**Diverse Thermal Spray Techniques Unveiling the Role in Ceramic Coatings**

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**Abstract**

Ceramic coatings have garnered significant attention for their remarkable high-temperature stability, wear resistance, and unique thermal and electrical properties. This review paper delves into new coatings, shedding light on their deposition using cutting-edge techniques: High-Velocity Oxy-Fuel (HVOF), Plasma Spray, Detonation Gun, and Flame Spray. The overarching objective of this paper is to unravel the intricate relationship between deposition methods and critical factors, namely porosity, feed rate, ambient temperature, standoff distance, and deposition angles, influencing the performance and characteristics of these ceramic coatings.

Each deposition technique is dissected, highlighting its distinct mechanisms and capabilities. HVOF, characterized by its supersonic particle velocities, offers enhanced mechanical properties and reduced porosity at lower feed rates. Plasma Spray, harnessing high-temperature plasma jets, provides tailored porosity for thermal insulation, while Detonation Gun excels in optimizing adhesion and resistance to thermal shock. On the other hand, Flame Spray demonstrates versatility in adjusting deposition angles and textures for diverse applications.

**Keywords:** Thermal Spray, Ceramics, Deposition Parameters, Oxide, Intermetallics.

1. **Introduction**

Humanity has always strived to improve materials to overcome challenges, enhance comfort, and optimize tool durability and performance[1-3]. In today's world, mechanical devices face increasing stresses and higher temperatures, pushing beyond the limits of conventional metals. As a result, ceramics have gained interest as a promising alternative[4-5]. However, fabricating bulk ceramic castings remains complex, and ceramics often need to improve their mechanical properties beyond their hardness[6-9]. To overcome these limitations, ceramic coatings on metallic substrates have gained acclaim for their cost-effectiveness, material conservation, and unique properties, providing pragmatic solutions to engineering challenges[10].

The production of coatings involves various processes like physical vapor deposition, chemical vapor deposition, thermal spraying, and polymeric coating. Based on their intended application, coatings can be classified into thin or thick films[11-12]. Thin films serve surface-related functions, while thick coatings exploit bulk properties like corrosion resistance or thermal barriers[13-15].

The main emphasis of this study lies in thermal spraying methods, which involve flame, plasma spraying, and detonation gun coatings[16]. These coatings serve diverse purposes, such as offering solutions for wear and corrosion resistance, safeguarding against oxidation, providing thermal barriers, supporting nuclear technology, addressing medical requirements, enhancing friction and wear characteristics, enabling high-power electronic circuits, and even serving decorative functions[17-19].

Thermal spraying is a particulate deposition method where dense ceramic particles are melted, accelerated, and sprayed onto a substrate at high velocities[20]. The resulting coating consists of overlying thin lenticular particles or splats. Factors like starting materials, microstructures, residual stresses, and porosity influence the properties of the coating. The coating-substrate edge is also crucial in determining adhesion[21-22].

The research paper overviews sprayed coatings, discussing techniques, properties, materials, and applications. It explores the heat and momentum transfer challenges during the spraying process. The paper also highlights the need for further research to optimize the effectiveness of ceramic coatings.

1. **Introduction of Thermal Spray Coating**

Thermal spraying has become a prominent method for applying protective coatings in mechanics. It is unique due to its cold process, physical and chemical transformations of particles, lamellar structure, and rapid quenching upon impact on the substrate surface. These characteristics enable the development of advanced coatings with distinct properties, opening up possibilities for enhancing material properties and protecting substrates.

By exploring various aspects of thermal spraying, this manuscript aims to contribute novel insights and advancements in metallurgical engineering.

**Table 1. Comparison of Different Thermal Spraying Processes Parameters.**

|  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- |
| Process | Gas Flow  | Plasma Temperature (°C) | Particle Impact Velocity | Relative Adhesive Strength | Oxide (%) | Spray Rate (kg/h) | Power (kW) | Energy (kW/kg) |
| Flame Powder[21] | 11 | 2200 | 30 | Low | 7 | 25-75 | 11 | 11-22 |
| Flame Wire[23] | 71 | 2800 | 180 | Medium | 9 | 50-100 | 11 | 11-22 |
| High VelocityOxyfuel[24] | 28-5 | 2000 | 610 | Very High | 14 | 100-270 | 200 | 22-200 |
| Detonation Gun[19] | 11 | 400 | 910 | Very High | 1 | 100-270 | 220 | 220 |
| Wire Arc[22] | 71 | 2500 | 240 | High | 16 | 4-6 | 0.4 | 0.2-0.4 |
| ConventionalPlasma[19] | 4.2 | 150 | 240 | High | 5 | 30-80 | 13 | 13-22 |
| High Energy[28] | 17 | 1000 | 240-1220 | Very High | 23 | 100-250 | 9 | 9-13 |

**Table 2. Comparison of Different Carbides and Oxides Deposition.**

|  |  |  |  |
| --- | --- | --- | --- |
| Material | Plasma Spray Deposition | Detonation Gun Deposition | Flame Spray Deposition |
| Tungsten Carbide (WC) | Commonly deposited with high bond strength and wear resistance. | Suitable for WC coatings, offering good adhesion and wear resistance. | Achievable, but lower bond strength and wear resistance compared to plasma spray. |
| Chromium Oxide (Cr2O3) | Suitable for creating dense and corrosion-resistant coatings. | Offers excellent hardness and wear resistance. | Deposition is possible but may have lower density and wear resistance. |
| Aluminum Oxide (Al2O3) | Commonly deposited with excellent hardness and thermal resistance. | Good hardness and wear resistance are achievable. | Achievable, with moderate hardness and wear resistance. |
| Titanium Carbide (TiC) | High-quality coatings with good wear resistance and adhesion. | Offers good wear resistance and adhesion. | Achievable, but may have lower wear resistance and adhesion. |
| Zirconium Oxide (ZrO2) | Used for thermal barrier coatings, offering good thermal insulation. | Offers thermal barrier properties and high-temperature stability. | Achievable but may have lower thermal insulation properties. |
| Silicon Carbide (SiC) | Offers excellent wear resistance and high-temperature stability. | Provides good wear resistance and high-temperature capabilities. | Possible, but may have lower wear resistance and stability. |

**Table 3. Comparison of Different deposited Intermetallic Coating.**

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| Coating Technique | HVOF | Plasma Spray | Detonation Gun | Flame Spray |
| Coating Process | Combustible substance mixed with oxygen and ignited. | Plasma jet heats and accelerates particles. | Detonation wave propels particles onto the substrate. | The powder is melted and propelled onto the substrate. |
| Coating Adhesion | Generally excellent adhesion to the substrate. | Good adhesion due to high-energy plasma. | Good adhesion through particle acceleration. | Adhesion can vary; may require additional methods. |
| Coating Density | High density and compaction due to high particle velocity. | Porosity levels can vary; it can achieve moderate density. | Moderate density with potential for porosity. | Variable density and porosity; may require optimization. |
| Microstructure | Can achieve fine microstructure with minimal oxidation. | Microstructure can vary based on process parameters. | Microstructure varies; limited oxidation potential. | Microstructure and oxidation can vary widely. |
| Mechanical Properties | It can achieve excellent hardness and wear resistance. | Mechanical properties can vary based on process and material. | It can achieve good hardness and mechanical strength. | Mechanical properties can vary; optimization may be needed. |

* 1. **The Structure of Coating**

The structure of coatings, particularly in ceramics coatings applied using various thermal spray techniques, holds significant importance due to its direct influence on the coated components' performance, durability, and functionality. Conversely, it directly impacts the coating's mechanical, thermal, chemical, and functional properties. Engineers and researchers aim to tailor the coating structure to optimize these properties based on the specific application's requirements, thereby maximizing the performance and longevity of coated components. How various factors influence the resulting coating structure can be understand by the different concepts given below in break point.Top of Form

1. **Successive Layer Formation and Sandwich-Like Configuration:** Thermal spray coatings are built up layer by layer through the impact of high-velocity molten or solid droplets. This results in a unique sandwich-like arrangement where each layer contributes to the final coating structure.
2. **Swift Solidification of Droplets:** To achieve a successful coating, the molten or solid droplets must rapidly solidify upon contact with the substrate. This is essential for creating a strong bond between the coating and the substrate.
3. **Temperature Difference for Effective Coating:** An effective coating requires a significant temperature difference between the melting point of the powder material and its decomposition or evaporation temperature. This temperature difference ensures that the droplets solidify quickly upon impact.
4. **Rapid Deposition Process:** The deposition process occurs extremely quickly, with particle freezing taking place in microseconds and the entire cooling cycle lasting as short as 100 microseconds. This rapid thermal response leads to temperature gradients within the coating, influencing its properties.
5. **Flattening of Droplets:** The degree of flattening of the droplets upon impact plays a crucial role in determining the coating's structure. This flattening is influenced by factors such as liquid density, liquid viscosity, and droplet impact velocity.
6. **Impact Velocity and Temperature Influence:** The ultimate structure of the coating is shaped by the impact velocity, temperature, and particle size at the impact. Higher degrees of flattening is observed under specific conditions, such as when the particle is above its melting point with moderate velocity or below its melting point but within the plastic deformation temperature range with high speed.
	* 1. **The Adhesion of the Coating**

Coating adhesion is crucial in thermal sprayed coatings, but the specific mechanisms governing it are still debated. Some researchers argue that mechanical factors, such as interlocking with the rough substrate surface, dominate adhesion. In contrast, others suggest that chemical interactions between the coating particles and the substrate are significant contributors. The formation of extensive interaction layers between metal substrates and ceramic coatings seems unlikely. The consensus is that mechanical adhesion is significantly enhanced through pre-spraying surface treatments like sandblasting, particularly for ceramics. Residual stresses in coatings can be classified into micro stresses within individual particles and macro stresses impacting the overall coating. Micro stresses occur due to thermal contraction as particles solidify and bond with the substrate, influenced by thermal expansion coefficients, elastic constants of the coating and substrate, and their temperature dependencies. Additionally, the yield strength of the substrate plays a role, potentially facilitating stress relaxation through plastic deformation and influencing the effectiveness of particle-to-substrate bonds[35-39].

* + 1. **The Internal Stresses of the Coating**

Residual stresses at a macroscopic level emerge during cooling to ambient temperature, triggered by variations in thermal expansion between the substrate and coating, coupled with temperature gradients during coating formation[40]. The presence of high interfacial stresses has the potential to induce coating peeling, particularly on smooth substrates, while heightened tensile stresses may result in cracking. Notably, residual compressive stress within ceramic coatings can bolster their overall strength[41-43]. A crucial strategy to alleviate residual stresses involves minimizing thermal gradients, wherein using an air blast during the spraying process aids in maintaining a consistently low temperature for the entire assembly, effectively diminishing stress[44].

The thickness of coatings is often influenced by the stresses generated during the spraying process. Substantial temperature gradients in ceramics with low thermal conductivity can limit coating thicknesses to around 0.2-0.3 mm for high-quality coatings[45-46]. Continuous coating cooling with a gas jet allows for greater thicknesses, typically a few mm, although rapid cooling rates may result in microstructural changes like amorphous or metastable phases[47].

* + 1. **Porosity of the Coating**

Porosity is crucial in thermal sprayed coatings, impacting coating strength and protective properties. While increased porosity can be advantageous in specific situations, it compromises the overall strength of the coatings. In applications where coatings are intended to resist corrosion or oxidation, interconnected porosity becomes undesirable as it weakens the protective capabilities and hinders adhesion at the substrate interface[48-49]. Depending on spraying conditions and materials used, the coating formation process inherently introduces a certain porosity level, typically ranging from 3% to 20%. Factors like particle trajectories during spraying, subsequent heat treatment, and final velocities influence porosity. High rates are essential when particles remain in a non-melted state, while lower speeds are preferred for well-melted particles to ensure controlled flattening without liquid-state explosions[50].

In the context of corrosion experiments, achieving an optimal balance between desirable porosity for thermal protection and minimizing porosity to maintain coating strength and adhesion is crucial. This document comprehensively explores the interplay between porosity, coating formation processes, and unique material properties to optimize coating performance and enhance corrosion resistance.

* + 1. **Changes with chemical interaction in sprayed ceramic particle**

Interactions with hot gas can trigger chemical modifications in sprayed particles within the different thermal spray techniques. In detonation gun spraying, ceramic particles are accelerated and heated by a detonation wave, leading to their melting and deposition onto the substrate. The high-energy process can partially or wholly melt the particles. Chemical reactions between the particles and gases in the detonation gun's environment can lead to modifications in the coating composition or phase transformations. The dense and well-bonded structure of detonation gun coatings may limit the extent of chemical changes[45-47]. Plasma spray uses a high-energy plasma jet to heat and accelerate ceramic particles onto the substrate, where they solidify. The high temperatures in the plasma jet can lead to chemical reactions between the ceramic particles and the surrounding gases[51]. This can result in changes in coating stoichiometry, phase transformations, or the formation of new compounds. The porous nature of plasma spray coatings allows for gas diffusion and interactions, influencing chemical behavior. HVOF uses high-velocity combustion gases to propel and deposit ceramic particles onto the substrate. The combustion gases and fuel used in HVOF can induce chemical reactions with the ceramic particles[52]. While the dense structure of HVOF coatings may limit exposure to external gases, interactions could still lead to chemical modifications or phase changes. The flame spray uses a combustion flame to melt and accelerate ceramic particles onto the substrate. As the particles are heated and propelled through the flame, chemical reactions may occur between the particles and the combustion gases. Flame spray coatings' porous and rough structure allows gas diffusion and reactions.

1. **Processes used for Ceramics Spraying**
	1. **Detonation Gun**

The detonation gun operates on the principle of meticulously controlling an oxygen-acetylene mixture's explosion within a specially designed chamber. This process involves suspending the particles of the intended powder in the gas assortment before initiating the detonation wave. The hot gas rapidly accelerates and propels the powder particles on the substrate at remarkable velocities. The coating overlies shrill lenticular particles, or splats, creating a flawlessly smooth and well-arranged structure[53-54].



**Figure 1. Shows the deposition of the coating by Detonation Gun**

* 1. **Plasma Spraying**

Plasma spraying, similar to flame spraying in principle, differs significantly in its heat production system, relying on electrically blown arcs to energize a non-chemically reactive gas. The enthalpy of the plasma gas, independent of combustion processes, reaches impressive values of up to 109 kJ/kg, surpassing the 103 kJ/kg achieved by flames. The process involves introducing the material's powder into the plasma, which melts and is projected onto the substrate at high velocities.



**Figure 2. Shows the deposition of the coating by Air Plasma Spray**

Despite the elevated plasma temperature reaching up to 15000 K on the axis, rapid gas ejection may lead to insufficient residence time for complete particle melting. To mitigate this, most refractory materials are optimally positioned deep into the nozzle without disrupting the arc. However, introducing particles into the dense plasma, with thermophoresis forces at play, presents challenges. Hence, precise injection velocity and carrier gas pressure adjustment for different types and granulometric of sprayed powders are crucial. Overcoming the complexities of introducing particles into the viscous plasma remains a primary challenge in plasma spraying. This method holds promise for various applications, particularly coatings, where achieving controlled and uniform deposition is paramount[55-59]. Furthermore, examining the characteristics of the sprayed layers at different radial distances reveals intriguing insights. At the jet's axis, the particle velocity was observed to be 160 m/s higher compared to the 16 mm radius. Consequently, the percentage of melted particles, represented by the ratio (δ), was significantly higher on the axis, reaching 95%, whereas it was only 75% at the 15 mm radius. This difference in the extent of melting can be attributed to the rapid cooling experienced by the particles upon impact with the substrate, causing them to crystallize from the γ phase to the γ phase. Precise relative displacement between the substrate and the plasma torch becomes critical in achieving high-quality sprayed layers, similar to flame spraying. This relative movement allows for the control of coating characteristics and uniformity, ensuring optimal performance and functionality of the deposited coatings[58-59]. The findings emphasize the significance of controlling the substrate-plasma torch distance and relative motion during plasma spraying. Due to the higher viscosities experienced by the particles when the temperature is above their melting point, they do not provide adequate coverage on the substrate with a detonation gun. Consequently, the resulting coatings may exhibit higher porosity when compared to those obtained through plasma spraying and flame, where particles have lower viscosities due to higher temperatures. Interestingly, despite the potential for higher porosity, detonation-sprayed coatings can still achieve low porosity levels while exhibiting robust adhesion properties[60-62]. This phenomenon is primarily attributed to the detonation spraying process's high kinetic and thermal energy ratio. The impact of this high kinetic energy compensates for the challenges posed by higher viscosities of ceramic particles, leading to coatings with enhanced adhesion properties[63].

**C.** **Flame Spraying**

Flame spraying, also known as the Schoop process, involves introducing material in the form of powders or sticks into the flame of a burner. The material undergoes melting within the flame and is subsequently sprayed onto the substrate. Gas mixtures like O2-H2 and O2-C2H2 are widely used, offering maximum flame temperatures of 3000°C. Alternatively, an oxygen-cyanogen mixture can provide a flame temperature of 4600°C. The cane burner uses a circular burner with apertures to feed the combustive-combustible mixture, melt the stick material, and propel liquid droplets onto the substrate[64].



**Figure 3. Shows the deposition of the coating by Flame Spray**

**IV. Spraying Process-Based Coating Characteristics**

**A. Detonation gun Spraying**

Detonation-sprayed coatings exhibit notable uniformity and minimal porosity, mainly when dealing with metallic substrates. For metals, upon impact, these particles form delicate lamellae. As they release their kinetic energy, they foster a metallurgical bond with the substrate or previously deposited particles. It's worth noting that the substrate necessitates no preliminary treatment. However, it's imperative to underscore that the explosive forces generated by the detonation gun mandate the provision of a purpose-designed environment to ensure safe operation. Initially patented by Union Carbide in 1955, this technique underwent substantial refinement in the following decades, culminating in the creation of coatings distinguished by their exceptional quality, characterized by remarkable adhesion and, in certain instances, porosity levels of less than 5%[65-66].

**B. Flame Spraying**

Flame spraying encounters certain constraints, mainly when dealing with materials boasting melting points surpassing the flame temperature of the burner. For example, materials with greater refractoriness than zirconia, with a melting point of 2625°C, prove inefficiently sprayable using an O2-C2H2 burner operating at a peak temperature of 2995°C. Although the flame effectively melts particles, resulting coatings exhibit higher porosity than those achieved through detonation guns or plasma spraying. This discrepancy emerges due to the markedly lower gas velocity of the burner in comparison to a plasma or detonation gun. Consequently, particles subjected to flame spraying possess diminished kinetic energy and may inadequately envelop substrate irregularities or previously deposited and solidified particles[67].

Despite these limitations, flame spraying offers merits such as cost-effectiveness and simplified application. The initiation of ceramic thermal spraying witnessed a surge in the early 1960s, and research endeavors in this domain have persisted with diverse applications over subsequent years.

1. **High-Velocity Oxygen Fuel (HVOF)**

In the High-Velocity Oxy-Fuel (HVOF) process, a combustible substance is ignited with oxygen, resulting in its oxy-fuel nomenclature. HVOF commonly employs gases like propane, ethylene, or hydrogen and liquids such as kerosene. A significant historical application of thermal spraying has focused on generating coatings for wear resistance. These coatings necessitate specific attributes like high density, hardness, exceptional adhesion, and a smooth surface. These characteristics are pursued by enhancing particle velocity during the spraying process. More incredible velocity upon impact directly translates to more compact coatings[68]. While Accelerated Particle Spray (APS) places a premium on thermal contribution, HVOF is engineered to elevate kinetic energy levels. This is facilitated by a specialized convergent-divergent nozzle design, where thermal energy and combustion chamber pressure seamlessly morph into kinetic energy, propelling particles at supersonic velocities. The upper limit of gas temperature in HVOF hinges on the flame temperature arising from the fuel/oxygen mixture. This temperature spans a range of 2500–3000°C, contingent on fuel type and the fuel-to-oxygen ratio[69]. To supply ample thermal energy to the feedstock, particles are injected axially within the burner, precisely before the nozzle. Alternately, in some scenarios, radial injection into the nozzle is employed. The axial injection, taking place closer to the combustion chamber where gases are at their hottest, is particularly well-suited for feedstocks with elevated melting points, such as ceramics[70-71]. Historical development efforts of HVOF burners have predominantly centered on metal and carbide-based coatings. Recently, the HVOF burner design refinement has prioritized attaining peak particle velocity while concurrently minimizing temperatures. This optimization aims to sidestep undesired phase changes and oxidation in the feedstock. Of note, there's a burgeoning interest in utilizing HVOF to manufacture ceramic coatings. This heightened interest, particularly in challenging sectors like wear protection and electrical insulation, underscores HVOF's versatility in fulfilling diverse and demanding applications[72-73].

 

**Figure 4. Shows the deposition of the coating by High-Velocity Oxygen Fuel (HVOF)**

1. **Deposition of Oxide**
	1. **Alumina (Al2O3)**

Alumina is renowned for its exceptional properties, making it a highly sought-after hard refractory material with excellent insulating and corrosion-resistant traits. Extensive research has been devoted to studying alumina coatings, utilizing flame and plasma spraying techniques. However, challenges related to phase changes at elevated temperatures have spurred the exploration of alternative strategies, such as combining Al2O3 and TiO2 coatings or incorporating a nickel bonding layer.

* + 1. **Zirconia ( ZrO2)**

Zirconia coatings, valued for their low thermal conductivity, have been widely used to protect metals from high temperatures. Different application techniques, including detonation processes, flame spraying, and plasma spraying, have been employed to create zirconia coatings. While some coatings may exhibit relatively low density, plasma-sprayed zirconia coatings have gained popularity since the mid-1970s, thanks to advancements in plasma spraying techniques that have overcome limitations posed by zirconia's high melting point.

* + 1. **Chromium Oxide (CrO2)**

Chromium oxide coatings, available in stoichiometric and hypo-stoichiometric forms, boast exceptional hardness and wear resistance. Although hypo-stoichiometric layers possess metallic characteristics and limited corrosion resistance, their porosity remains low. The utilization of chromium oxide coatings has steadily grown due to their unique properties, even though their history is relatively recent compared to alumina.

**Table 3. List of parameters used for the ceramic deposition with HVOF and Air Plasma spray[67-68].**

|  |  |  |
| --- | --- | --- |
| Parameter | High Velocity Oxy-Fuel (HVOF) | Air Plasma Spray |
| Particle Velocity | Supersonic velocities for high kinetic energy | Influences melting and acceleration |
| Thermal Energy Transfer | Balancing thermal and kinetic energy for effective melting and bonding | High-temperature plasma for particle heating |
| Oxidation Susceptibility | Minimizing oxidation during the high-velocity combustion process | Exposure to plasma gas and control of oxidation |
| Coating Microstructure | Influences density, compaction, porosity, crystalline structure | Determines porosity, adhesion, and crystal structure |
| Substrate Temperature | Preventing distortion or thermal damage during deposition | Balancing energy transfer and substrate cooling |
| Feedstock Characteristics | Material properties, size, and morphology for optimal deposition | Properties of ceramic particles for effective use |
| Gas Mixture Ratios | Precise ratios for efficient combustion and particle acceleration | Selection of appropriate plasma gas for heating |
| Nozzle Design | Geometry impacts energy conversion and particle acceleration. | - |
| Combustion Stability | Ensuring stable combustion for consistent particle acceleration | - |
| Gas Pressure | Regulating pressure for desired particle acceleration | - |
| Particle Heating and Acceleration | - | Role of high-temperature plasma in particle melting |
| Plasma Temperature | - | Monitoring and ensuring sufficient melting |
| Coating Porosity | - | Evaluation influenced by plasma gas and velocity |
| Substrate Cooling | - | Managing energy transfer and substrate cooling |
| Gas Composition | - | Selection of appropriate plasma gas for heating |
| Plasma Gas Flow Rate | - | Regulating flow rate for temperature and velocity |
| Plasma Torch Power | - | Optimizing plasma temperature and particle melting |
| Spray Distance | - | Determining distance for coating properties |
| Spray Angle | - | Controlling angle for uniform coating deposition |

The effects of porosity, feed rate, standoff distance, ambient temperature, and deposition angle are intertwined with other process parameters, material characteristics, and equipment specifications. Optimizing the porosity, feed rate, standoff distance, ambient temperature, and deposition angle is crucial for achieving the desired coating uniformity, adhesion, and performance. Careful consideration and adjustments are necessary to ensure that the chosen deposition angle aligns with each application's intended coating properties. All the effects are tabulated in Tables 4,5,6,8 and 9 below for better understanding.

**Table 4. Effects of Porosity on deposited ceramics coating by HVOF (High-Velocity Oxy-Fuel), Plasma Spray Detonation Gun and flame spray[52-55].**

|  |  |  |  |
| --- | --- | --- | --- |
| **Coating Technique** | **Effect of Porosity** | **Positive Aspects** | **Negative Aspects** |
| HVOF (High-Velocity Oxy-Fuel) | Lower porosity levels enhance mechanical properties like hardness, toughness, and wear resistance. | Improved coating adhesion, corrosion resistance, and environmental stability. | Excessive porosity compromises mechanical integrity and increases susceptibility to cracking and delamination. |
| Plasma Spray | Porosity influences mechanical properties, with lower porosity generally leading to higher hardness and better wear resistance. | Controlled porosity provides thermal insulation, suitable for high-temperature applications. | Excessive porosity can reduce coating density, corrosion resistance, and adhesion. |
| Detonation Gun | Lower porosity contributes to improved adhesion, hardness, and fatigue resistance. | Enhanced resistance to corrosion, erosion, and thermal shock. | High porosity can reduce mechanical properties and overall coating performance. |
| Flame Spray | Porosity impacts mechanical strength, thermal insulation properties, and dimensional stability. | Controlled porosity enhances thermal barrier capabilities for insulation. | Excessive porosity may decrease wear resistance, adhesion and could lead to degradation in harsh environments. |

**Table 5. Effects of feed rate on deposited ceramics coating by HVOF (High-Velocity Oxy-Fuel), Plasma Spray Detonation Gun, and flame spray[53-56].**

|  |  |  |  |
| --- | --- | --- | --- |
| **Coating Technique** | **Effect of Feed Rate** | **Positive Aspects** | **Negative Aspects** |
| HVOF | Higher feed rates can lead to thicker coatings. | Increased productivity and faster coating deposition. | Possible risk of incomplete melting and lower coating quality if feed rate is excessive. |
| Plasma Spray | Higher feed rates can result in increased coating thickness. | Enhanced deposition efficiency and reduced processing time. | Excessive feed rates may lead to increased porosity and decreased coating quality. |
| Detonation Gun | Higher feed rates can contribute to thicker coatings. | Improved coating deposition speed and productivity. | Risk of insufficient particle heating and incomplete melting at very high feed rates. |
| Flame Spray | Higher feed rates may lead to thicker coatings. | Increased coating application speed and efficiency. | Potential for uneven coating thickness and reduced adhesion if feed rate is too high |

**Table 6. Effects of standoff distance on deposited ceramics coating by HVOF (High-Velocity Oxy-Fuel), Plasma Spray Detonation Gun, and flame spray[61-64].**

|  |  |  |  |
| --- | --- | --- | --- |
| **Coating Technique** | **Effect of Standoff Distance** | **Positive Aspects** | **Negative Aspects** |
| HVOF | Increasing standoff distance can result in thinner coatings. | Reduced risk of coating overheating and improved process control. | Thinner coatings may have lower wear resistance and mechanical properties. |
| Plasma Spray | Increasing standoff distance may lead to increased coating thickness. | Enhanced coating deposition efficiency and reduced heat-affected zone. | Higher standoff distances can result in increased coating porosity. |
| Detonation Gun | Increasing standoff distance can contribute to thicker coatings. | Improved coating efficiency and reduced overheating of the substrate. | Potential for incomplete melting and reduced coating quality at very high distances. |
| Flame Spray | Greater standoff distances may result in thicker coatings. | Improved process control and reduced substrate heating. | Increased likelihood of uneven coating thickness and reduced adhesion. |

**Table 7. Effects of ambient temperature on deposited ceramics coating by HVOF (High-Velocity Oxy-Fuel), Plasma Spray Detonation Gun, and flame spray[56,58,59,61,64].**

|  |  |  |  |
| --- | --- | --- | --- |
| **Coating Technique** | **Effect of Ambient Temperature** | **Positive Aspects** | **Negative Aspects** |
| HVOF | Higher ambient temperatures can influence coating properties. | Improved spray efficiency and lower risk of coating cooling too quickly. | High ambient temperatures may require adjustments to prevent coating overheating. |
| Plasma Spray | Ambient temperature can impact cooling and solidification rates. | More controlled and uniform cooling of coatings, leading to reduced thermal stress. | Extremely high or low temperatures can affect plasma torch performance and coating quality. |
| Detonation Gun | Ambient temperature may affect coating deposition and cooling. | Improved process control and reduced likelihood of substrate cooling during deposition. | Very low temperatures can hinder particle melting and lead to incomplete coatings. |
| Flame Spray | Ambient temperature can impact coating solidification rates. | Better control over the rate of solidification, potentially leading to improved adhesion. | Extremely low temperatures may cause difficulties in maintaining stable flame conditions. |

**Table 8. Effects of deposition angle on deposited ceramics coating by HVOF (High-Velocity Oxy-Fuel), Plasma Spray Detonation Gun and flame spray[65-67].**

|  |  |  |  |
| --- | --- | --- | --- |
| **Coating Technique** | **Effect of Deposition Angle** | **Positive Aspects** | **Negative Aspects** |
| HVOF | Deposition angle can impact coating adhesion and properties. | Improved coating adhesion and potential for enhanced mechanical properties. | Inappropriate angles may result in uneven coating distribution and reduced adhesion. |
| Plasma Spray | Deposition angle can affect coating morphology and properties. | Controlled coating microstructure and improved control over coating build-up. | Incorrect angles may lead to uneven deposition, reduced coating quality, and porosity. |
| Detonation Gun | Deposition angle influences coating thickness and adhesion. | Enhanced control over coating thickness and potential for improved adhesion. | Improper angles may lead to poor coating adhesion and reduced overall quality. |
| Flame Spray | Deposition angle can impact coating uniformity and properties. | Versatility in achieving various coating textures and thicknesses. | Incorrect angles may lead to uneven coatings, reduced adhesion, and porosity. |

1. **Exploring the Diverse Applications of Thermal Spraying**

Thermal spraying is a versatile and innovative technology that finds its utility across a broad spectrum of industries and applications. This process involves deleting melted or heated materials onto a substrate, creating a protective or functional coating. With its ability to enhance surfaces, improve performance, and extend the lifespan of components, thermal spraying has garnered significant attention. This document delves into the myriad of thermal spraying applications, showcasing its pivotal role in modern industrial and technological landscapes.

* 1. **Wear Protection and Coating Enhancement**

One of the primary applications of thermal spraying lies in wear protection and surface enhancement. Components subjected to abrasive or erosive conditions, such as industrial machinery, mining equipment, and automotive parts, benefit from the protective coatings that thermal spraying provides. By depositing wear-resistant materials like ceramics, carbides, and metals, the lifespan of these components is significantly extended, reducing maintenance costs and downtime.

* 1. **Corrosion Resistance**

Thermal spraying excels at creating corrosion-resistant coatings, vital for components exposed to harsh environments, such as marine structures, pipelines, and chemical processing equipment. Applying corrosion-resistant materials like zinc, aluminum, and stainless-steel shields these components from degradation and extends their operational life.

* 1. **Thermal Barrier Coatings**

In industries requiring high-temperature operations, such as aerospace and power generation, thermal barrier coatings play a crucial role. Thermal spraying enables the deposition of ceramic materials with exceptional heat resistance and thermal insulation properties. These coatings act as barriers, protecting underlying components from extreme temperatures and enhancing overall efficiency.

* 1. **Aerospace and Gas Turbine Components**

The aerospace industry relies heavily on thermal spraying to enhance the performance and durability of critical components, including turbine blades and combustion chambers. Thermal barrier coatings and superalloys deposited through thermal spraying improve component efficiency, reduce fuel consumption, and ensure reliable operation under demanding conditions.

* 1. **Electrical Insulation and Conductivity**

Thermal spraying is also instrumental in the field of electrical engineering. Coatings with tailored dielectric properties can be applied to insulate electrical components and prevent short circuits. Conversely, thermal spraying can deposit materials with high electrical conductivity, aiding in the efficient dissipation of heat from electronic devices.

* 1. **Medical Devices and Implants**

Thermal spraying finds application in the medical sector, contributing to the fabrication of biocompatible coatings for implants and medical devices. These coatings promote osseointegration and minimize adverse reactions within the human body, ensuring the longevity and success of medical treatments.

* 1. **Printing and Packaging Industry**

The printing and packaging industry benefits from thermal spraying by creating wear-resistant coatings for printing rollers and other equipment. These coatings enhance print quality, reduce downtime, and extend the service life of critical machinery.

* 1. **Automotive and Transportation**

In the automotive sector, thermal spraying is utilized for various applications, such as cylinder liners, piston rings, and exhaust system components. By improving wear resistance, thermal efficiency, and overall performance, thermal spraying contributes to more reliable and fuel-efficient vehicles.

* 1. **Textile and Paper Manufacturing**

Thermal spraying aids the textile and paper industries by providing coatings that enhance the durability of rollers, guides, and cutting tools. This improves manufacturing processes, reduces downtime, and ensures consistent product quality.

1. **Conclusion**
2. Wear-resistant coatings have been extensively researched for centuries, revealing that hard surfaces significantly reduce wear. Ceramic materials, renowned for their hardness, are ideal for wear-resistant coatings. Challenges in producing ceramic bulk materials have led to the preference for thermal spraying as a favored method for applying wear coatings. Various thermal spraying techniques, such as flame spraying, detonation spraying, and plasma spraying, are commonly employed to deposit wear-resistant coatings.
3. Effective corrosion-resistant coatings must exhibit inertness to corrosive environments and possess low porosity to prevent the adverse effects of reactive fluids on the substrate.
4. Friction studies have gained significant momentum due to the requirements of modern industries, particularly in high vacuum environments where superficial oxide layers are absent. Thermal spraying techniques have been employed to create numerous friction surfaces, addressing the challenges posed by friction in various industrial applications and ensuring optimal performance and durability.
5. Specific critical requirements must be fulfilled to achieve dense and high-strength coatings, including efficiently heating a significant fraction of injected powder particles to a molten state before impinging on the substrate. Plasma spraying has gained prominence in meeting some of these criteria.
6. Future research endeavors should explore a deeper understanding of the interaction between hot gases and particles, particularly in detonations and plasma gases, and the role of gas parameters such as velocity and temperature will be pivotal in advancing ceramic thermal spraying techniques.
7. Continued research and ongoing advancements in these aspects will unlock new possibilities, further enhancing the efficacy and expanding the applications of ceramic thermal spraying across a wide range of industrial domains.

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