coatings

Editorial

Research and Application of High-Velocity Oxygen Fuel Coatings

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With the development of modern industrial technology, there is an increasingly urgent need for the preparation of high-strength and high-performance coatings on the surface of traditional metal materials. Since the 1980s, the emergence of high-velocity oxygen fuel (HVOF) spraying has brought revolutionary progress to the technological development and industrial application of thermal spraying technology. The main contribution of HVOF is that it greatly improves the bond strength, density, and hardness of thermally sprayed coatings, while reducing or even eliminating oxide mass fraction in the coating [1]. HVOF spraying has ultra-high flame velocity (2000 m/s) and relatively low temperature (1300–3000 °C), achieving a good combination of thermal energy and kinetic energy. It shows obvious technical advantages in the preparation of high-performance coatings, making HVOF spraying technology one of the most dynamic and promising thermal spraying technologies. Research on HVOF coatings has expanded the application of thermal spray technology in various fields of the national economy such as aviation, aerospace, machinery, petroleum, chemical industry, electronics, weapons, metallurgy, energy, shipbuilding, and so on [2,3].

In the HVOF process, fuel (propane, kerosene, acetylene, etc.) and oxidant oxygen are injected into the combustion chamber to be mixed and ignited. The combustion creates high pressure, which pushes the gas through the nozzle, creating a supersonic jet into the surrounding air. Particles are injected radially or axially into the jet by a carrier gas (usually argon or nitrogen). After heating and acceleration, the particles collide with the substrate in a molten, semi-molten, or solid-state and undergo plastic deformation, eventually forming a well-adhered and dense coating.

Compared with plasma spraying and arc spraying, the coating produced by HVOF spraying technology is less prone to phase change, oxidation, and decomposition of particles.

Based on the torch geometry and power level, the HVOF spray gun system has undergone three generations of development. Pursuing the HVOF technique development from generation to generation, the aim is to increase the gas pressure and the particle velocity and to reduce the flame and particle temperature [4]. The first generation of HVOF spray guns included a relatively large combustion chamber with a straight nozzle or a convergent barrel. In the second generation, the nozzle geometry was upgraded to a Laval nozzle. The pressure generated by the combustion of the first and second-generation spray guns is 3–5 bars, and the spray particle is injected into the combustion chamber axially; the nozzles of the two generations of spray guns are equal-section nozzles. The combustion chamber pressure of the third generation HVOF spray gun is 6–10 bars, and the spray particles can be injected into the combustion chamber from a radial or axial direction. The gun is designed with a Laval nozzle, which accelerates the flame flow through a compression-expansion action. The third generation HVOF spraying technology can effectively increase the particle speed by 30–50%, and it can also more easily control the heating speed of the particles, thereby improving deposition efficiency.

HVOF spraying technology is a complex process involving a series of physical and chemical reactions such as combustion and heat transfer, compressible flow, turbulent mixing, and multiphase interaction [5–8]. The application performance of the HVOF coatings is strongly affected by the microstructure of the coating, and the microstructure depends, to a larger extent, on the physical and chemical states of the sprayed particles when they are deposited on the substrate. In the HVOF spraying process, various spraying parameters jointly affect the particle state [9–12], mainly the gas flow rate and the ratio of oxygen and fuel, which determine the temperature, speed, pressure, and gas composition of the HVOF spray gas flow, which, in turn, affect the temperature, melting state and oxidation state of the sprayed powder, and ultimately affect the density and porosity of the coating. The spraying particle parameters such as particle diameter, particle shape, particle feeding rate, and particle injection location also affect the coating quality. When the particle feed is too small, the particle in the spray gun easily over-melts or burns, resulting in a single spray that cannot completely cover the spray path and increases the porosity in the coating. On the contrary, when the particle feeding amount is too large, the particle in the spray gun often cannot be fully melted, which reduces the deposition efficiency, reduces the bonding force between the coating and the substrate, and makes the coating more prone to cracking and peeling. Spray gun parameters such as spraying distance, spraying angle, and moving speed of the spray gun also have a significant impact. When the spraying distance is too large, the temperature and kinetic energy of the particles will drop too much in the air, and they will not be able to deform enough during deposition. As the bonding strength of the substrate decreases, the particles are more likely to bounce back, and the deposition efficiency decreases. When the spraying distance is too small, the particles have not cooled to the optimal melting state, which will cause the surface of the workpiece to overheat, splash during deposition, and increase the porosity of the coating. In summary, the spraying parameters determine the transfer of momentum and heat between the high-temperature airflow of HVOF spraying and the spraying particle and have a decisive influence on the temperature and speed of the spraying particle, affecting the porosity and oxidation content of the coating, as well as various properties such as wear resistance and corrosion resistance of the coating. To improve the coating performance, researchers have carried out a number of experiments and simulations to study the influence of the above spraying process on the thermal spray coating and develop a series of functional coatings.

A variety of coatings have been prepared by HVOF spraying. Using micron-scale ceramic powder and an appropriate spray gun structure design, aluminum-based ceramics, $BaTiO_3$, etc., can be deposited. The coating has the advantages of high density, excellent adhesion, and a smooth surface profile [13]. Meanwhile, HVOF spraying technology is a good choice for preparing an amorphous alloy coating. Vignesh et al. [14] obtained large hardness and small porosity coatings by optimizing HVOF spraying parameters and adjusting the structure of the Fe-based amorphous coatings. Wang et al. [15] studied the effect of process parameters on the microstructure of HVOF sprayed amorphous coatings. and found that the porosity and un-melted particles ratio decreased with the oxygen/fuel ratio, and increased with the powder feed rate, while the content of the oxide exhibited the opposite trend. Zhang et al. [16] used three different spraying parameters to prepare Fe-based metallic glass coatings, and found that with the increase of spraying power, the coating porosity decreased continuously, and the amorphous phase content first increased and then decreased.

The HVOF spraying process includes the compressible turbulent multiphase flow and impact deformation process, which are difficult to observe and explain directly through experiments. Carrying out systematic simulations of particle in-flight and impact behavior is critical to improving coating performance in industry and academia. Over the past 30 years, a variety of finite element software has been used in spray simulation research, especially computational fluid dynamics (CFD) simulation and Abaqus dynamic impact simulation. Tabbara and Gu [17] established the geometric model of the JP5000 liquid fuel HVOF spray gun and used the computational fluid dynamics Fluent software to study the effect of the fuel droplet size on the gas phase flame flow. Patel et al. [18] studied the effects of oxygen-fuel ratio, total gas flow, and combustion chamber size on the gaseous flame flow of an HVOF spray gun. Wang et al. [19] used Fluent software to calculate the combustion characteristics of HVOF spraying in three cases of pure oxygen, air, and combined oxygen-air combustion based on gas–solid two-phase flow. He et al. [20] used numerical simulation techniques to study the effect of spraying distance on the porosity of Fe-based amorphous coatings. When the spraying distance is 360–380 mm, the amorphous particles are in a semi-melted state when they hit the substrate, and the coating-obtained porosity is low. Liu et al. [21] compared the jet Mach number distribution, dynamic pressure, and jet entrainment characteristics of different Laval nozzle structures under high-temperature conditions.

In the future, it is necessary to study the influence of process parameters on the physical and mechanical properties of coatings through experiments and simulations. Under the international "two-carbon" goal, green manufacturing and materials with low pollution, low energy consumption, and high performance are becoming more and more important. The HVOF spray coating can prolong the life of related components for a long time and provide a new method for the world's low-carbon green manufacturing, which is worthy of research and discussion by scholars. This Special Issue of *Coatings* entitled "Recent Advances in High-Velocity Oxygen Fuel (HVOF) Coatings" aims to publish the latest research results in HVOF coatings and discuss the research progress in the development and application of spraying equipment, spraying technology, advanced coatings, and functional coatings such as anti-corrosion, wear-resistant, and thermal barrier.

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