplets impact on the cold target surface and cool down [22–24]. The conductor, a wire or a foil, is exploded by a discharge of a battery of condensers (Fig. 1).

However, this method is relevant only by coating internal surfaces of cylindrical parts up to a diameter of 120 mm. Thick coatings on flat or external

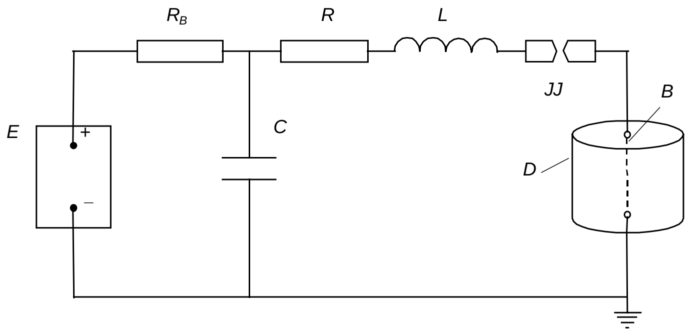

Fig. 1. Principle scheme of the method of electro-thermal wire explosion spraying: *E* – current source, *C* – a battery of condensers, *B* – exploded wire or a foil, *D* – a part subjected to coating, *JJ* – an ionization switch.

cylindrical surface can hardly be produced, because the exploded vapour-droplet streams are of annular shape. As a result, only a certain part of the stream particles is consumed, and the produced coatings have non-homogeneous properties (Fig. 2).

In order to eliminate this drawback, special diverters of two different configurations from caprolone were applied (Fig. 3). It enabled to develop a regular vapour and droplets flow, which had the required direction. Thus the directional electro-thermal wire explosion spraying technique (DEWES) was developed, which enabled to form coatings on internal and external cylindrical, plane or profiled surfaces.

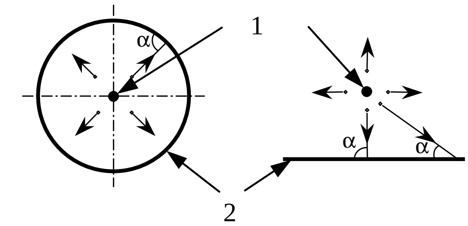

Fig. 2. Coating of internal cylinder (a) and plane profile (b) surfaces by EWES: 1 – sprayed wire, 2 – part.

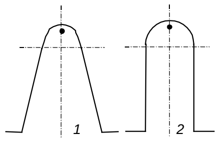

Fig. 3. Wire vapour and droplets diverters.

3. MATHEMATICAL MODELLING

One of the most important properties of any coating is adhesion. Adhesion strength often limits the application of coatings when strengthening or renewing parts. The most important factor, which determines the adhesion of obtained coating, is the contact temperature of the coating and the coated surface. It is impossible to experimentally measure the contact temperature. Thus mathematical models are developed, which describe heat exchange between the coating and the coated surface, from which the contact temperature may be calculated by cooling the part. Several mathematical models are developed, which determine the heat exchange of the hot coating and cold surface. While solving them, the contact temperature of the coating-coated surface is estimated. However, none of these models is suitable for the description of the heat exchange of the electro-impulsive wire-explosion coated surface since coating is formed by overheated fine drops, which exhibit spraying material boiling temperature. The model, which has a precise solution and estimates finite coating thickness and overheating of this layer over fusion temperature, has not been developed yet due to mathematical problems. Model development requires some simplifications of the real process of heat exchange between the coating and the surface.

We have developed a mathematical model based on the following assumptions.

1. The coating is of finite thickness. It is melted and heated to its boiling temperature. Its heat-conduction coefficient is non-zero only in the direction normal to the contact plane. Heat conduction in this direction equals to the time-dependent heat conduction of the melted substance. The specific heat of crystallization of the coating is emitted in the $T_1-(T_1-300\,\text{K})$ range.
2. The surface is of finite thickness. Its initial temperature is stable at $T = 20\,°\text{C}$. Its heat conduction coefficient is non-zero only in the direction normal to the contact plane. It is equal to the temperature-dependent heat conduction of the substance.
3. The coating–surface contact covers instantaneously the whole area and is ideal; there is no heat exchange between the surface and the coating or with the surrounding environment.

Mathematical expressions of the model are as follows:

for the coating

$$\frac{\partial T_1}{\partial t} = \frac{a_1 \partial^2 T_1}{\partial X^2}, \qquad 0 \le X \le X_1, \tag{1}$$

$$T_1(t=0) = T_{10}, \qquad 0 \le X \le X_1, \tag{2}$$

for the surface

$$\frac{\partial T_2}{\partial t} = \frac{a_2 \partial^2 T_2}{\partial X^2}, \qquad X_1 \le X \le X_2, \tag{3}$$

$$T_2(X,0)=T_{20}, \qquad X_1 \le X \le X_2, \tag{4}$$

for the surface-coating contact

$$\lambda_1 \frac{\partial T_1}{\partial X} + L_1\rho_1 \frac{\partial X_1}{\partial t} = \lambda_2 \frac{\partial T_2}{\partial X}, \qquad X = X_1, \tag{5}$$

$$T_1(X,t)=T_2(X,t), \qquad X = X_1, \tag{6}$$

where t is time (s), X_1 and X_2 are variables for the coating and for the surface, respectively (mm), T_1 and T_2 are temperatures of the coating and the surface (°C), T_{10} and T_{20} are initial temperatures of the coating and the surface (°C), λ_1 and λ_2 are heat conduction coefficients of the coating and the surface (W/m·K), ρ_1 is density of the coatings (kg/m^3), a_1 and a_2 are temperature diffusivities of the coating and the surface (m^2/s) and L_1 is crystallization heat of the coating (kJ/kg).

When calculating the contact temperature, the following values of the parameters were considered: $X_1 = (0.01–0.05)$ mm, $X_2 = 5$ mm, $T_{10} = 3030$ °C, $T_{20} = 20$ °C. The developed mathematical model was solved using the following thermal-physical parameters of iron: melted material – heat conductivity coefficient $\lambda_1 = 10$ W/m·K, density $\rho_1 = 7.23 \times 10^3$ kg/m^3, crystallization heat $L_{cr} = 314$ kJ/kg, temperature conductivity coefficient $a_1 = 2 \times 10^{-6}$ m^2/s, crystallization temperature (1300–1530) °C; heat conductivity of the solid material ($t = 1000$ °C), $\lambda_2 = 20$ W/m·K and the temperature conductivity coefficient $a_2 = (6–27) \times 10^{-6}$ m^2/s.

Distribution of the points of the coating and coated surface, where temperature calculations were carried out, was the following: 1 – the free surface of the coating; 2 – an internal point of the sprayed coating; 3 – a point of the coating at the plane of the coating and substance contact; 4 – a substance point at the plane of the coating and substance contact; substance points 5, 6, 7, 8, 9, 10, 11, 12, distant from the contact plane at 2, 3, 4, 6, 10, 20, 40 and 80 coating thicknesses.

The temperature of the coated surface and its variation by cooling and spraying for different thicknesses of the iron coating is given in Fig. 4.

Calculation results reveal that temperature of the basic surface reaches iron fusion temperature within 5×10^{-7} s. Depending on the coating thickness, the temperature of the substance surface reaches the biggest value $(25–300) \times 10^{-6}$ s after the beginning of the contact formation. Cohesion of the coating and substance occurs by minimal contact temperature. Thus estimating the interaction, lower temperature of merged surfaces (i.e. the temperature of substance surface) should be analysed. Calculation also reveals that at the points of the substance, which are located at 20, 40 and 80 coating thicknesses from the contact plane, temperature variation has not been observed after $(5–8) \times 10^{-3}$ s from the beginning of interaction. Temperature, which may initiate thermal impact of the substance, may be formed only in the substance's layer, which is located at two or three coating thicknesses from the contact plane. Due to small

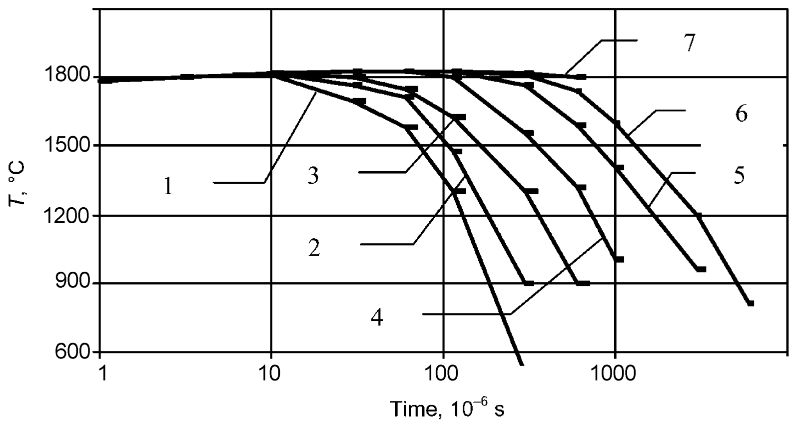

Fig. 4. Influence of the thickness of the coatings on the temperature of the substance surface (1 – 0.005 mm; 2 – 0.01 mm; 3 – 0.015 mm; 4 – 0.02 mm; 5 – 0.03 mm, 6 – 0.04 mm, 7 – 0.05 mm).

duration, the thermal impact is insignificant, whereas at the point, distant from the contact plane for four coating thicknesses, temperature reaches only 760 °C. Thus here thermal impact will not be present. Possibility of the thermal impact is real at the point on the contact plane, where surface temperature rises up to 1920 °C. All this reveals that while spraying the coating, depth of the thermal impact does not exceed 0.055 mm; thus further calculations were carried out using this depth.

In the beginning, the temperature of the substance surface does not depend on the coating thickness. Later, after spraying a thicker coating, the substance surface heats up more slowly, the maximum value is reached later whereas cooling occurs more slowly. This is a guarantee of solid adhesion between the coating and the substance. Thus the thicker coating, formed with one spraying cycle, will adhere to the substance better than the thinner coating.

Figure 5 presents variation of the temperature of the coating and substance contact surface after spraying 0.03 and 0.05 mm thickness iron coatings. Curve 5 shows the calculated 90% dependence of the reaction time of the coating and substance adhesion angle on the contact temperature.

As can be seen from Fig. 5, by spraying of 0.03 and 0.05 mm coatings, calculated temperature of substance surface is much higher than the temperature, which is required to obtain a 90% interaction of the coating and the coated surface.

Obtained results and performed comparative calculations reveal that the interaction of the sprayed coating with the coated surface is close to 100%. Thus adhesion of coatings, obtained by the DEWES, is higher than of the coatings, obtained by the gas-explosion, plasma and electric arc spraying methods [1,3,5,16].

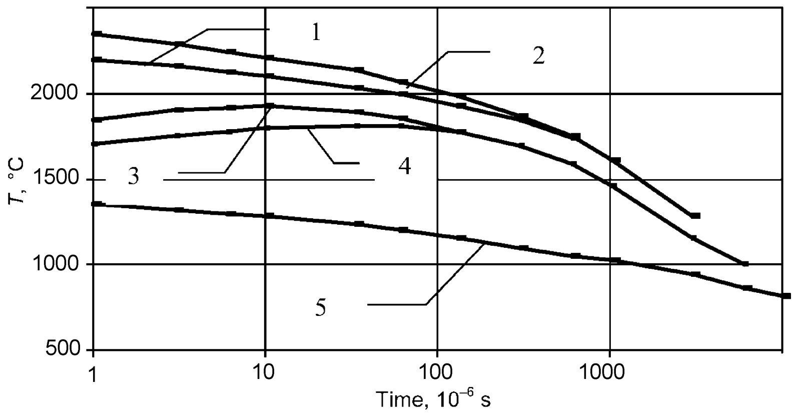

Fig. 5. Variation of temperatures of coatings (1, 2) and substance contact surface (3, 4) after spraying iron coatings of the thickness of 0.03 and 0.05 mm; 5 – 90% angle curve of the interaction between the coating and the substance.

4. CONCLUSIONS

1. An original directional electro-thermal wire explosion spraying device has been developed, which enables to coat not only internal small diameter (up to 120 mm) cylinder surfaces, but also external cylinder, plane and profile surfaces of parts.
2. A mathematical simulation technique has been compiled to predict the surface–coating adhesion. It takes into account finite thickness of the coatings as well as the heat of overheating and crystallization of the sprayed particles.
3. Obtained results and performed comparative calculations reveal that the interaction of the sprayed coating with the coated surface is close to 100%; thus the strength of the contact area is almost equal to the strength of the substance.
4. In the beginning of spraying, temperature of the substance surface does not depend on the coating thickness. Later, after spraying a thicker coating, the substance surface heats up more slowly and the maximum value is reached later, whereas cooling occurs more slowly. Thus the thicker coating, formed with one spraying cycle, will adhere to the substance better than the thinner coating.
5. Adhesion of the coatings, obtained by the directional electro-thermal wire explosion spraying, is higher than of the coatings, obtained by gas-explosion, plasma or electric arc spraying methods.

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Plahvatuspinde ja alusmaterjali vahelise soojusvahetuse matemaatiline modelleerimine

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Klassikalise elekterimpulss-pindamisprotsessi suurimaks puuduseks on asjaolu, et pinnata saab vaid silindriliste detailide sisepindu eeldusel, et nende läbimõõt ei ole suurem kui 120 mm. Selle probleemi lahendusena töötati välja spetsiaalne muundur, mis lisaks sisepindamisele võimaldab saada pindeid ka detailide välispindadel, sh tasapinnal. Pinde adhesioon alusmaterjaliga on oluline tegur, mida mõjutavad märkimisväärselt pinnet moodustavate pulbriosakeste ja alusmaterjali kontakttemperatuurid. Kontakttemperatuuri määramine katseliste meetoditega ei ole võimalik, seepärast on selle parameetri määramiseks välja töötatud matemaatiline mudel. Saadud tulemused näitavad, et pinde ja alusmaterjali vahel saavutatakse plahvatuspindamisel peaaegu ideaalne nake, st saadud pinde nakketugevus on lähedane alusmaterjali nakketugevusele. Kasutatud suunatud elekterimpulss-pindamisprotsessi abil saadud pinnete nakketugevus on mitmeid kordi suurem, võrreldes plasma- ja elekterkaarsulatuspindamise abil saadud pinnetega.