THERMAL SPRAYING OF COATINGS USING TIPS

A.P. MURASHOV
E.O. Paton Electric Welding Institute, NASU, Kiev, Ukraine

Application of special tips in thermal spaying reduces the number of uncontrolled factors influencing the process, increases the speed of jet outflowing, lowers the degree of its interaction with the ambient atmosphere, and reduces the opening angle. The paper gives recommendations for designing the tips, and shows their effectiveness at coating deposition.

Keywords: *thermal spraying, coatings, application of tips, high-temperature gas jet, speed distribution, average temperature of the field, sprayed particles, gas-dynamic effect*

Thermal spraying (TS) of coatings refers to unique technology which allows obtaining and applying the coatings from metals, ceramics, plastics and their combinations [1]. Such possibilities of TS predetermined the development of the process, creation of large number of spraying devices, development of spraying consumables, obtaining of the layers with multiple functional properties, i.e. from wear-resistant, antifriction, heat-resistant, insulating etc. up to coatings with the nanostructures, with specified porosity and other special properties [2–6].

Coatings in TS are formed from separate particles due to their chemical and physical activity rising in heating and acceleration. The particles in such an active state can interact with elements of the spraying jet, ambient gas atmosphere and substrate. Oxidation of the spraying consumables, the degree of which is determined by many factors including method of spraying, is possible due to its activity.

Oxidation of the coating material takes place in spraying of wire by air, during particle flight and formation of the coating [7] in the case of application of simple electric arc metallizing. Methods of wire spraying using inert gases were developed for protection from oxidation and reduction of amount of oxygen in the coating. Methods of activating (Figure 1) and supersonic metallizing [8–11] had appeared.

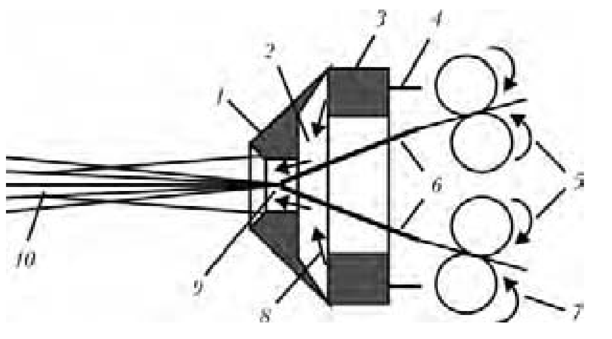

Figure 1. Scheme of activating electric arc metallizing [8]: *1* — nozzle; *2* — collector; *3* — combustion chamber; *4* — mixture of air with combustible gas; *5* — feeder; *6* — guides; *7* — wires; *8* — spraying gas; *9* — arc; *10* — jet

Application of shielding or reducing atmosphere promotes increase of quality of coating due to reduction of oxide content in the electric arc metallizing, and decreases time of particle flight, reduces possibility of interaction of surface of heated particles with atmospheric oxygen and increases coating density in the supersonic metallizing.

High velocity oxy-fuel and detonation spraying are characterized by small interaction of the spraying material with ambient atmosphere due to application of a tip in a form of shank and supersonic speed of spraying particles. However, the application of combustion materials of fuel gases and oxygen for heating and acceleration of the particles promotes the conditions for interaction of materials with oxygen of spraying atmosphere.

Excess of gases is used for reduction of oxidation degree, ane reducing medium is created, however, it can sometimes be impossible on technological reasons.

Pressure is created in a plasmatron at outflowing of high-temperature plasma jet from it to stable ambient atmosphere due to thermal contraction of arc and jet. It exceeds the pressure of environment at exit from the plasmatron. This result in jet expansion, moreover, it expands quicker at very edge of the plasmatron than at the rest of the section where pressure difference gradually decreases [12]. Turbulent mixing and viscous friction of the spraying jet leads to increase of content of ambient gases in it, areas with temperature and speed gradient appear in radial section of the jet. The heated and accelerated to different extent particles from spraying material, predicted synthesized combinations and phases take part in coating formation. They can have uncontrolled interaction with the gases of ambient atmosphere. Such an interaction can be referred to the uncontrolled factors having influence on content and properties of the coating obtained in free outflowing of jet (submerged).

Degree of expansion of the jet is determined by difference of pressure of flows in presence of assist gas as in the first case. The degree of mixing of gas atmosphere reduces at insignificant difference of pressures in flows, and gas shield of the main jet is formed. An intermediate layer developed at feed of the assist gas does not eliminate the possibility of admixing of ambient atmosphere in it, but limits or protects the spraying jet from interaction with the atmosphere components.

Protection of a tip from entering of ambient atmosphere in it and consequent mixing is provided at application of the tip and shielding assist gas. At that risk of formation of fields with large temperature and speed gradient is reduced. Figure 2 shows that application of the tip results in increase of average flow speed, and reduces gradient of the speed and enthalpy on cross-section of the jet in the center and on the periphery.

Possibility of interaction of the spraying jet with the ambient atmosphere determines the possibilities of coating deposition with and without tip application. Properties of the spraying jet as well as type of sprayed material are considered at that. Powders for spraying can contain particles of different size and shape or consist of particles with different density.

It is known fact that a flow force effect on particle R is determined by density ρ, flow speed v, coefficient of gas-dynamic (head) resistance C_d and effective area of influence S_p:

$$R = C_d \rho v^2 / 2S_p.$$

Shape of the particle determines its coefficient of head resistance. A degree of nonsphericity Φ was proposed to be used for the particles of nonround shape by R. Busroid [14]. It is determined by ratio of surface area of sphere with volume, equal to particle volume V_p, to surface area of particle, increase of which promotes rise of coefficient of head resistance:

$$\Phi = \pi (6V_p/\pi)^{2/3} S_p^{-1}.$$

Gas-dynamic effect of the jet on the flake-shape particles can promote appearance the side constituents at their different orientation besides the change of their coefficient of head resistance and acceleration. As a result of that part of them get into the jet periphery. This reduces the level

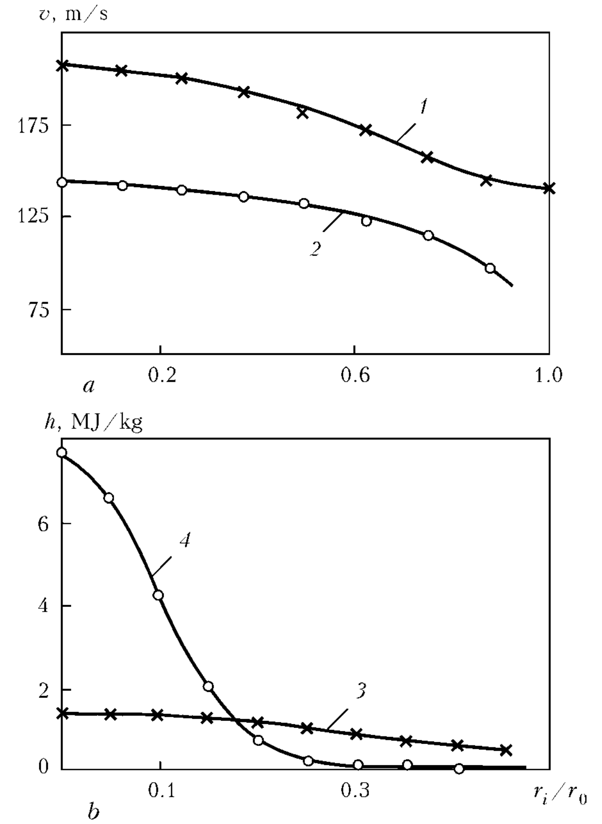

Figure 2. Distribution of speed (*a*) and enthalpy (*b*) of particles on radius of spraying spot in application of tip (*1*, *3*) and without it (*2*, *4*) [13]

of heating of such particles, effects their acceleration, and predetermines appearance of the cold particles in the coating structure that reduces coating quality at application of the submerged jet. If insignificant difference of heating and acceleration of the particles of different shape is provided at control of the process in coating spraying using spherical powders, then number of cold or oxidized particles has uncontrolled rise, quality of coating decreases and material utilization is reduced in use of fragment or flake-shaped particles.

Interaction of the jet with ambient gases is limited or prevented, temperature and speed of the jet on cross-section are adjusted and length of high-temperature field are increased at application of the tip and assist shielding gas. This influences the degree of heating and acceleration of the particles, in particular, the particles with large size differences, various density or irregular shape.

The negative moment of the tip equipping lies in impossibility of visual control of consumption of a transporting gas with powder on the shape of spraying jet, possibility of pickup of consumable on a side surface of the tip with formation of «accretion» and inflow of cold air inside the tip. These disadvantages result in inconvenience

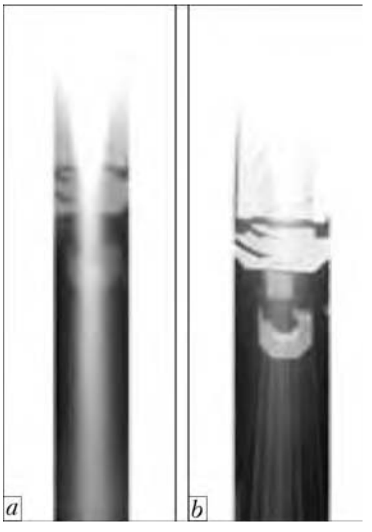

Figure 3. Appearance of plasma jet in spraying of metallic (*a*) and ceramic (*b*) powders

of operation, impair technological effectiveness of the process and limit application of the tip in industry.

Works [15, 16] show the schemes of existing tips. Consideration of structure, classification of tips on economy and technological indices and analysis of their peculiarities and efficiency of shielding were carried out.

Variant of the tips with feed of shielding gas in its lower part and extraction of gas are shown in [13]. Such a solution as well as application of «hot internal wall» reduce content of oxygen in the coating and allow increasing the average speed and temperature of sprayed particles.

Study [17] shows a tip designed for increase of outflowing speed of spraying jet and reduction of inflow of ambient atmosphere inside the tip. Larger consumption (more than 90 m^3/h) of periphery gas is necessary for providing its functions based on operation experience.

It is impossible to remove a deposit of the consumables on the side walls of the tips, as well as inflow of the ambient atmosphere inside the tip in the mentioned tip structures.

Thus, there are no criteria for designing of the shielding tips determining optimum structure, its capability to provide increase of coating quality through reduction of a level of material oxidation due to absence of the cold particles in its formation. An attempt was made in the present work to develop a tip, the design of which would provide quality spraying of the coatings without pickup at opening angle, equal or smaller than opening angle of spraying submerged jet, would reduce or eliminate the presence of cold particles in the coating and would decrease oxygen content in the coating. Besides, it was planned to increase the speed of jet outflowing and speed of sprayed particles.

Experience of designing of tip structures [15, 16] as well as mechanisms of outflowing of gas jets, given in the studies on gas dynamics [18, 19], was used for selection of tip shape. Inner surface of the tip should represent itself contracting and expanding cone in order to increase speed of gas outflowing. A cylinder surface with supply of assist gas can be used as a contracting one. The gas entering the cone forms a wedge at operating consumptions. At that critical section can be created and condition for jet acceleration is provided. Besides, it was assumed that feed of the assist gas would form a wall gas layer and protect inner surface of the tip from consumable pickup, and presence of excessive pressure in the layer would prevent entering of atmosphere gases inside.

Angle of expansion of the conical part was taken considering the shape of spraying jet obtained for the case of spraying of metallic and ceramic powders at free outflowing of the plasma jet. Figure 3 shows the type of spraying jet at application of PT-NA-01 (95Ni + 5Al) powders of +(10–45) μm fraction and Al_2O_3 electrocorundum of 15A grade with 28 μm average particle size. Opening angle of the jet makes 4 and 8°, respectively. Inner diameter of the cylinder part equals 12–14 mm and length was 15 mm. Opening angle equal 6.5° was taken for the conical part. Its minimum inner diameter was 0.5 mm larger than inner diameter of the cylinder part. At that cross sizes of the cone equal the sum of jet diameter in this section and size of 1.0–1.5 mm gap for feed of the assist gas.

Length of the tip makes 90 mm that gives the possibility of process control and reduces the risk of jet interaction with the ambient medium at 100–140 mm distance normally used for spraying.

The assist gas was supplied on a circle owing to sampling at the nozzle (Figure 4) for the purpose of formation of evenly distributed wall layer.

Cylindrical part in one of the variants was made in a form of insulating insert that eliminated a possibility of formation of arc between the cathode and anode. However, application of argon or argon–nitrogen plasma forming medium provides no arc formation.

Increased consumption of the transporting gas is set at transportation of fine powder or powder with poor flowability due to possibility of formation of «clogs». The value of speed of particles, at which they can fly past central part of the jet, is achieved at outlet of the feed connection, the diameter of which significantly smaller the internal diameter of powder pipeline. The particles can pickup to the inner surface of the tip or fly past the heating zone and take no part in coating formation entering periphery of the jet.

A feed flow at increased consumption of the transporting gas was preliminary divided into two channels for reduction of speed of powder particles at its feed in the plasmatron. Powder was introduced in the plasmatron by channels through two connections [3], symmetrically situated in one plane with jet axis. The powder was fed in a cross point of jet axis and edge line of the plasmatron at −(6–30)° towards the main jet in order to increase heating efficiency and eliminate particle pickup. Separate feed of the powders in different points was used in spraying of the coatings from mixture of powders having different melting temperature, for example, from metal and ceramics. Points of powder feed were preliminary determined using a program for calculation of flying path and particle temperature.

Conditions for feed of metallic (Ni) and ceramic (Al_2O_3) powders were preliminary selected based on computer model of process of plasma spraying carried out with the help of CASPSP system [20].

Path of the particles for the case of entering of metal particle at −(6–30)° and ceramic particle at −30° in consumption of 0.12–0.18 m^3/h of transporting gas was located in the central area of the jet that corresponds with the condition of their heating from solid state up to melt. At that melting of the particles takes place at around 20 mm distance from nozzle edge.

A double feed system for ceramic and metallic powders containing two feeders and two channels with two inputs was used for obtaining of the coatings including metallic and ceramic constituents. This allows depositing the coatings from metals, ceramics and their compositions and obtaining gradient coatings with 0–100 % component content.

Testing of inner surface of the tip showed no pickup of consumables on the side wall. At that, general consumption of the transporting gas

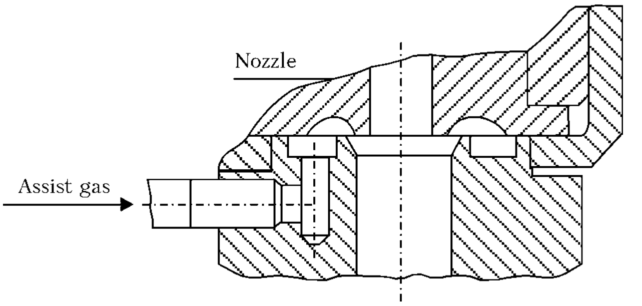

Figure 4. Scheme of feed of assist gas in a tip

made 0.168–0.270 m^3/h that 2 times exceeds its value at spraying without tip with one connection. Consumption of the assist gas made 0.28–0.30 m^3/h.

The pickup of part of the particles takes place on inner side of the tip at consumption of assist gas not less than 0.18 m^3/h and transporting gas not less than 0.12 m^3/h or more than 0.36 m^3/h, and is observed in a contraction point where cylinder part of the tip comes into conical one (Figure 5).

It can be assumed that getting in of the part of consumables at jet periphery, where obtained speed and temperature of the particles are enough for formation of the deposit on a barrier (contraction), can be the reason of pickup. Half-molten, loose state of the deposit material proves this fact. At that the coating sprayed on the sample is dense and has little defects on the boundary with substrate.

Increase of consumption of the assist gas more than 0.48–0.60 m^3/h results in «cooling» of the jet that gains number of «cold» particles and reduces of material utilization.

Figure 6 shows appearance of a spraying spot without and with tip application. The spraying spot with tip is 1.5–2 times larger than that in spraying without tip with the same material and distance. This indicates reduction of spraying angle in tip application. Level of interaction of coating material and environment characterizes the coating besides the difference of the spraying spot sizes.

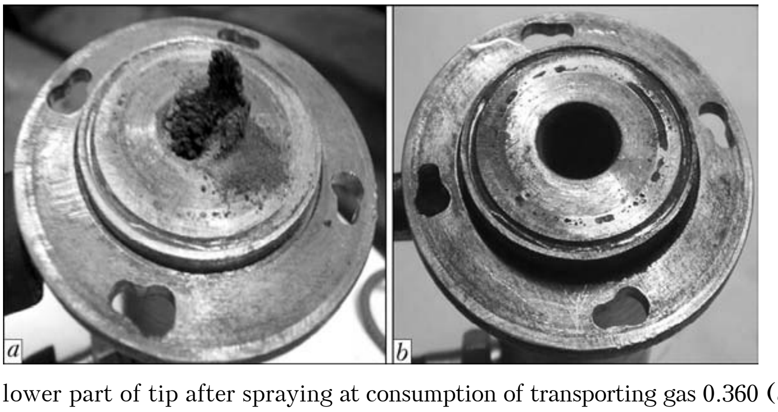

Figure 4. Appearance of lower part of tip after spraying at consumption of transporting gas 0.360 (*a*) and 0.264 (*b*) m^3/h

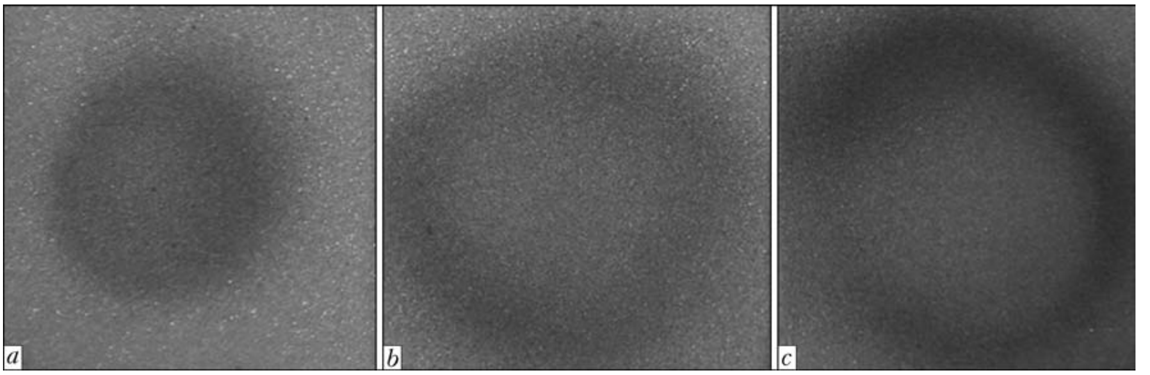

Figure 6. Spraying spot in coating with application of tip (*a*), cylinder part of tip (*b*) and without it (*c*)

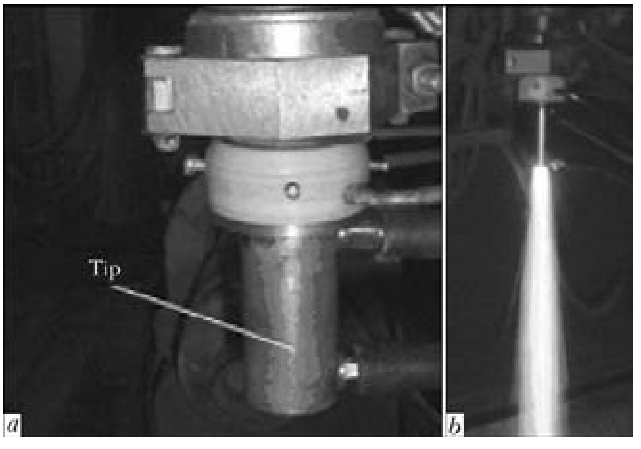

Figure 7. Appearance of tip (*a*) and spraying jet (*b*) with application of PT-NA-01 powder

Traces of powder oxidation at spot periphery are observed in the spraying spot obtained without shielding tip application. The coatings obtained with the tip application have no observable places of oxidation. This verifies absence of oxidation medium inside the tip and air inflow.

The spraying jet has cone shape with angle close to angel of tip inner surface at more than 250 mm distance from tip edge (Figure 7) in coating of metallic powder, for example, PT-NA-01 with 10–45 μm size having round shape. Jet cone in spraying of fragment-shaped aluminum oxide powder of average fraction 28 μm preserves its configuration at 50–60 mm distance from nozzle edge, after which expansion angle increases by 12° and more.

CONCLUSION

The inner surface in designing of the tip is recommended to be made in a form of expanding cone with up to 8° angle in order to increase jet outflowing.

Shape and dimensions of the tip inner surface, density of powder material, size and shape of its particles determine the opening angle of spraying jet. Angle made 4–6° and is preserved at 250 mm or more length in spraying of metallic powders with round-shaped particles. Opening angle increases up to 8° for ceramic powders having fragment-shaped particles. At that opening angle of the jet increases after jet exit from the tip and makes 12° or more at distance of spraying more than 120 mm.

The inner geometry of the tip should be close to the shape and dimensions of the submerged jet, obtained in spraying of spherical powders, for elimination of inflow of ambient atmosphere inside the tip and interaction with the jet. Application of assist shielding gas and development of excessive pressure in the tip are recommended. Ratio of consumptions of assist and transporting gases determines the pickup of consumable on the tip inner surface. Consumption of assist gas should make not less than 0.28 m^3/h for the tip with 6° opening angle.

1. Krechman, E. (1966) *Spraying of metals, ceramics and plastics*. Moscow: Mashinostroenie.
2. Hasui, A. (1967) *Technique of spraying*. Moscow: Mashinostroenie.
3. Kudinov, V.V. (1977) *Plasma coatings*. Moscow: Mashinostroenie.
4. Tsvetkov, Yu.V., Panfilov, S.A. (1980) *Low-temperature plasma in repair processes*. Moscow: Nauka.
5. Kalita, V.I. (2005) Physics, chemistry and mechanics of formation of coatings strengthened with nanosized phases. *Fizika i Khimiya Obrab. Materialov*, **4**, 46–57.
6. Suzuki, M., Sodeoka, S., Inoue, T. (2003) Study on alumina-based nanocomposite coating prepared by plasma spray. In: *Proc. of Int. Thermal Spray Conf.* (Ohio, USA, May 5–8, 2003).
7. Korobov, Yu.S., Boronenkov, V.N. (2003) Kinetics of interaction between sprayed metal and oxygen in arc metallizing. *Svarochn. Proizvodstvo*, **7**, 30–36.
8. Dorozhkin, N.N., Baranovsky, V.E., Elistratov, A.P. (1983) Activated arc metallizing process. *Vesti AN BSSR. Series Physics and Technology*, **3**, 73–78.
9. Verstak, A., Baranovski, V. (2004) HVAF arc spraying. In: *Proc. of Int. Thermal Spray Conf.* (Osaka, Japan, 10–12 May, 2004).
10. Karp, I.N., Petrov, S.V., Rudoj, A.P. (1991) Arc metallizing in high velocity flow of methane burning products. *Avtomatich. Svarka*, **1**, 62–65.
11. Buryakin, V. (2004) Improvement of thermal spraying equipment. *Svarochn. Proizvodstvo*, **5**, 30–35.
12. Dresvin, S.V., Donskoj, A.V., Goldfarb, V.M. et al. (1972) *Physics and technology of low-temperature jet*. Moscow: Atomizdat.
13. Kudinov, V.V., Kalita, V.N., Komlev, D.N. et al. (1992) Analysis of distribution of particle velocity

and specific enthalpy on radius of spraying spot in using of conic orifice. *Fizika i Khimiya Obrab. Materialov*, **5**, 82–85.
14. Busroid, R. (1975) *Gas flow with suspended particles*. Moscow: Mir.
15. Linnik, V.A., Pekshev, P.Yu. (1985) *Current technology of thermal spraying of coatings*. Moscow: Mashinostroenie.
16. Kudinov, V.V., Kosolapov, A.N., Pekshev, P.Yu. (1967) Nozzles for providing of local protection in plasma spraying. *Izvestiya SO AN SSSR. Series Technical Sci.*, **21**, Issue 6, 69–75.
17. Borisov, Yu.S., Korzhik, V.N., Chernyshov, A.V. et al. (1991) Optimization of parameters and conditions of gas-dynamic nozzle application in thermal spraying. *Avtomatich. Svarka*, **8**, 67–70.
18. Povkh, I.L. (1974) *Aerodynamical experiment in machine-building*. Leningrad: Mashinostroenie.
19. Abramovich, G.N. (1969) *Applied gas dynamics*. Moscow: Nauka.
20. Borisov, Yu.S., Krivtsun, I.V., Muzhichenko, A.F. et al. (2000) Computer modeling of the plasma spraying process. *The Paton Welding J.*, **12**, 40–50.

CONTROL OF FORMATION OF WELDED JOINTS IN ESW (Review)

I.V. PROTOKOVILOV and **V.B. POROKHONKO**
E.O. Paton Electric Welding Institute, NASU, Kiev, Ukraine

Some technological approaches and methods for affecting the process of electroslag welding (ESW), aimed at optimisation of structure of the weld and HAZ metals, are considered. It is shown that the external magnetic fields providing the force effect on the weld pool by a contactless method are an efficient tool to control solidification of metal in ESW. The most effective schemes of electromagnetic control of the ESW process, ensuring homogenisation and refining of structure of the weld metal, are studied.

Keywords: *electroslag welding, solidification, macrostructure, weld, electromagnetic effect, hydrodynamics, magnetic field*

Electroslag welding is an efficient method for joining thick-walled pieces of alloys based on iron, titanium, aluminium, copper and other metals. One of the key advantages of ESW is its high productivity and the possibility of joining metal with thickness from 30 mm to several metres in one pass without groove preparation [1–5].

However, despite the apparent advantages, ESW is often limited in practical application because of the unfavourable effect of the thermal welding cycle and hydrodynamic processes occurring in the weld pool on formation of structure of the weld and HAZ metals. These peculiarities of ESW may lead to formation of a coarse large-grained structure of the weld metal and embrittlement of HAZ, as well as negatively affect properties of the welded joints.

As a rule, heat treatment of the welded joints eliminates heterogeneity of structure and mechanical properties of different regions of a welded joint. However, it makes the ESW process much more complicated and expensive. Moreover, it is often inapplicable for super-large parts. Different approaches are employed to decrease overheating of metal during the welding process. In a number of cases such approaches make it possible to provide the required properties of the welded joints without postweld heat treatment. However, decrease in the extent of overheating of the weld and HAZ metals was and is one of the key problems of the ESW technology [6].

In this connection, the topical problem of ESW is development of the technological approaches and methods for affecting the welding process, which are aimed at improving structural homogeneity of the weld metal and reducing the negative effect of the thermal welding cycle on the HAZ metal (Figure 1). Such methods are based on adding different modifiers and fillers to the weld pool [3, 7], utilisation of an extra dead wire [8], application of forced cooling of the weld and HAZ metals [9], portioned energy input into the welding zone [10], increase of the electrode extension [11], concurrent heating of the weld and HAZ metals for local continuous normalising [3], introduction of ultrasonic and mechanical oscillations [12], affecting by external magnetic fields [13, 14] and other principles.

Metallurgical methods for increasing the efficiency of ESW are aimed at development of new welding consumables with special strength and thermal-physical properties, which are insensitive to the thermal welding cycle. Also, different modifiers and fillers can be added to the weld pool. Such methods are efficient enough to control properties of the weld metal. However, they exert only a slight effect on the HAZ metal.