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Fundamentals of Arc Spraying

Physical and Chemical Regularities

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Preface

Among the technologies of efficient use of resources, the group of thermal spraying methods is intensively developed. Studies from the standpoint of gas dynamics, heat transfer, mechanics, metallurgy, and physical chemistry allowed reliably reflection of the processes of motion, the heating of the particles, and their contact with the substrate, studying the structure and properties of coatings applied to the flame, plasma, detonation spraying. Great contribution was made by V.A. Barvinok, M.A. Belotserkovsky, G.V. Bobrov, Y.S. Borisov, V.S. Klubnikin, V.V. Kudinov, S.V. Petrov, A.F. Puzryakov, and others. On this basis, the equipment and the technologies were developed to produce coatings of stable and high quality.

In this group of methods, the Arc-Sprayed coatings are 3–10 times cheaper than the coatings produced by other methods according to the relative costs. Currently, arc spraying takes more than 20 % of the market of thermal spraying coatings, which has been developed dynamically over the last decade. However, its development is constrained by poor quality of the obtained coatings. This is due to the method specificity, which is expressed in a combination of a powerful influence on the sprayed material of the carrier gas, similar to other methods of thermal spraying, and the arc, spraying similar to the arc welding processes. This combination leads to rapid oxidation and splashing of sprayed metal.

Current state of researches does not reflect physical and chemical processes in arc spraying accurately, fairly and adequately. It makes it impossible to improve purposefully the equipment and technologies for this method, to predict the chemical composition and properties of the coatings.

This paper deals with the development and systematization of modern representations of the arc-spaying method. The processes of forming the droplets from the sprayed metal by the influence of the arc, movement, heating along the spraying distance, the chemical interaction of spray material and a gas phase and oxygen supply into the droplets. The interrelation of the processes with the properties of the obtained coatings was distinguished. On the basis of these studies, the possible ways of improving the equipment and improving the properties of the coatings were analyzed; and the proposals for their implementation were developed.

This monograph is the result of co-work of experts who have successfully engaged in the study of high temperature metallurgical processes and in the practical implementation of arc spraying in various branches of industry.

The monograph is designed for scientific and engineering specialists who are engaged in the field of welding and thermal spraying. It can also be used by students, undergraduates, and graduate students who are trained in relevant specialties.

The authors deeply appreciate their colleagues at the Department of Welding Technology, from the Ural Federal University, especially Shalimov M.P., Shanchurov S.M., Shumyakov V.I., as well as employees from the sided organizations Gudnev N.Z., Mishin V.M. (“Uraltransmash”, Ekaterinburg), Lukanin V.L. (“Novator”, Ekaterinburg), Pryadko A.S., Cherepko A.E. (Joint Institute of Mechanical Engineering, Belarus), Baranovsky V.E. (Unique Coat Technologies, USA) for their valuable comments during the discussion of materials and participation in bringing the experiments.

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Created methods for predicting the composition and properties of multicomponent metal and slag melts in the Metal Refining, Welding and Thermal Spraying. From 1983 to 2000 worked as Head of the Welding Technology Department in the Ural Federal University. Under his leadership, three doctoral and 19 master's theses were defended. He is the author of 230 publications, including four monographs. He was president of the Ural Welding Association, Deputy Chairman of the National Certification Committee for Welding, Vice-President of Russian Welding Society.

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At Uraltransmash developed the technologies of Welding and Thermal Spraying for defense and civil products. Since 2012 has been working as Head of the Welding Technology Department in the Ural Federal University. Works on modeling of physics-chemical high temperature processes, studies the properties of the coatings. Author of 240 publications including the monograph. More than 20 Thermal Spraying bays were organized under his technical supervision. Director of the Ural Welding Institute, Honored Inventor of Russia.

Introduction

Discussion of materials presented in the book "Fundamentals of Arc Spraying. Physical and Chemical Regularities" began a long time ago. Vladislav Boronenkov made the main scientific contribution, of course. His fundamental knowledge of the theory of metallurgical processes combined with unique abilities in solving various technical problems. He clearly identified the major problem and was able to find the best way to solve it. He was a world-recognized scientist in the field of modeling of high-temperature metallurgical processes.

He was known and appreciated in Germany, Israel, the USA, Ukraine, and Japan. Vladislav Boronenkov was doing his research with a great enthusiasm. I felt it physically while working with him. Unfortunately, we were not able to finish the work together. Surely, the scientific value of this work would have been much higher. Thank my lucky stars that I have been given the opportunity to work with such a great scientist, and I hope that the work will be interesting for readers as well as for its authors.

Yury Korobov

Chapter 1
Conception of Arc Spraying Method

Thermal Spraying makes an essential contribution to the economy of the developed countries. Among the methods for applying coatings the Arc Spray process (AS) seems more preferable by criteria of thermal efficiency, cost of spraying materials, and ease of maintenance. The AS shows its similarity to other TS methods. Here high-velocity gas jet of a high mass flow rate is used for the formation and transportation of the sprayed material. AS is also close to Arc Welding by nature of application of the arc as a power source. Direct transfer of arc heat to atomized metal causes its positive features. By the specific energy consumption of sprayed metal, the AS is on the same level with Arc Welding and several times more efficient than Plasma Spraying. In addition to high heat, the benefits of arc spraying include:

- high feed rate of spraying;
- the possibility of obtaining the coatings of high thickness, up to a few millimeters;
- ease of implementation compared to other thermal spray processes (except flame spraying);
- compatibility with the typical welding engineering;
- low cost of equipment.

But specific features of AS also determine intense burnout of alloying elements from the metal and the saturation of the sprayed coating with atmospheric gases. It leads to lowering of the alloying elements concentration, the excess content of oxides in the coating. In addition, electromagnetic forces in arc zone differ from desired direction of particle's trajectory. It lowers the deposition efficiency of the sprayed material and reduces the density of the coating on the spray pattern periphery. All these factors lead to a decrease of the coating quality. Additionally, Arc Spraying disadvantages include: sprayed materials are limited with conductive wires, nevertheless using of cored wires widen a range of applicable materials; high feed rate causes a large amount of emitted aerosols, high level of noise, ultraviolet, and infrared radiation, so high safety requirements take place. All these factors limit the widespread use of easy in operation and inexpensive spraying method. Basing on AS system analysis, the ways of improving of coating performance are discussed in the monograph. All influencing factors were divided into the following groups of

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parameters: input, internal, external, and output ones. Output parameters describe the system as a whole; internal parameters show the elements of the system; input parameters define the range of the internal parameters; external parameters have no relation to the AS process but influence on it. The present work is devoted to the analysis of physical and chemical relationships of processes at AS, their mutual influence and usability.

1.1 Essence of the Method

Metal losses through wear and corrosion resistance of machine components and steelworks account for about 30 % of their mass. The promising direction to reduce losses is to improve the properties of surface contacting with the external environment. The results of the research and practical developments show that it can increase the life of products 2–3 times.

The group of methods of thermal spraying (TS) is developing intensively. The analysis results show that the use of thermal spraying makes an essential contribution to the economy of the developed countries. The technologies world market volume of TS in 2000 amounted to 1,600 million euros, today it has increased to 6,500 million euros, Table 1.1.

According to an estimate of DVS (Deutscher Verband für Schweißen und verwandte Verfahren—German Welding Society), EWF (European Federation of Welding) and GTS (Association of Thermal Spraying), the use of TS in the European Community brought profits of more than €900 million and provided 20 thousand workplaces [3].

The market volume of TS in Japan in 2009 amounted to $500 million, over the last 50 years it has been increased 50 times. TS is on the list of 20 key technologies, supported by government programs [4].

The rapid development of TS we also can see in the emerging economies. In China, the market volume of TS in 2002 amounted to 145 million dollars [5]; by the end of the first decade, it rose to $500 million. Since 1992, the TS market in India has been developing rapidly: the number of shops increased from 5 to 55 in 2008, the consumption of powders was $3 million applied to the most developed the process of plasma spraying [6].

The TS share in gross domestic product was: the USA—0.21 %, Japan—0.17 %, Germany—0.25 %, China—0.12 % [2].

Table 1.1 Technologies world market volume, billions of dollars [1, 2]

Region	Years		
	1990	2000	2013
Europe	300	400	2100
North America	600	800	2100
Asia, Australia, Middle East	300	400	2300
Total	1200	1600	6500

The inventor of a method of thermal spraying was Max Ulrich Shoop (Fig. 1.1), who in 1909 filed a patent for spraying technology using flame as a heat source. Over 35 years of work, he had proposed technical solutions for flame spraying and arc spraying equipment and technologies. In particular, he developed processes for interrupting the metal spraying without cooling the metal bath, for spinning on meltable material, for electrical metal spraying, for creating photographic images, for repairing castings, for soundproofing walls, floors and ceilings, for manufacturing metallic paints, and for a mass metallisation machine [7–9].

Industrial applications, however, were only possible after scientific research focused on fundamentals of this type of thermal spray process in the 1950s and 1960s [10–13]. Arc spraying is very economical and therefore, has prevailed in many applications in spite of newly developed high-energy techniques such as plasma, detonation gun, and high-velocity flame spraying. Fields of application are broad due to system variety and mobility, further developments in systems design, and extended range of appropriate spray materials [14–18].

In the USSR, the basic organizations dedicated to flame and arc spraying were Avtogenmash Institute, Remdetal [19]. So, in 1944 on tank repair plants the recovery technology of crankshaft journals and crankpins of tank engines basing on spraying was developed, these companies were actively engaged in the application of anti-corrosion zinc and aluminum coatings [20].

Due to the development of mechanical engineering, first rocket and space and aviation industry, the coatings, which could withstand increased thermal and mechanical loads, were needed. This led to the rapid development of plasma spraying in the 1950–1960s of the 20th century. The pioneer of this field in the United States was the company Thermal Dynamic Corp. (Lebanon, NH) [21]. In the USSR, such academic institutions as Metallurgical and Metal Science Institute named after A. Baykov, Moscow; Bauman Moscow State Technical University; Novosibirsk Heat and Mass Transfer Institute, Electric Welding Institute named after E. Paton; and others were actively engaged in the process [22–24].

Fig. 1.1 Max Ulrich Shoop, inventor of thermal spraying

The basic principles of thermal spraying are defined in DIN EN 657 [25]. In general, the sprayed material is fed into a heat source within or outside the apparatus in the form of powder, wire, or rod. Here, it is heated to the plastic or molten state. A gas jet atomizes the heated material and accelerated it toward the prepared substrate where it is deposited as a coating. During coating deposition the substrate usually remains unmelted.

Graphically, it can be represented by the following scheme, Fig. 1.2. Under the influence of an external energy source the sprayed material is atomized as discrete particles, which are accelerated under the influence of gas jets. The particle's condition, softened or melted, will depend on the heating intensity by the heat source. Under impacting on the substrate the single droplet is strongly deformed, hardens, and takes the form of a thin disk. A set of such particles reaching the surface at a given point in time forms a layer. The coating is formed by sequential layers overlay.

This process is accompanied by a high cooling rate in the range of 10^4–10^6 degrees per second, due to the heat transfer into base substrate. Due to this feature small thermal deformation and, in many cases, the absences of structural changes in the detail are typical for TS processes. In addition, there are small restrictions on the composition of the sprayed materials. Entering the subsequent particles leads to the growth of coating thickness and the formation of layer structure (Fig. 1.2).

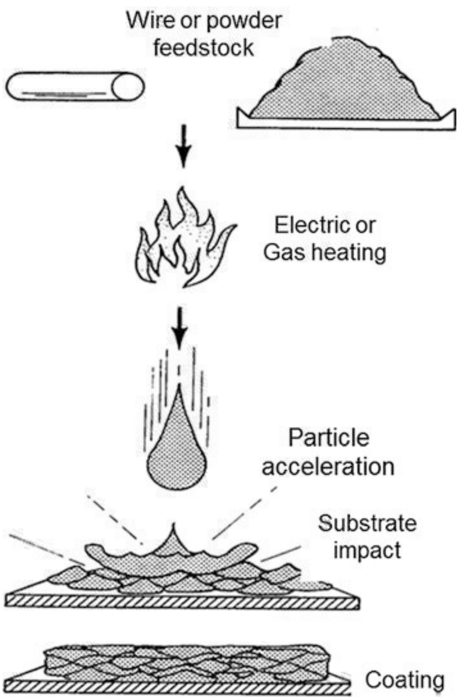

Fig. 1.2 Scheme of thermal spraying process

The TS process scheme determines some of its features:

- Practically no restrictions on the type of coating material, it could be metals, ceramics, plastics, cermet (metal ceramics);
- The substrate, which is coated, remains in a solid state; it is characterized by a low level of thermal stress and by lack of structural changes;
- It is possible to perform coatings in local areas of the surface;
- It is possible to run processes on-site;
- There are almost no restrictions of the base material;
- It is possible to perform coatings with high capacity in a wide range of thicknesses (from 20 μm to several millimeters).

These features provide TS attractiveness for improving the performance of products.

The spraying conditions and features of the sprayed material exert a dominant influence on the properties of sprayed coatings. They, in turn, determine the characteristics of the coating-base system.

The formation of the coating takes place as follows. The individual particles are deformed or splashed while hitting the surface of the substrate. Under such conditions, their rapid solidification occurs due to intensive heat transfer to substrate. Consequently, thermal spraying coatings are usually characterized by a lamellar structure having pores and inclusions of micro cracks, they differ in properties' anisotropy. Except lamellas formed from the initial sprayed material, the structure may include particles not fully molten or secondarily crystallized before hitting the surface, Also products of reactions between the particles and atmospheric gases take place (Fig. 1.3).

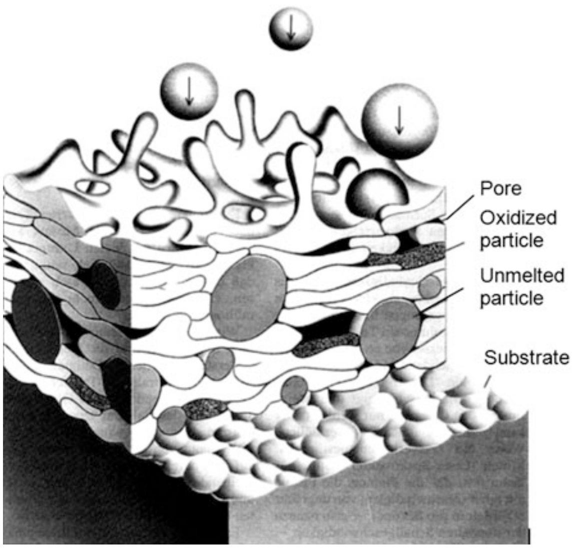

Fig. 1.3 Scheme of coating formation