

IMPROVING THE RELIABILITY OF METALLURGICAL EQUIPMENT PARTS VIA THERMAL SPRAYING AND WAYS TO CONTROL COATING PROPERTIES

Alexander P. Zhiltsov¹, Yuriy A. Kharlamov², Dmitriy A. Vishnevskiy²

¹ Lipetsk State Technical University
30 Moscovskaya Str., 398055 Lipetsk, Russia
E-mail: kaf-mo@stu.lipetsk.ru

² Donbass State Technical University
Alchevsk, Ukraine

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ABSTRACT

The characteristics of the basic methods of coating thermal spraying are briefly considered. A trend in the thermal spray coating market development is their increasing application to harden and repair various parts of metallurgical equipment. Examples are given from the experience of using thermal spray coatings (TSC) in Russian and foreign industries. The design and manufacture of TSC products require taking into account a set of structural, technological and operational factors that guarantee the reliability of both the coating and the whole product. This also determines a corresponding necessity to create reliable technological processes of obtaining TSC which would ensure the required coating quality parameters and its performance properties, and, hence, the reliability of the coating and the whole product. TSC failures can be caused by three groups of reasons: 1) errors and poor technical decisions in the design of coatings and coated products, the regulation of specifications for their parameters; 2) insufficient level and reliability of technological processes of obtaining coatings including all operations of pre-spraying and post-spraying treatment; 3) insufficient account of the influence of residual and side effects caused by the technological processes of both manufacturing the whole product and obtaining a coating, assembly processes and product operation. A block diagram of obtaining TSC is considered; it takes into account all stages of obtaining TSC, as well as the main phenomena and factors affecting their course and coating properties, which guarantees a more reasonable approach to the selection and design of equipment and technology for obtaining coatings with required properties. The main systems and subsystems of technological processes for obtaining TSC are considered. The main systems include those of thermal spraying, of sprayed products and of sprayed coating treatment.

***Keywords:** recovery of parts, thermal spray coatings, reliability, coating treatment, surface preparation, scheme for coatings obtaining, technological heredity, manufacturability of coatings.*

INTRODUCTION

Among a wide variety of coating and surface modification techniques – chemical, electrochemical (electroplating), chemical-thermal (cementation, nitriding, cyanidation, etc.), physical (laser and electron-beam powder surfacing), a special part are thermal spraying techniques (TST) – plasma flame spraying (PFS), high-speed plasma flame spraying (HPFS), electric-arc spraying (EDS), plasma spraying (PS), detonation gas spraying (DGS), etc. The great

scientific and practical interest in these techniques is determined by their wide potential both according to the type of sprayed coating materials with a homogeneous, heterogeneous or mixed structure with various required properties and layer-cultivation products of different size and geometry [1 - 4]. This stipulates a wide number of fundamental and applied research of these processes, as well as the development of new types of processes including fundamentally new ones, such as, e.g., cold gas spraying (CGS). A brief description of thermal spraying techniques is given in Table 1. A large

variety of thermal spraying techniques, their types and combinations, equipment, special materials, working gases, technological spraying processes and related operations, technological modes, etc. lead to a rather large variation in the controlled properties of coatings. The data in Table 1 are averaged.

ANALYSIS

Thermal spraying of metallurgical equipment parts

The metallurgical complex machines and equipment operate under extremely difficult conditions and are exposed to high loads and temperatures, corrosion, abrasive and other types of wear. Moreover, these effects frequently occur simultaneously in various combinations and lead to premature equipment failures. To eliminate or to reduce the intensity of many failures, modern metallurgical enterprises increasingly use thermal spraying of protective and functional coatings. This is fully consistent with the global growth trend of the TST market, more than \$1 billion annually.

The development and implementation of durable coating technologies open up a great potential for solving a whole range of metallurgical production problems. Many parts of the metallurgical complex equipment are known to be hardened and restored by thermal coatings: in coke and agglomeration production (blower rotors [5], roll disks for coke sorting [6], etc.); in blast-furnace production and direct production of iron (blast furnace tuyeres [7], briquetting machine screws [8], reactor cones [8], etc.); in steelmaking [10 - 13] (canal walls of dust-collecting systems of electric arc furnaces and oxygen converters, tuyeres, spears and nozzles for supplying gases, converter tuyere tips, CCM mold walls, tundish nozzles, etc.); many parts of hot and cold rolling mills, electroplating lines [9, 11 - 13], etc. Depending on the temperature and other operating conditions, oxides of aluminum, chromium, titanium, zirconium, zirconium silicate, WC-Co, WC-CoCr, MoB-CoCr alloys, self-fluxing alloys, cermet, chromium carbides and their mixtures, etc. are used as coating materials [5, 7, 9]. To increase the adherence

Table 1. Characteristics of main thermal spraying techniques [1 - 4].

Characteristics	Thermal spraying techniques					
	PFS	EDS	DGS	HPFS	PS	CGS
<u>Spray gas jet:</u> Temperature, °C	3000	4000	4000	3000	10000-15000 300-1000	0-700
Speed, m/s	80-100	50-100	Over 2500	500-2000		300-1200
Gas (oxidation agent/fuel agent)	O ₂ /C ₂ H ₂ , propane, hydrogen	air, nitrogen, argon	O ₂ /C ₂ H ₂ , propane, butane, hydrogen	O ₂ /natural gas; ethylene, propylene, propane, kerosene, H ₂	Ar, He, H ₂ , N ₂ , mixes	N ₂ , He, air
Capacity kW	20-100	5-10	100-270	100-300	40-200	-
<u>sprayed material in the jet:</u> Temperature, °C	2500	Up to 3000	Up to 2500	3000	Over 3800 50-400	250 300-1500
Speed, m/s	40-100	50-150	500-750	800		
Coatings: Porosity, %	10-15 (0*)	10-20	Up to 2.0	Up to 2	5-10	Up to 5
Thickness, mm	0.1-2.5	0.1-2.0	0.1-0.4	0.05-2.0	0.1-1.5	0.25-0.6
Strength of adhesion	Medium	Medium	High	High	High	High
Productiveness on the sprayed material, kg/h	2-6	10-25	1	1-9	2-10	1-5

*For coatings from self-fluxing alloys after reflow

of coatings with the main part material, intermediate sublayers of self-fluxing alloys, NiCr, MCrAlY, etc. are used. According to their design, coatings can be continuous, discrete, multilayer, gradient, cermet-ceramic, etc. For the most important parts, such techniques of thermal spraying are used as PS, HPFS, DGS, with lower requirements to the level of the coating properties PFS and EDS are also used. Since thermal coatings are used both in the manufacture of parts and in their restoration, then, accordingly, they can be arbitrarily subdivided into fabrication and restoration thermal coatings.

Manufacturability of thermal coatings

The design and manufacture of products with thermal spray coatings (TSC) require the consideration of the entire complex of structural, technological and operational factors. The latter should include: current mechanical stresses, loads and deformations; working temperature and its fluctuations; environmental (working) environment and its corrosive effects; required service life (time or number of cycles) - durability and expected reliability of the coating and the surface to be protected; change in operating costs when using coatings, etc. From the materials science point of view, the design of coatings and the development of their spraying technology must take into account the chemical composition and microstructure of the coating (phase composition, oxide content, crystal size, porosity), the structure and parameters of the transition zone (between the coating and the substrate), and its thickness.

No less important are the structural parameters of the coating, such as thickness, lamination and functionality of the individual layers, whether the coating is uniform or gradient, solid or discrete, the presence of any structural elements on the coated surface, its possible effect on the fatigue strength of the part and other properties, etc.

This set of coating requirements and parameters determines the necessity to create reliable technological processes for obtaining TSC that ensure the required parameters for the quality of the coating and its performance properties, and, hence, the reliability of the coating and the product as a whole.

Control of properties of thermal coatings

Unacceptable TSC failures result from the imperfection of the technological process and the technological reliability of the equipment. These failures may be due to a

number of reasons that can be divided into several groups: 1) errors and unsuccessful technical solutions when designing coatings and products with them, regulating specifications for their parameters; 2) insufficient level and reliability of technological processes (TP) of obtaining the coating, including those in all operations of pre-spraying and post-spraying processing; 3) insufficient consideration of the effects of residual and side effects caused by the technological processes of both the manufacture of the product as a whole and the production of coating, assembly processes and maintenance. The block diagram of obtaining a thermal coating with account of all its production stages and the main phenomena and factors influencing their course and coating properties is shown in Fig. 1. This diagram makes it possible to follow all the steps and operations of the process of obtaining coatings, as well as a more reasonable approach to the selection and design of equipment and technologies for producing coatings with desired properties. Unsuccessful experience of using thermal coatings is often caused by an insufficient analysis of their entire life cycle. For instance, it was for these reasons that in the 1970s the Kommunarsk metallurgical plant did not succeed in obtaining positive results in increasing the service life of blast tuyeres via plasma spraying.

The formation of coatings with the required properties is determined both directly in TST operations and during the manufacture and preparation of the initial sprayed materials, during the preceding operations of obtaining the workpiece and its treatment, during the special preparation of the sprayed surfaces, as well as during the pre-spraying and post-spraying treatment of the coating and the entire part. Thus, the TST technology must be developed with account of the technological heredity influence on the properties of coatings at three stages of obtaining coatings on a particular product: 1) operations concerning manufacturing a part from the basic material and preparing the surface for spraying; 2) gas spraying operations; 3) subsequent treatment operations of the coating and the entire product.

Surface preparation affects mainly the adhesion strength of the coating and the fatigue strength of the entire part. The properties of the sprayed coatings are also determined to a significant degree by the basic material, the spraying modes and conditions. These properties, however, can be significantly changed during the subsequent coating treatment.

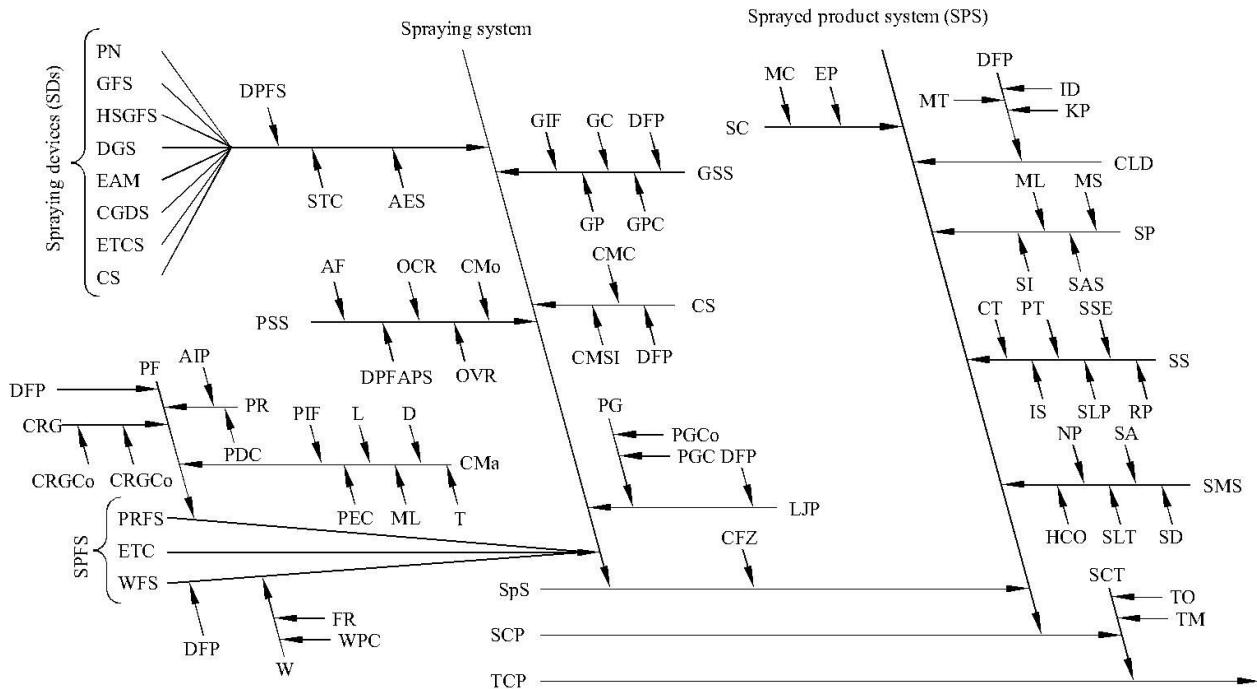


Fig. 1. The block diagram of obtaining a thermal coating: AES - additional energy source; AF - arcing features; AIP - additional impact on powder; CFZ - impact on the coating formation zone; CGDS - cold gas-dynamic sprayer; CGS - cooling system; CLD - carrying and loading device; CMa - carrying main; CMSI - cooling medium and its state on input; CMo - current modulation; CMC - cooling medium consumption; CRG - carrier gas; CRGCo - CRG composition; CRGCo - CRG consumption; CS - combined sprayers; CT - coating thickness; D - diameter; DFP - design features and parameters; DGS - detonation gas sprayer; DPFAPS - design features and parameters of the arc power source; DPFS - design features and parameters of the sprayer; EAM - electric arc metallizer; EP - environment parameters; ETC - other; ETCS - other types of sprayers; FR - feed rate; GC - gas consumption; GFS - gas flame sprayer; GIF - features of gas injection into the sprayer; GP - gas preparation; GPC - composition and properties of gases; GSS - gas supply system; HCO - heating, cooling and other impacts; HSGFS - high-speed gas flame sprayer; ID - installation device; IS - isolation of surfaces not subject to spraying; KP - kinematic parameters; L - length; LJP - local jet protection; MC - medium composition; ML - material; MS - mass; MT - movement trajectory; NP - number of passes (single layers); OCR - operating current range; OVR - operating voltage range; PDC - powder consumption; PEC - powder electrostatic charging; PF - powder feeder; PG - protective gas; PGCo - PG composition; PGC - protective gas consumption; PIF - features of powder injection into the sprayer; PN - plasmatron; PR - powder; PRFS - powder feed system; PSSPEAS - power supply system of plasma and electric arc sprayers; PT - preparation technique; RP - relative position; SA - spraying angle; SAS - shape and size; SC - spraying chamber; SCP - sprayed coating properties; SCT - sprayed coating treatment; SDs - spraying devices; SD - spraying distance; SI - impact during spraying; SLP - surface layer properties; SLT - single layer thickness; SMS - spraying modes; SP - sprayed product; SPFS - sprayed material feed systems; SpS - spraying spot; SS - sprayed surface; SSE - type and surface structural elements; STC - technical condition of sprayer; T - trajectory; TCP - treated coating properties; TM - treatment modes; TO - treatment operations; W - wire; WFS - wire feed system; WPC - composition and properties of wire.

The analysis of the thermal spraying (TST) parameters must be considered in stages: the transformation of energy, materials and gases in a spray gun to create a spraying jet; transformations in the spraying jet, including particles of the basic material; the interaction of the sprayed material

particles with the product; the formation of single layers and coating spraying spots on the product surface; the formation of a coating of single layers and spraying spots. The formation of single spraying spots is characteristic of impulse spraying techniques. According to several

authors, the number of TST parameters affecting the properties of the resulting coatings reaches about 50 - 60, according to our estimates there are more than 100 of them [14]. It is usually assumed that three groups of factors have a decisive influence on the TST properties: 1) The TST process and modes (influence on the coating microstructure, thickness, distribution, adhesion strength, etc.); 2) The installation devices and protective masking of adjacent surfaces, the kinematics of the spraying process influence the uniformity of coating formation within the surface; 3) Powder or other basic material influence the microstructure and properties of the coating. However, the consideration and analysis of only these groups of factors is often insufficient and all TST systems and subsystems must be considered.

RESULTS AND DISCUSSION

Spraying system. In its most general case, it includes the following subsystems: spraying devices (SD); a gas supply system (GSS); a system of controlling the sprayer's technical condition (STC); a cooling system (CS); a power supply system (PSS); a sprayed material feed system (SPFS); local jet protection (LJP). The output is the coating obtained by the interaction of the spraying jet with the surface of the stationary product called a spraying spot (SpS).

Spraying devices (SD) differ in the thermal spraying technique (TST) and their main types are: spraying plasmotrons (PN); gas flame sprayers (GFS); high-speed gas flame sprayers (HSGFS); detonation gas sprayers (DGS); electric arc metallizers (EAM); cold gas-dynamic sprayers (CGDS); other types of sprayers (ETCS); combined sprayers (CS). Sprayers are designed to obtain a stream of sprayed particles with given speed and temperature value and are the most significant units in the TST plant structure. They differ both in the spraying technique and in the design features and parameters influencing the formation of the spraying jets. In plasma spraying, these are arc plasma sprayers (plasmotrons) and high-frequency induction sprayers; in gas flame spraying they are gas-flame injection and direct sprayers; detonation gas sprayers notable for detonation combustion chambers, gas types, gas exchange systems, etc.; electric arc and high frequency metallization sprayers, etc.

The design features of *sprayers* are different for different spraying techniques and their modifications [1 - 3]. For instance, on the plasmatron side, the input parameters will be its design features (type); the anode and cathode shape, size and materials; their design features; the amount of their wear; the size and location of cooling channels; plasmatron wear, the condition of its elements (contamination, clogging, sediment, etc.); power input; plasma gas injection, etc.

Thus, plasmotrons operating at relatively low voltages (40 - 90 V) and high currents (400 - 800 A) and higher have a major drawback - the long-term instability of plasma parameters, their pulsation, high currents, relatively low electrode lifetime, which means serious limitations in process capabilities. High-voltage plasmotrons provide a significantly better long-term stability of plasma parameters and a relatively long-term stability of the speed and temperature of the sprayed particles.

So far, a large number of plasma sprayers have been developed and they are characterized by a wide variety of schematic diagrams and designs [1 - 3]. They differ in power, performance, technological capabilities of the sprayed materials, coating quality.

In arc plasmotrons, the most critical element is electrodes. Their design determines the arc length and stability, the jet speed and outflow nature, and thereby the plasmatron thermal efficiency and the sprayed material heating efficiency. The wear of the anode walls leads to a voltage shift and, accordingly, to the parameter variation of the sprayed particles. Cathode erosion leads to possible contamination of the coating by erosion particles, changes the arc pulsation characteristics and, accordingly, the parameters of the sprayed particles.

Sources of instability are present in almost all TST systems.

In *gas supply systems* (GSS), the sources of instability are primarily gas flow control and excessive gas whirl in sprayers, which leads to unstable quality indicators of coatings.

Cooling systems (CGS) also exert a significant impact on the reliability of sprayers and the quality of coatings. In a number of TST technologies, sprayed products and coating formation zones are cooled. Coating temperature control and regulation in the formation process determine their structure and properties.

Power supply systems (PSS). They play an important part in plasma and electric arc spraying systems.

The requirements for power sources determine the characteristics of arcing. In coating plasmatrons, the arc current is a technological parameter of the material heating mode and it is regulated both in the process of technology elaboration and in the process of its application. Therefore, current random deviations from the set value cause a violation of the process stability. The power source must not allow significant changes in the operating current at the arc length accidental changes, electrode wear, plasma gas flow. Low-frequency oscillations of the arc voltage and current do not allow the heating of the powder particles. When using rectifiers, the powder utilization rate is reduced in some cases by 15 - 20 %.

With the plasma jet pulsation in the range of 10 - 30 kHz at a speed amplitude of 20 - 30 % of its average value, the heat exchange of those sprayed with plasma is intensified by 20 - 30 %.

Sprayed material feed systems (SMFS). Two SMFS feeding groups are distinguished: 1) powders; 2) wire and rods. They are the devices that influence a number of parameters affecting the following coating formation conditions: the sprayed material feed stability; the ability to control the sprayed material flow; the compactness and low weight for easy handling and positioning for convenient spraying with regard to the product surface; the possibility of automated simultaneous feed of several sprayed materials with a change in their consumption during the spraying process; high general operational safety and reliability, etc. The most common are powder feeders. They must guarantee a stable feed of both mono- and polydisperse powders with the minimal influence of the carrier gas (CRG), as well as, if possible, the powder drying at 100 - 150°C in the hopper of the feeder with heated CRG.

Local jet protection (MZS). The TST processes are classified according to the degree of protection as follows: without protective atmosphere, with local or general protective atmosphere. Economically, it is more accessible to create local protective atmosphere, it eliminates or limits the ingress of air into the sprayed area and contributes to improving the quality of coatings.

The sprayed product system (SPS) includes the following subsystems: a spraying chamber (SC); a carrying and loading device (CLD); a sprayed product (SP); a sprayed surface (SS); spraying modes (SMS). The output is the sprayed coating properties (SCP).

The sprayed coating treatment system (SCT) includes the following subsystems: treatment operations (TO); treatment modes (TM). The output is the properties of the treated coating (TCP) and of the whole product.

The structure of thermal spraying systems described above is typical for high-tech spheres and specialized industries. It is more common to use simpler TST plant structures. This is considered on the example of the most commonly used plasma arc spraying in air (PASA). In its simplest case, the PASA TST structures include the following subsystems: 1) plasma spray plant; 2) carrier and loading device; 3) sprayed product.

The plasma spraying plant includes the following subsystems: 1. Plasmatron; 2. Plasma gas feed system; 3. Power supply; 4. Cooling system; 5. Powder feed system. System analysis makes it possible to consider the main parameters critical for developing the technology.

On the plasma gas feed side, the input parameters are plasma gas composition (or the component ratio when mixtures are used); fed gas pressure, temperature and quantity, gas flow control and its accuracy; purity of gases, their humidity. On the power supply side, the input parameters are current, voltage, ripples. On the cooling system side, they are the cooling medium type (water, gas, etc.), pressure, temperature at the entry into and exit from the plasmatron, cooling medium consumption and its control.

On the side of the powder feed system, the input parameters are: the technique of powder injection into the plasma jet; powder type and characteristics; carrier gas, its consumption; powder and gas consumption; single-point or multi-point powder inlets and their location, etc. Stable optimal powder feed and injection are necessary to obtain stable coating quality, deposition efficiency and coating thickness distribution. There are several reasons for the instability of powder feed and injection. They may relate to powder, equipment operation and process setup. The sprayed powder is a material whose condition may affect the quality and stability of the TST process. The powder manufacturer describes its composition, production technology, particle size and some other properties. But there are characteristics that are not specified but must nevertheless be controlled. They are primarily powder moisture and homogeneity. Therefore, the costs for creating proper storage conditions and special devices for simultaneous drying and mixing of powders are

justified. The classification and requirements for TST powders are discussed in standards EN 1274 and ISO 14232, and those for wires, rods and flexible cords are discussed in EN ISO 14919.

There are many problems in ensuring the reliability of dosing and powder feed systems which require separate consideration. It is necessary to take into account electrostatic charging, erosive wear effect, unstable carrier properties of the powder and many others. TST efficiency largely depends on the injection of powder particles into the spraying jets (plasma, combustion and explosion products). For instance, PASA axial internal powder injection can provide the best conditions for treating particles in plasma, but its technical implementation is extremely difficult. It is also possible that the powder supply injectors be plugged or that powder layers would be formed on the front of the plasmatron nozzle.

Separate consideration of reliability is necessary for many other TST subsystems and elements: the cooling system, power source, gas feed and control, carrier and loading device, TST process diagnostics, additional sources of influence on the formed coating, installation devices, etc.

The sprayed product is also an important TST subsystem. Its general characteristics are mass, overall dimensions, basic material, part class, thermal and chemical heat treatment, sprayed surface, the need to protect adjacent and mating surfaces and elements, masking used, etc. The sprayed surface is characterized by such factors as type, size, structural elements presence and type, the initial state, relative location and accessibility for TST, roughness, waviness, form macro-deviations, the presence of a special relief, chemical composition, structure, physical and mechanical properties, purity, etc.

CONCLUSIONS

- It is possible to achieve a positive effect from using thermal coatings on parts of metallurgic equipment operating in difficult working conditions via an integrated approach to developing product design, choosing or developing materials, equipment and technology of thermal spraying.

- Thermal spraying of critical products can be regarded as high-tech technologies and their development cost is justified by obtaining a significant effect from

their use.

- Production of high-quality thermal spray coatings requires proper monitoring of a large number of parameters both directly in the spraying process and materials used and in the reliability of the main and auxiliary equipment.

- The fundamentals of the theory and practice of ensuring the reliability of technological processes of producing thermal coatings must be researched more deeply with account of technological heredity at all stages of their production.

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