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STATE-OF-THE-ART OF THE FLAME-SPRAYING TECHNOLOGY OF COMPOSITE COATINGS IN GLOBAL PRACTICE

This review presents a systematic analysis of recent studies (primarily, in 2019–2025, with reference to foundational earlier works) concerned with flame spraying of composite coatings, with an emphasis on the underlying physical mechanisms governing structure formation and service properties. Flame spraying is considered as complex multiphysics process involving coupled heat and mass transfer, gas dynamics, phase transformations, and mechanical deformation of particles during their interaction with the substrate. The analysis demonstrates that the physical state of particles, namely, temperature, velocity, and degree of melting, plays a decisive role in splat formation, development of interlamellar boundaries, and porosity evolution, which collectively determine the microstructure of flame-sprayed coatings. As shown, microstructure acts as a key link between process parameters and macroscopic properties, including adhesion strength, mechanical and tribological behaviour, damping capacity, and fatigue durability. Special attention is paid to the functional role of interlamellar boundaries and pores, which, beyond being structural defects, serve as dominant sources of internal friction and mechanical-energy dissipation under cyclic and dynamic loading. The review highlights the inherent trade-offs between hardness, wear resistance, adhesion reliability, residual stresses, and damping properties, emphasising the necessity of a physically grounded compromise-based design approach. The prospects for further development of flame-spraying technology are discussed in the context of *in situ* diag-

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nostics, numerical modelling, multiscale analysis, and physics-based process control. These approaches enable the transition from empirical-parameter selection toward predictive design of composite and multilayer coatings with tailored and reproducible properties, expanding the application of flame-sprayed coatings in modern engineering systems from the physical-science perspective.

Keywords: flame spraying, composite coatings, microstructure formation, thermophysical and kinetic processes, adhesion strength and porosity.

1. Introduction

Flame spraying remains one of the most widely used thermal spray techniques for producing protective and functional coatings in mechanical engineering, power generation, and the metallurgical industry [1–3]. Contemporary review studies emphasise the technological flexibility of this method and its capability to provide enhanced corrosion resistance, oxidation stability, and wear protection under severe service conditions [2, 3]. At the same time, the evolution of thermal-spray technologies has led to increasing attention to the physical mechanisms governing coating formation, rather than solely to technological optimisation [4].

In subsequent studies, particular attention has been devoted to composite and multilayer coatings, which enable the combination of metallic matrices and reinforcing phases to achieve improved wear resistance and functional adaptability [5–7]. It has been demonstrated that the performance characteristics of such coatings are largely governed by the thermokinetic state of particles during spraying, including their temperature, velocity, and degree of melting before impact with the substrate [5, 6]. These parameters influence directly splat formation, interlamellar bonding, and porosity evolution.

Modern investigations emphasise that flame spraying represents a complex multiphysics process involving heat and mass transfer, gas dynamics, phase transformations, and mechanical deformation [8–10]. Variations in flame jet parameters can affect significantly coating microstructure, including density, phase distribution, and the morphology of interlamellar boundaries [9, 10]. Therefore, a physically grounded analysis of particle heating and motion is required to predict coating structure and service properties.

A distinct research direction focuses on the analysis of microstructural factors determining the functional properties of flame-sprayed composite coatings. According to the findings reported in Refs. [11, 12], the porosity and morphology of interlamellar boundaries exert a decisive influence not only on mechanical strength and wear resistance but also on the thermal, electrical, and damping characteristics of coatings. As emphasised, the microstructure is formed as a result of the combined action of thermal and dynamic factors acting on particles during the spraying process.

In recent years, considerable attention has also been focused to the issue of adhesion strength of flame-sprayed coatings. Studies reported in Ref. [13] have shown that adhesion is formed through mechanical interlocking, plastic deformation of particles, and, in some cases, metallurgical interaction at the coating–substrate interface. The physical nature of these processes is closely related to the kinetic energy of particles and heat-transfer conditions in the contact zone. Insufficient adhesion strength remains one of the primary causes of coating failure during service, which determines the relevance of systematic analysis of it.

Additional interest in contemporary research is associated with the investigation of the damping properties of flame-sprayed composite coatings. According to data presented in Refs. [14, 15], the presence of metallic matrices with reduced elastic modulus, interlamellar boundaries, and porous structures contributes to an increased ability of coatings to absorb mechanical energy and reduce vibration levels. Damping is considered to result from internal friction and microplastic deformation arising under cyclic loading, making this aspect particularly important for dynamically loaded components and structures.

Despite the substantial number of publications concerned with individual aspects of flame spraying, there remains a need for a comprehensive review analysis focused on the physical mechanisms governing the formation of the structure and properties of composite coatings. Most studies address individual process parameters or specific coating properties, whereas systematic consolidation of contemporary results from the standpoint of process physics is still insufficiently represented in the scientific literature.

The present review article aims to summarise and analyse contemporary studies (2019–2025) concerned with flame spraying of composite coatings, with emphasis on the physical processes of particle heating and motion, microstructure and porosity formation, adhesion strength, damping behaviour, and service performance of coatings. The presented review seeks to identify the key relationships determining the properties of flame-sprayed coatings, as well as to outline promising directions for further research in this field.

2. Current State of Research on Flame-Spraying Processes and Regimes for Composite Coatings

2.1. Evolution of Flame Spraying: From a Technological Technique to a Physically Controlled Process

For a long period of time, flame spraying was regarded primarily as a technological method for producing protective and functional coatings, where process regimes were selected mainly on an empirical basis. Early investigations focused on achieving the required coating thickness and

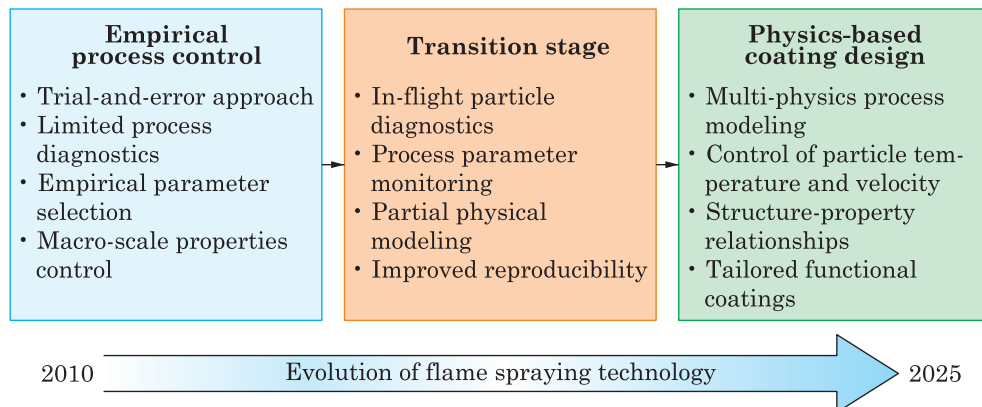


Fig. 1. Schematic evolution of flame spraying from empirical process control to physics-based coating design based on generalised literature data [16]

macroscopic properties, whereas the physical mechanisms of particle heating, acceleration, and interaction with the substrate were analysed to a limited extent. However, contemporary studies interpret increasingly flame spraying as a physically controlled process governed by coupled heat transfer, gas-dynamic effects, and interfacial phenomena [16, 17]. The general evolution of flame-spraying approaches, from empirical optimisation toward physics-based control, is schematically illustrated in Fig. 1.

Recent investigations demonstrate that the physical state of particles within the flame jet, namely, their temperature, velocity, and degree of melting, plays a decisive role in splat formation and interlamellar bonding [18]. The implementation of *in situ* diagnostic systems has enabled real-time measurement of particle parameters, providing quantitative data for process optimisation [19]. Furthermore, the integration of experimental diagnostics with numerical modelling contributes to the transition toward predictive design of coating microstructure and performance [20].

In studies published during 2019–2025, flame spraying is regarded increasingly as a controllable physical system, whose parameters can be purposefully optimised to produce coatings with tailored microstructure and functional properties [1, 7]. Contemporary investigations confirm that even minor variations in particle temperature and velocity within the flame jet may lead to significant changes in coating density, interlamellar bonding characteristics, and phase composition [3, 9]. These effects are particularly pronounced in composite systems, where differences in thermophysical properties of metallic matrices and reinforcing phases intensify the complexity of heat transfer and solidification processes [6].

A substantial contribution to the development of a physically grounded approach has been made by the implementation of advanced process diagnostics. Experimental studies demonstrate that *in situ* measurements

of particle temperature and velocity using optical and pyrometric techniques provide quantitative real-time data on particle state and process stability [18, 19]. These data serve as a basis for constructing numerical models describing particle heating, acceleration, impact, and phase transformations during spraying [11, 20].

The rapid advancement of numerical modelling has further strengthened the scientific foundation of flame spraying. Modern simulation approaches account for the interaction of thermal, gas-dynamic, and mechanical factors and enable prediction of particle state as a function of process parameters and powder characteristics [16, 17]. This creates a transition from qualitative empirical descriptions toward quantitative prediction of coating structure and performance.

Thus, analysis of contemporary publications indicates that flame spraying is transforming from a traditional technological technique into a physically controlled process for the formation of functional surface layers [1, 7]. In this framework, coating microstructure is considered the result of purposeful control over particle heating, motion, deformation, and solidification processes.

2.2. Contemporary Regimes and Parameters of Flame Spraying of Composite Coatings

During 2019–2025, scientific publications have paid considerable attention to the analysis of flame-spraying parameters and their influence on the formation of microstructure and properties of composite coatings. Contemporary studies emphasise that the key factors determining the spraying outcome include particle temperature and velocity, gas composition and flow rates, flame jet geometry, as well as the thermophysical properties of powder materials [7, 8].

According to the results of a number of studies, particle temperature and velocity within the flame jet are interrelated parameters that define the thermodynamic state of particles at the moment of impact with the substrate [3, 9]. It has been shown that variations in combustion regimes and gas-flow rates lead to substantial changes in the thermal balance of particles, which affect their degree of melting and deformation behaviour upon impact [10, 11]. For composite powders, these effects are further intensified due to differences in heat capacity and thermal conductivity of the constituent phases.

Modern investigations demonstrate that the distributions of particle temperature and velocity within the flame jet are statistical in nature and exhibit significant scatter even under fixed spraying regimes [12]. This results in the simultaneous presence of fully molten, partially molten, and solid particles in the deposition zone, which is considered one of the main causes of microstructural heterogeneity in flame-sprayed coatings [13]. In

this regard, recent studies emphasise the necessity of a comprehensive consideration of both thermal and gas-dynamic process parameters.

A separate research direction is associated with the influence of powder granulometric composition and morphology on the stability of the spraying process. Several studies have shown that the use of agglomerated and compositionally modified powders allows a reduction in the scatter of particle temperatures and an improvement in the reproducibility of coating microstructure [12]. Such powders ensure more uniform particle heating and motion within the flame jet compared to mechanical mixtures, which is particularly important for the formation of composite coatings with tailored properties.

Significant attention in recent publications is paid to the problem of particle oxidation during atmospheric flame spraying. Studies reported in Refs. [10, 14] have established that the formation of oxide interlayers between splats has a substantial impact on the mechanical, tribological, and adhesion properties of coatings. It is emphasised that the degree of oxidation is determined not only by flame composition, but also by the residence time of particles in the high-temperature zone, as well as by their size and velocity.

In recent years, methods for monitoring and controlling flame spraying parameters have been actively developed. The use of *in situ* diagnostics of particles' temperature and velocity is regarded as an effective tool for stabilising spraying regimes and improving the reproducibility of coating properties [11, 14]. Some studies have demonstrated that the combination of experimental data with numerical modelling enables optimisation of process parameters and prediction of coating microstructure as a function of selected spraying regimes [15].

Thus, analysis of contemporary research indicates that the development of flame spraying of composite coatings is characterised by a transition from empirical selection of regimes to physically grounded control of process parameters. Particles' temperature and velocity, powder characteristics, and gas-dynamic conditions are considered as interrelated factors governing the formation of microstructure and service properties of flame-sprayed coatings [7, 9, 16].

2.3. Main Application Areas of Flame-Sprayed Composite Coatings

Analysis of publications from 2019 to 2025 indicates that the development of flame spraying has been accompanied by an expansion and diversification of application areas for composite coatings. Whereas earlier studies primarily focused on the formation of protective layers with enhanced wear and corrosion resistance, contemporary research increasingly addresses functional coatings, whose properties are purposefully tailored to specific service conditions [1, 2, 7].

One of the most traditional and widely represented application areas remains the use of flame-sprayed composite coatings to improve the wear resistance of components operating under abrasive, adhesive, and fatigue wear conditions. Recent studies have shown that the introduction of reinforcing phases into the metallic matrix can significantly enhance wear resistance; however, the effectiveness of such coatings is largely governed by their microstructure, porosity level, and the nature of interlamellar boundaries [6, 8, 12]. In this regard, the necessity of a comprehensive approach to the design of coating composition and structure is emphasised.

In recent years, considerable attention has been paid to flame-sprayed composite coatings with damping properties intended to reduce vibrations and absorb mechanical energy in dynamically loaded components. According to the results reported in Refs. [6, 16], the damping behaviour of such coatings is determined by a combination of factors, including the presence of interlamellar boundaries, porous structure, and the use of metallic matrices with reduced elastic modulus. These coatings are regarded as functional elements capable of simultaneously performing protective and vibration-damping functions.

A promising direction in contemporary research is the development of multilayer and directionally graded flame-sprayed coatings. Studies reported in Refs. [17, 18] have shown that distributing functions among individual layers, such as strengthening, damping, and adhesion layers, makes it possible to overcome the contradiction between the requirement for high surface hardness and the need to ensure reliable coating–substrate bonding. This approach opens up opportunities for creating coatings with a balanced set of service characteristics.

Another area of interest in recent publications concerns the application of flame-sprayed composite coatings to enhance the thermal and thermomechanical stability of components. Studies in Refs. [4, 18] indicate that control over coating microstructure and phase composition enables improved performance under cyclic thermal loading, which is particularly important for components used in power engineering and metallurgical equipment.

Current trends also point to a growing interest in functionally oriented coatings that combine mechanical, tribological, and physical properties. Several studies emphasise that flame spraying, owing to its technological flexibility, represents an effective tool for producing such coatings tailored to specific operating conditions without the need for substantial equipment modernisation [2, 7, 16].

Thus, analysis of contemporary research demonstrates that the application areas of flame-sprayed composite coatings are significantly expanded and now include not only traditional protective functions but also solutions for vibration damping, durability enhancement, and functional adaptation of surface layers. This underscores the relevance of further de-

velopment of physically grounded approaches to the design and application of flame-sprayed composite coatings [1, 2, 7].

3. Physics of Particle Heating and Motion during Flame Spraying of Composite Coatings

3.1. Particle Heating and Heat–Mass Transfer in the Flame Jet

The physical processes of particle heating and motion within the flame jet constitute the fundamental basis for the formation of the structure and properties of deposited coatings. In contemporary research, flame spraying is regarded as a multiphysics process involving heat transfer, gas dynamics, phase transformations, and mechanical interaction of particles with the substrate [13]. The combined action of these processes determines the thermodynamic state of particles at the moment of impact and, consequently, the nature of formation of the deposited layer.

Recent studies have shown that particle heating within the flame jet is of non-stationary nature and depends on particle size, their thermophysical properties, and the trajectory of motion within the hot gas flow [14]. According to the results reported in Ref. [15], fine particles reach the melting temperature within the short time; however, they are subjected to intensive oxidation, whereas larger particles may retain a solid or partially molten core.

Investigations presented in Ref. [16] indicate that the distribution of particle temperatures within the flame jet is broad even under fixed spraying regimes. This results in the simultaneous presence of fully molten, partially molten, and solid particles in the deposition zone. Such a polydisperse thermal regime represents one of the main causes of microstructural heterogeneity in flame-sprayed coatings. The main stages of particles' heating, acceleration, and splat formation during flame spraying are schematically shown in Fig. 2.

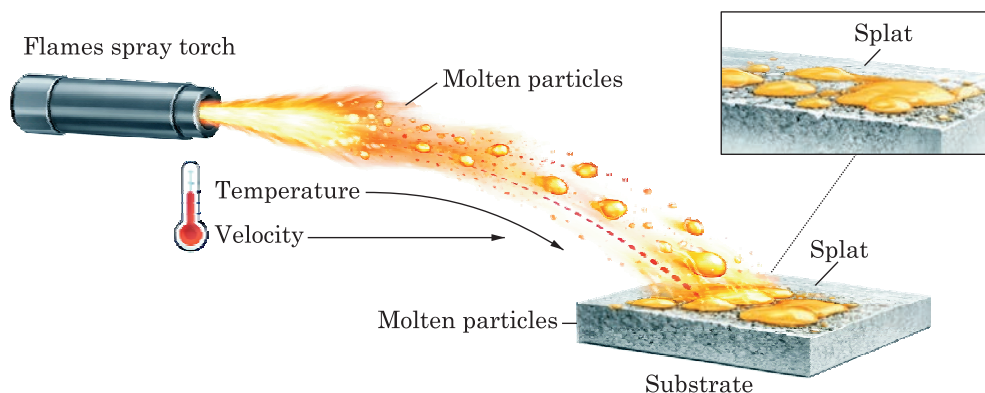


Fig. 2. Schematic representation of particles' heating, acceleration and interaction with the substrate during flame spraying [16]

Modern numerical models of heat transfer confirm that the intensity of particles' heating is governed by the balance between convective heat exchange, thermal conduction within the particles, and the thermal effects associated with phase transformations [17]. It has also been demonstrated that variations in flame composition and gas-flow rates make it possible, within certain limits, to control the thermal state of particles [18, 19].

3.2. Particles' Motion and Acceleration in the Gas Flow

Along with temperature, particle velocity represents a key parameter governing the physics of the spraying process. Contemporary studies have established that particles' acceleration within the flame jet is determined by the balance between drag forces, inertia, and interaction with the gas flow [18]. Particles' size and density exert a significant influence on their acceleration behaviour and final velocity.

It has been shown in Ref. [19] that an increase in particle velocity leads to higher kinetic energy, which promotes more intensive plastic deformation of the molten material upon impact with the substrate. This, in turn, improves splat spreading and contributes to the formation of a denser coating microstructure. However, excessively high particles' velocities increase the probability of particles' rebound and splat fragmentation, indicating the necessity of optimising spraying regimes [18].

Modern experimental investigations emphasise that particle velocity is closely related to temperature: particles in a molten state deform differently from solid state or partially molten particles at the same kinetic energy [20]. This highlights the necessity of a combined analysis of thermal and dynamic parameters.

3.3. Particle State upon Impact with the Substrate and Splat Formation

The physical state of particles at the moment of impact with the substrate is a determining factor in splat formation and the development of interlamellar bonding. Studies reported in Ref. [21] have shown that fully molten particles form thin, well-spread splats with a large contact area, whereas partially molten particles lead to the formation of heterogeneous and defective structures.

It has been established in Ref. [22] that substrate temperature also exerts a significant influence on the particles' spreading process. An increase in substrate temperature reduces the cooling rate of the molten material, prolongs the spreading time, and promotes improved adhesion between splats. These effects are particularly pronounced for composite coatings, where differences in the thermophysical properties of constituent phases enhance non-uniform solidification.

Modern high-speed visualisation techniques confirm that the splat-formation process is accompanied by complex hydrodynamic phenomena,

including the formation of splashes, microcraters, and localised vortex structures [23]. These processes have a direct impact on the microstructure and porosity of the coating.

In recent years, methods for *in situ* diagnostics of particles' parameters have undergone significant development. Study [24] has demonstrated that the application of two-colour pyrometry and optical velocity-measurement techniques enables the acquisition of quantitative real-time data on particles' temperature and kinematics. This provides a foundation for physically grounded control of the spraying process.

According to the results reported in Ref. [25], the use of diagnostic systems allows a substantial reduction in the scatter of coating properties by stabilising the particle state. The authors emphasise that such methods represent an essential component of contemporary research and industrial optimisation of flame spraying.

Analysis of contemporary studies indicates that the physical processes of particle heating and motion during flame spraying are closely interrelated and should be considered in an integrated manner. Particles' temperature, velocity, and degree of melting determine their deformation behaviour upon impact, splat formation, and the development of interlamellar bonding, which ultimately governs the microstructure and properties of composite coatings [26].

4. Formation of Microstructure and Porosity of Flame-Sprayed Composite Coatings

4.1. Splat Formation and Its Role in Coating Microstructure

The primary structural element of flame-sprayed coatings is the splat, which forms as a result of the impact of a molten or partially molten particle on the substrate surface. Study [27] has shown that splat geometry and morphology are governed by the temperature and viscosity of the molten material, as well as by the kinetic energy of particles. Fully molten particles form thin, well-spread splats with a high degree of interfacial contact, whereas partially molten particles give rise to heterogeneous structures containing solid fragments. A generalised lamellar microstructure with characteristic defects typical for flame-sprayed composite coatings is schematically shown in Fig. 3.

Contemporary studies employing high-speed imaging and numerical modelling demonstrate that the splat-spreading process is accompanied by intensive hydrodynamic effects, including the formation of microsplashes, localised vertical flows, and non-uniform temperature distribution over the contact surface [28]. These effects have a direct impact on the formation of interlamellar boundaries and local porosity.

The microstructure of flame-sprayed composite coatings is characterised by the presence of pronounced interlamellar boundaries formed as a

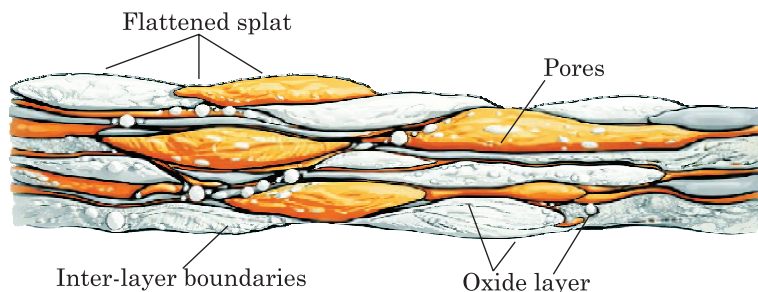


Fig. 3. Generalised lamellar microstructure of flame-sprayed composite coatings, illustrating splats, interlamellar boundaries and porosity [27]

result of successive deposition of splats. Study [29] has established that interlamellar boundaries represent regions with reduced density and an increased concentration of defects, including oxide interlayers and micropores. These regions play a key role in the formation of the mechanical, thermal, and damping properties of coatings.

Composite systems are characterised by a complex phase distribution within individual layers. According to the results reported in Ref. [27], solid reinforcing particles may be either uniformly distributed within the metallic matrix or localised in interlamellar regions, depending on particles' heating conditions and dynamics. Such phase distribution has a significant influence on local stress states and coating failure mechanisms.

4.2. Mechanisms of Porosity Formation

Porosity is one of the most characteristic features of flame-sprayed coatings and is considered in contemporary studies as an inevitable consequence of the physics of the spraying process. Investigations reported in Ref. [12] have shown that the primary mechanisms of pore formation include incomplete splat spreading, gas entrapment during melt solidification, and the presence of solid or partially molten particles.

Modern quantitative studies indicate that porosity is governed not only by global process parameters but also by local conditions of structure formation. Study [28] has demonstrated that increasing particles' temperature and velocity leads to a reduction in the volumetric fraction of pores; however, complete elimination of porosity during atmospheric flame spraying is not possible. It is emphasised that (open or closed) pore characteristics exert a more pronounced effect on coating properties than their total content.

The composition of composite powders has a significant impact on the formation of coating microstructure. Studies reported in Ref. [23] have shown that differences in the thermophysical properties of the metallic

matrix and reinforcing phases result in non-uniform particles' heating and complex solidification regimes. This may promote the formation of microcracks and localised stresses in the vicinity of phase boundaries.

It has been noted in Ref. [24] that the use of composite powders with a pre-formed structure (agglomerated and coated powders) enables improved phase-distribution uniformity and a reduction in coating defectiveness. This approach is regarded as a promising direction for the formation of coatings with controlled microstructure.

4.3. Relationship between Microstructure and Physical and Functional Properties

Contemporary studies emphasise a close relationship between the microstructure of flame-sprayed composite coatings and their physical properties. Study [25] has shown that an increase in structural density and a reduction in porosity lead to enhanced thermal conductivity and adhesion strength of the coating. At the same time, the presence of interlamellar boundaries and pores contributes to increased internal friction, which has a positive effect on damping properties.

Investigations reported in Ref. [16] indicate that the optimal microstructure of flame-sprayed composite coatings represents a compromise between density, adhesion, and the ability to absorb mechanical energy. This highlights the necessity of a physically grounded approach to controlling the processes governing microstructure formation.

Thus, analysis of studies published during 2019–2025 demonstrates that the microstructure and porosity of flame-sprayed composite coatings are formed under the influence of a complex set of interrelated physical processes. Control over particle heating and motion parameters, as well as powder composition, enables purposeful tailoring of coating structure and adaptation of its properties to specific service conditions [27].

5. Materials for Strengthening Layers of Composite Flame-Sprayed Coatings

In contemporary studies of flame-sprayed composite coatings, materials used for the strengthening layer are regarded as one of the key factors determining the service performance of coatings. Analysis of the literature indicates that the selection of the strengthening layer composition should be carried out with consideration of operating conditions, wear mechanisms, and requirements for the combined mechanical and functional properties of the coating [2, 7, 12].

In most studies, the strengthening layer is formed on the base of a metallic matrix with the introduction of dispersed reinforcing phases [30]. Nickel-, iron-, copper-, and aluminium-based alloys are most widely used as matrix materials, as they provide sufficient plasticity, good adhesion to

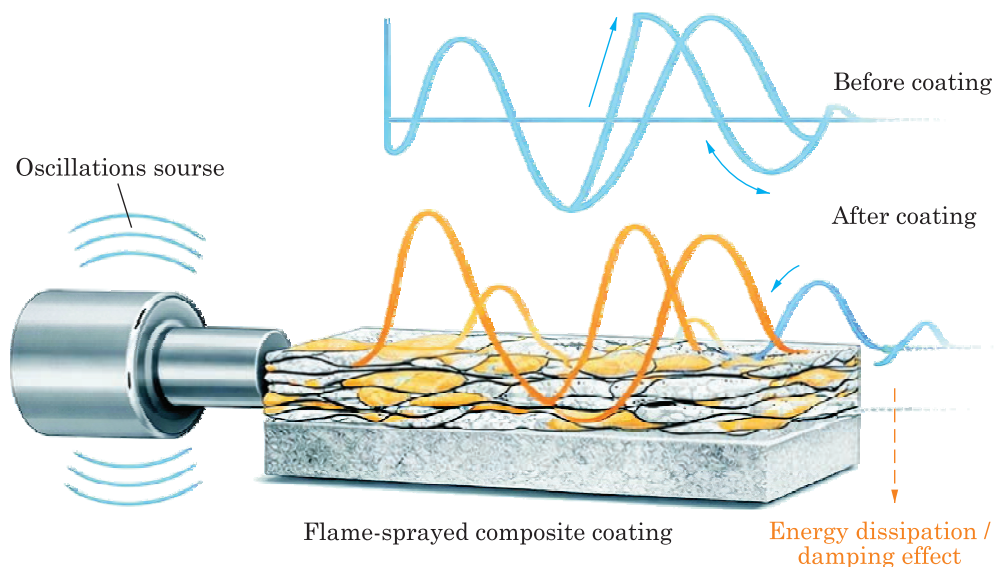


Fig. 4. Classification of materials used for strengthening layers in flame-sprayed composite coatings [18]

the substrate, and the ability to form a dense structure during flame spraying [8, 9, 16]. The choice of a specific matrix is determined by service temperature conditions, corrosion resistance requirements, and compatibility with the substrate material [28].

Carbides, borides, and oxides possessing high hardness and wear resistance are most commonly employed as reinforcing phases in flame-sprayed composite coatings. Studies reported in Refs. [6, 12, 18] have demonstrated that the incorporation of tungsten, chromium, and titanium carbides can significantly enhance resistance to abrasive and adhesive wear. At the same time, it is emphasised that the effectiveness of strengthening is governed not only by the chemical composition of the phases but also by their size, distribution, and the nature of their interaction with the metallic matrix.

Special attention in contemporary research is given to the stability of reinforcing phases during the flame-spraying process. Several studies have noted that, at high flame temperatures, partial decomposition or oxidation of carbide and boride phases may occur, leading to changes in their strengthening effect [10, 19]. In this context, the necessity of optimising spraying regimes and selecting powders with enhanced thermal stability is emphasised.

A promising direction involves the use of composite and agglomerated powders, in which reinforcing phases are uniformly distributed within the metallic matrix already at the material preparation stage [18]. According to data reported in Refs. [12, 18], such powders ensure a more homogene-

ous structure of the strengthening layer and reduce the risk of phase segregation during spraying. This contributes to improved reproducibility of coating properties and stability of their service performance. A generalised classification of materials used for strengthening layers in flame-sprayed composite coatings is schematically shown in Fig. 4.

In recent years, functionally oriented strengthening layers have also been considered, in which hard phases are combined with matrices exhibiting a reduced elastic modulus or enhanced fracture toughness [30]. Studies reported in Refs. [25, 28] have shown that this approach enables not only improved wear resistance but also a reduction in the susceptibility of coatings to brittle failure under dynamic and cyclic loading conditions.

Thus, analysis of the literature indicates that materials for the strengthening layers of flame-sprayed composite coatings should be regarded as elements of an integrated ‘material–process–structure–properties’ system. Optimisation of the strengthening layer composition, in combination with control over flame spraying parameters, makes it possible to produce coatings with a tailored set of service characteristics adapted to specific operating conditions [7, 12, 16].

6. Adhesion Strength and Interfacial Interactions in Flame-Sprayed Composite Coatings (2019–2025)

6.1. Physical Nature of Adhesion in Flame Spraying

Adhesion strength is one of the key characteristics of flame-sprayed coatings, determining their reliability and durability under service conditions. Contemporary studies consider adhesion not as a single parameter, but as the result of the combined action of physical mechanisms occurring at the coating–substrate interface and within the interlamellar regions of the coating [27]. In this context, adhesion is closely associated with the kinetic energy of particles, their thermal state, the nature of plastic deformation, and heat-transfer conditions in the contact zone.

Contemporary studies have shown that adhesion of flame-sprayed coatings is formed through several simultaneously acting mechanisms, including mechanical interlocking, physical contact accompanied by plastic deformation, and, in certain cases, metallurgical or diffusion interactions [28]. The dominant mechanism is governed by particles’ temperature and velocity, as well as by the condition of the substrate surface.

According to the results reported in Ref. [29], mechanical interlocking plays the primary role during flame spraying and is associated with penetration of the molten material into the micro-roughness of the substrate surface. Plastic deformation of particles upon impact contributes to an increased contact area and the formation of strong interfacial bonds. It is emphasised that insufficient kinetic energy of particles leads to incomplete spreading and a reduction in adhesion strength.

6.2. Influence of Particle Temperature and Velocity on Adhesion

The thermal state of particles is one of the determining factors governing adhesion formation. Study [30] has shown that fully molten particles provide higher adhesion strength compared to partially molten ones, as they possess a greater ability for plastic deformation and penetration into substrate microroughness.

Particle velocity exerts an equally significant influence. According to the results reported in Refs. [31], an increase in velocity leads to higher kinetic energy and intensification of plastic deformation upon impact, which contributes to improved coating–substrate bonding. However, excessively high velocities may result in splat fragmentation and the formation of defective zones, indicating the existence of an optimal range of process parameters.

Contemporary studies emphasise the importance of substrate-surface condition for the formation of adhesion strength. Study [32] has established that increasing surface roughness promotes adhesion enhancement due to intensified mechanical interlocking. However, excessive roughness may lead to local stress concentration and a reduction in interfacial bond strength.

Some studies have shown that thermal and mechanical pre-treatment of the substrate prior to spraying affects heat transfer in the contact zone and the solidification rate of the molten material [33]. This, in turn, influences the nature of interfacial bond formation and the level of residual stresses [34].

The adhesion strength of flame-sprayed coatings is closely related to the level of residual stresses formed during the spraying process. Studies reported in Ref. [34] have shown that residual tensile stresses may promote coating delamination, whereas moderate compressive stresses, by contrast, enhance the stability of interfacial bonding.

Composite coatings are characterised by a complex stress distribution at phase boundaries. Study [35] has established that differences in the coefficients of thermal expansion between the metallic matrix and reinforcing phases lead to localised stresses, which may either enhance or weaken adhesion strength, depending on the microstructure and spraying conditions.

6.3. Methods for Evaluating Adhesion Strength

Contemporary methods for evaluating the adhesion of flame-sprayed coatings include pull-off, shear, and bending tests, as well as instrumental techniques for fracture analysis [36]. Recent studies emphasise that interpretation of adhesion test results should account for microstructural features of the coating and the fracture mode, namely, cohesive or adhesive ones [27, 33].

Study [37] has demonstrated that the combined use of mechanical testing and microstructural analysis enables a more accurate assessment of the physical mechanisms governing interfacial bond failure. This integrated approach is regarded as the most promising for the analysis of adhesion in composite coatings.

Contemporary studies indicate that adhesion strength has a direct influence not only on the mechanical reliability of coatings but also on their functional properties. Study [38] has demonstrated that high adhesion promotes more effective load transfer and reduces local stress concentrations, which has a positive effect on the damping characteristics of the coating.

Investigations reported in Ref. [39] emphasise that the use of damping interlayers can simultaneously enhance adhesion strength and reduce the level of residual stresses. This makes integrated analysis of adhesion and damping particularly relevant for multilayer and composite flame-sprayed coatings.

Thus, contemporary studies (2019–2025) confirm that the adhesion strength of flame-sprayed composite coatings is formed under the influence of a set of interrelated physical factors. Control over particle temperature and velocity, substrate surface condition, and coating microstructure enables purposeful enhancement of adhesion and reliability of deposited layers.

7. Damping Materials and Impact Energy Absorption in Composite Coatings

7.1. Physical Nature of Damping in Composite Coatings

In recent years, the damping properties of flame-sprayed composite coatings have attracted increasing attention from researchers due to the need to enhance vibration resistance and service life of components operating under cyclic and dynamic loading conditions [39]. Unlike conventional protective coatings, damping coatings are considered functional elements capable of effectively absorbing and dissipating mechanical energy through internal friction mechanisms and microplastic deformation [40]. The vibration-damping mechanism provided by composite flame-sprayed coatings is schematically illustrated in Fig. 5.

Recent studies indicate that damping in flame-sprayed composite coatings is governed by a combination of several physical mechanisms. It has been established in Ref. [41] that the primary sources of energy absorption include internal friction within the metallic matrix, microplastic deformation in the vicinity of interlayer boundaries, and energy dissipation at structural defects such as pores and microcracks.

For composite systems, an additional contribution to damping arises from the presence of phases with different elastic moduli. According to

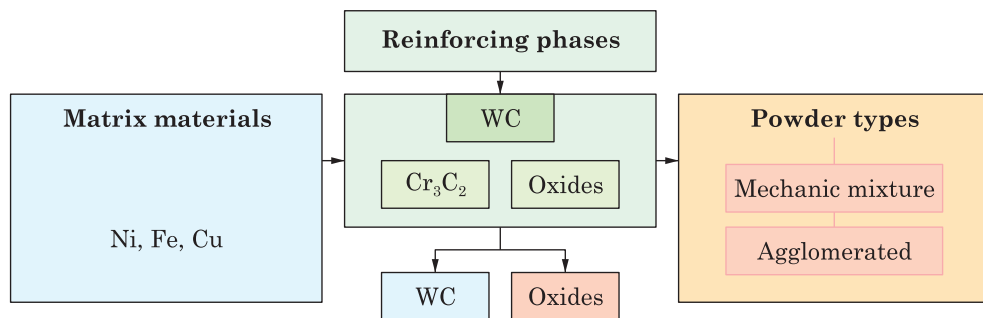


Fig. 5. Schematic illustration of vibration damping effect provided by composite flame-sprayed coatings [40]

the results reported in Ref. [42], differences in the deformation behaviour of the metallic matrix and the reinforcing phases lead to the development of local stresses and microsliding at phase interfaces, which is accompanied by enhanced dissipation of mechanical energy.

7.2. Role of Microstructure and Porosity in Damping

The microstructure of flame-sprayed coatings plays a decisive role in determining their damping characteristics. Studies reported in Ref. [43] have shown that an increase in the volume fraction of pores and interlayer boundaries leads to a higher internal friction coefficient, as these structural features act as zones of strain localisation under cyclic loading conditions.

However, recent investigations emphasise that excessive porosity may adversely affect the mechanical strength and adhesion reliability of the coating. It was established in Ref. [44] that optimal damping properties are achieved with a compromise microstructure combining moderate porosity with sufficient density and strength of interlayer bonding.

Particular attention is paid to the role of interlayer boundaries. According to the results presented in Ref. [45], interlayer boundaries serve as the primary sites of energy dissipation under vibrational loading. Moreover, it has been demonstrated that the nature of these boundaries, including the presence of oxide interlayers, microroughness, and differences in splat orientation, significantly influences the magnitude of the damping effect.

The composition of composite coatings has a significant effect on their energy absorption capability. As shown in Ref. [46], metallic matrices with a reduced elastic modulus, such as copper-, aluminium-, and nickel-based alloys, exhibit higher damping characteristics compared to stiffer matrix materials.

The introduction of reinforcing phases, on the one hand, enhances the stiffness and wear resistance of the coating, while, on the other

hand, it may reduce its damping performance. According to the results reported in Ref. [37], optimal damping properties are achieved at a moderate content of hard particles, where the ability of the metallic matrix to undergo microplastic deformation is preserved.

Recent studies also demonstrate the effectiveness of multilayer and graded coatings. It was established in Ref. [38] that the presence of a damping interlayer between a rigid surface layer and the substrate makes it possible to reduce significantly vibration levels, while improving simultaneously the adhesion reliability of the coating.

The parameters of flame spraying have a direct influence on the damping properties of coatings. Studies reported in Ref. [39] have shown that particles' temperature and velocity determine the degree of plastic deformation and the nature of interlayer boundary formation, which, in turn, affect internal friction.

It was established in Ref. [47] that a reduction in particles' kinetic energy leads to increased porosity and enhanced damping, but it is accompanied by a decrease in coating strength. This highlights the need for a physically justified selection of spraying regimes that ensures an appropriate balance between damping performance and mechanical reliability.

7.3. Methods for Evaluating Damping Properties

Modern methods for evaluating the damping properties of flame-sprayed coatings include dynamic mechanical spectroscopy, resonance techniques, and vibration loading tests [48]. Recent studies emphasise that correct interpretation of damping test results requires consideration of the microstructural features of the coating and the conditions of attachment of it to the substrate.

It has been shown in Ref. [49] that a comprehensive approach combining mechanical testing, microstructural analysis, and modelling enables a deeper understanding of the physical mechanisms of energy dissipation and facilitates optimisation of the composition and structure of composite coatings.

Recent studies emphasise a close relationship between damping properties, adhesion strength, and the durability of flame-sprayed coatings. It was established that coatings exhibiting pronounced damping behaviour demonstrate higher resistance to fatigue failure due to a reduction in the amplitude of local stresses [46].

Studies reported in Ref. [50] have shown that the application of damping interlayers contributes to a reduction in residual stresses and enhances the resistance of coatings to delamination under cyclic loading. This makes damping an important functional parameter in the design of composite flame-sprayed coatings for dynamically loaded systems.

Thus, an analysis of studies published between 2019 and 2025 indicates that the damping properties of flame-sprayed composite coatings are governed by a combination of physical factors, including microstructure, composition, and spraying parameters. Targeted control of these parameters opens up opportunities for the development of functional coatings that combine protective and vibration-absorbing properties [51].

8. Mechanical and Tribological Properties of Flame-Sprayed Composite Coatings

8.1. Hardness, Wear Resistance and Elastic Modulus

The mechanical and tribological properties of flame-sprayed composite coatings are key indicators of their service performance and determine largely their areas of practical application. Contemporary studies consider these properties as the result of complex interactions between microstructural factors, phase composition, and spraying parameters, highlighting the need to analyse them from the standpoint of deformation and fracture physics of materials [44].

Hardness is one of the most commonly used characteristics for evaluating the mechanical properties of flame-sprayed coatings. Studies reported in Ref. [46] have shown that the hardness of composite coatings is determined not only by the content of reinforcing phases but also by structural density, degree of porosity, and the nature of interlayer boundaries. It has been established that an increase in the fraction of hard inclusions leads to higher microhardness, but is accompanied by a reduction in coating plasticity.

Recent investigations employing micro- and nanoindentation techniques demonstrate that the elastic modulus of flame-sprayed coatings is significantly lower than that of bulk materials with a similar composition [42]. This is attributed to the presence of pores, interlayer boundaries, and structural defects, which reduce the effective stiffness of the material. This effect is considered as one of the factors contributing to the enhanced damping properties of the coatings.

Wear resistance is one of the key service characteristics of flame-sprayed composite coatings. Studies reported in Refs. [43, 44] have shown that the wear mechanisms of such coatings depend on the type of contact interaction, loading conditions, and microstructural features of the coating. Composite systems are typically characterised by a combination of abrasive, adhesive, and fatigue wear mechanisms.

According to the results presented in Ref. [45], an increase in hardness and structural density contributes to a reduction in the intensity of abrasive wear. However, excessive enhancement of coating stiffness may lead to brittle fracture of interlayer boundaries and accelerated wear under impact and cyclic loading conditions. The generalised wear behaviour

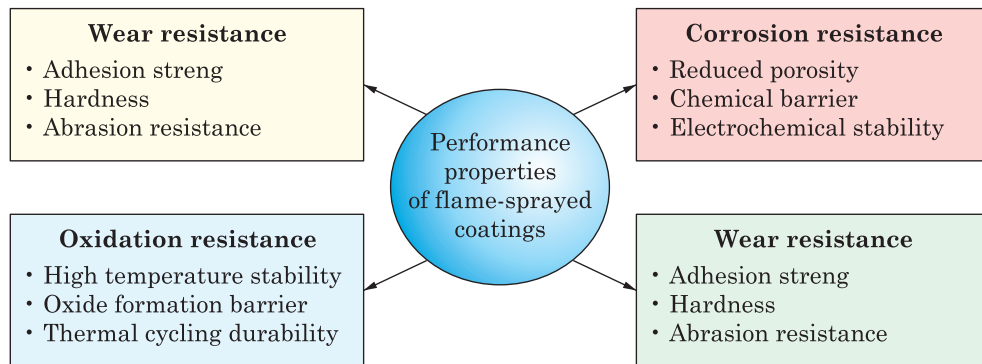


Fig. 6. Conceptual illustration of wear behaviour of coated and uncoated surfaces [45]

of coated and uncoated surfaces under different loading conditions is schematically illustrated in Fig. 6.

Studies reported in Ref. [42] emphasise that optimal wear resistance is achieved through a balanced combination of hard reinforcing phases and a ductile metallic matrix capable of absorbing part of the mechanical energy and inhibiting crack propagation.

8.2. Influence of Microstructure on Tribological Behaviour

The microstructure of flame-sprayed coatings plays a decisive role in determining their tribological characteristics. Studies reported in Ref. [51] have shown that porosity and interlayer boundaries can play a dual role: on the one hand, they act as stress concentrators and sources of damage, while, on the other hand, they promote the retention of wear debris and the formation of secondary tribolayers.

It was established in Ref. [42] that the presence of secondary tribolayers on the coating surface can reduce the coefficient of friction and stabilise the wear process. These layers are formed as a result of oxidation and mechanical mixing of coating components within the friction zone and depend on the conditions of contact interaction.

Recent studies emphasise a close relationship between adhesion strength, residual stresses, and the mechanical properties of flame-sprayed coatings. It was shown in Ref. [33] that insufficient adhesion leads to premature coating delamination and a sharp decrease in wear resistance, even in the presence of high surface hardness.

Residual stresses formed during the spraying process have a significant effect on the fatigue strength of coatings. According to the results reported in Ref. [45], moderate compressive stresses enhance resistance to crack initiation, whereas tensile stresses promote rapid crack propagation and degradation of interlayer bonding.

In recent years, increasing attention has been paid to the fatigue behaviour of flame-sprayed composite coatings, particularly, in the context of their application in dynamically loaded components. Studies reported in Ref. [25] have shown that the fatigue durability of coatings is governed by a combination of factors, including microstructure, adhesion, residual-stress level, and damping properties.

It was established in Ref. [46] that coatings exhibiting pronounced damping properties demonstrate enhanced resistance to fatigue failure due to a reduction in the amplitude of cyclic stresses. This confirms the importance of a comprehensive approach to the design of composite flame-sprayed coatings.

Recent studies emphasise the necessity of a comprehensive evaluation of the mechanical and tribological properties of flame-sprayed coatings. It was shown in Refs. [46, 47] that optimisation of a single parameter, such as hardness, does not guarantee improved service reliability of the coating without considering adhesion, residual stresses, and damping characteristics.

Thus, an analysis of publications from 2019 to 2025 indicates that the mechanical and tribological properties of flame-sprayed composite coatings are governed by a complex set of interrelated physical factors. Control of microstructure, phase composition, and spraying parameters enables the targeted development of coatings with tailored service characteristics [48, 51].

9. Discussion and Prospects for the Development of Flame Spraying of Composite Coatings

An analysis of recent studies (2019–2025) concerned with flame spraying of composite coatings indicates that the development of this field is characterised by a gradual transition from empirical selection of technological parameters to physically grounded control of the processes governing the formation of coating structure and properties. Contemporary publications emphasise that the service characteristics of flame-sprayed coatings cannot be considered in isolation, but are formed as a result of complex interactions among thermal, gas-dynamic, and mechanical factors.

One of the key conclusions drawn from the reviewed studies is the decisive role of the physical state of particles during the spraying process. Particles' temperature, velocity, and degree of melting directly affect splat formation, the development of interlayer boundaries, and coating porosity. These microstructural features, in turn, determine adhesion strength, mechanical and tribological properties, as well as the damping capability of the coatings. Thus, microstructure acts as a linking element between process parameters and the service performance of the coatings.

Particular importance in recent studies is attributed to understanding the role of interlayer boundaries. While they were previously considered primarily as structural defects, recent works emphasise their functional

significance. Interlayer boundaries and pores may act as zones of stress concentration and crack initiation; at the same time, they represent the main sources of internal friction and mechanical-energy dissipation. This aspect is especially important in the development of damping and vibration-absorbing coatings intended for operation under cyclic-loading conditions.

An analysis of the literature indicates that optimisation of the properties of flame-sprayed composite coatings requires a compromise-based approach. Maximum reduction of porosity and increased structural density aimed at enhancing hardness and wear resistance may lead to a deterioration of damping properties and an increase in residual stresses. Conversely, higher porosity and an increased number of interlayer boundaries promote improved damping performance, but are accompanied by reduced mechanical strength and adhesion reliability. In this context, the development of multilayer and graded coatings, in which individual layers perform specialised functions, represents a promising direction.

Recent studies also emphasise the importance of adhesion strength as an integral parameter determining the durability of flame-sprayed coatings. Adhesion is formed through a combination of mechanical interlocking, plastic deformation, and thermal effects at the coating–substrate interface. Control of substrate-surface condition, particles' temperature, and particles' velocity enables targeted enhancement of adhesion and reduction of the risk of coating delamination during service.

Special attention should be given to the development of *in situ* diagnostic and monitoring methods for the spraying process. The application of optical, pyrometric, and gas-dynamic techniques for measuring particles' temperature and velocity provides opportunities for adaptive process control and improved reproducibility of coating properties. In the long term, such approaches may form the basis for the development of digital twins of flame spraying processes and the integration of artificial intelligence elements into process control.

Recent developments also emphasise the expansion of thermal-spray technologies toward hybrid manufacturing concepts, including integration with additive manufacturing platforms [52]. Furthermore, advancements in warm spraying and modified high-velocity processes demonstrate enhanced control over particles' temperature and oxidation, contributing to improved coating uniformity and performance [53].

Future research directions in the field of flame spraying of composite coatings are associated with deeper investigation of interfacial-interaction physics, the development of novel composite powders with tailored structures, and the creation of functional coatings combining protective, damping, and tribological properties. Of particular interest is the integration of experimental studies with numerical modelling and multiscale analysis of coating structure and properties.

Thus, current trends in the development of flame spraying indicate its transformation from a conventional technological operation into a high-tech, physically controlled process capable of producing coatings with tailored and predictable properties.

10. Conclusions

A systematic analysis of recent studies (2019–2025) of flame spraying of composite coatings is carried out, with an emphasis on the physical mechanisms governing the formation of coating structure and service properties.

It has been shown that flame spraying is a multiphysical process, in which thermal and gas-dynamic parameters of the flame, as well as the physical state of particles at the moment of impact with the substrate, play a key role. Particles' temperature, velocity, and degree of melting determine the formation of splats, interlayer boundaries, and porosity, which, in turn, determine the microstructure of the coating.

It has been established that the microstructure of flame-sprayed composite coatings has a decisive influence on their adhesion strength, mechanical, tribological, and damping properties. Interlayer boundaries and pores, traditionally regarded as structural defects, acquire functional significance in contemporary studies, particularly, in the context of mechanical-energy dissipation and enhanced vibration resistance of coatings.

The analysis of recent publications demonstrates that optimisation of the properties of flame-sprayed coatings requires a comprehensive approach that accounts for the interrelation between spraying parameters, microstructure, and service characteristics. One of the most promising directions for further development is the creation of composite and multi-layer coatings with graded structures, ensuring a balance between strength, adhesion, wear resistance, and damping properties.

It is concluded that the further advancement of flame-spraying technology is associated with the implementation of *in situ* diagnostic methods, numerical modelling, and physically grounded process control. This will enable the transition toward the design of coatings with predetermined properties and expand the application areas of flame-sprayed composite coatings in modern engineering systems.

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tion (Sections 1 and 2). O.M.Zh. analysed literature data and systematised results related to microstructure formation, interlamellar boundaries, adhesion strength, and porosity of flame-sprayed composite coatings (Sections 3 and 4). A.M.S. developed the general concept of the review, analysed functional and damping properties of composite coatings, summarised the physical relationships between process parameters and properties (Sections 5 and 6), and wrote the manuscript with input from all authors. All authors discussed the results, contributed to the interpretation of the data, and approved the final version of the manuscript.

REFERENCES

1. D. Tejero-Martin, Rad M. Rezvani, A. McDonald, and T. Hussain, Beyond traditional coatings: A review on thermal sprayed functional and smart coatings, *Journal of Thermal Spray Technology*, **28**: 598–644 (2019); <https://doi.org/10.1007/s11666-019-00857-1>
2. S. Saber-Samandari and C.C. Berndt, Thermal spray coatings — A technology review, *International Heat Treatment and Surface Engineering*, **4**, No 1: 7–13 (2010); <https://doi.org/10.1179/174951410X12572442577381>
3. V. Lakkannavar, K.B. Yogesha, C.D. Prasad, R.K. Phanden, G. Srinivasa, and S.C. Prasad, Thermal spray coatings on high-temperature oxidation and corrosion applications — A comprehensive review, *Results in Surfaces and Interfaces*, **16**: 100250 (2024); <https://doi.org/10.1016/j.rsurfi.2024.100250>
4. A.D. Pogrebnyak, Yu.N. Tyurin, A.G. Boyko, M.L. Zhadkevich, M.K. Kalyshkanov, and Sh.M. Ruzimov, Electrolytic-plasma treatment and coating deposition on metals and alloys, *Progress in Physics of Metals*, **6**, No. 4: 273–344 (2005); <https://doi.org/10.15407/ufm.06.04.273>
5. H. Assadi, H. Kreye, F. Gärtner, and T. Klassen, Cold spraying - A materials perspective, *Acta Materialia*, **116**: 382–407 (2016); <https://doi.org/10.1016/j.actamat.2016.06.034>
6. R.S. Lima and B.R. Marple, Thermal spray coatings engineered from nanostructured materials, *Journal of Thermal Spray Technology*, **16**: 40–63 (2007); <https://doi.org/10.1007/s11666-006-9010-7>
7. E. Sadeghi, N. Markocsan, and S. Joshi, Advances in corrosion-resistant thermal spray coatings for renewable energy power plants. Part I: Effect of composition and microstructure, *Journal of Thermal Spray Technology*, **28**: 1749–1788 (2019); <https://doi.org/10.1007/s11666-019-00938-1>
8. S. Mariappan, N. Radhika, and B. Saleh, Duplex and composite coatings: a thematic review on thermal spray techniques and applications, *Metals and Materials International*, **29**: 1229–1297 (2022); <https://doi.org/10.1007/s12540-022-01302-9>
9. X. Wang, W. Zhao, T. Shi, L. Cheng, S. Hu, C. Zhou, L. Cui, N. Li, and P.K. Liaw, A Review on tribological wear and corrosion resistance of surface coatings on steel substrates, *Coatings*, **15**, No. 11: 1314 (2025); <https://doi.org/10.3390/coatings15111314>
10. S.T. Vagge and S. Ghogare, Thermal barrier coatings: Review, *Materials Today Proceedings*, **56**, No. 3: 1201–1216 (2022); <https://doi.org/10.1016/j.matpr.2021.11.170>

11. L. Ropyak, T. Shihab, A. Velychkovych, O. Dubei, T. Tutko, and V. Bilinskyi, Design of a two-layer Al–Al₂O₃ coating with an oxide layer formed by the plasma electrolytic oxidation of Al for the corrosion and wear protection of steel, *Progress in Physics of Metals*, **24**, No. 2: 319–365 (2023); <https://doi.org/10.15407/ufm.24.02.319>
12. S. Chandra and P. Fauchais, Formation of solid splats during thermal spray deposition, *Journal of Thermal Spray Technology*, **18**, No. 2: 148–180 (2009); <https://doi.org/10.1007/s11666-009-9294-5>
13. G. Mauer and C. Moreau, Process diagnostics and control in thermal spray, *Journal of Thermal Spray Technology*, **31**: 818–828 (2022); <https://doi.org/10.1007/s11666-022-01341-z>
14. B. Rakhadilov, Y. Molbossynov, N. Magazov, D. Kakimzhanov, and A. Kengesbekov, Influence of spraying process parameters on the characteristics of steel coatings produced by arc spraying method, *Coatings*, **14**, No. 9: 1145 (2024); <https://doi.org/10.3390/coatings14091145>
15. M. Saremi and Z. Valefi, The effects of spray parameters on the microstructure and thermal stability of thermal barrier coatings formed by solution precursor flame spray (SPFS), *Surface and Coatings Technology*, **220**: 44–51 (2013); <https://doi.org/10.1016/j.surfcoat.2012.08.019>
16. M.R. Mrdak, Transfer of heat and speed of plasma particles to powder particles in the plasma spray process at atmospheric pressure, *Vojnotehnički Glasnik*, **66**, No. 2: 415–430 (2018); <https://doi.org/10.5937/vojtehg66-12942>
17. Y. Li, X.F. Wang, S. Yin, and S.L. Xu, Influence of particle initial temperature on high velocity impact process in cold spraying, *Procedia Environmental Sciences*, **12**: 298–304 (2012); <https://doi.org/10.1016/j.proenv.2012.01.281>
18. J. Fiebig, J.P. Gagnon, G. Mauer, E. Bakan, and R. Vaßen, In-flight measurements of particle temperature and velocity with a high-speed IR camera during cold gas spraying of In718 and TiAlCrNb, *Journal of Thermal Spray Technology*, **31**: 2013–2024 (2022); <https://doi.org/10.1007/s11666-022-01426-9>
19. K. Bobzin, W. Wietheger, M.A. Knoch, and S.R. Dokhanchi, Estimation of particle mass flow rate in free jet using in-flight particle diagnostics in plasma spraying, *Journal of Thermal Spray Technology*, **29**: 921–931 (2020); <https://doi.org/10.1007/s11666-020-01027-4>
20. G. Mauer and E.J. Gildersleeve, Using optical emission spectroscopy in atmospheric conditions to track the inflight reduction of plasma sprayed TiO_{2-x} feedstock for thermoelectric applications, *Scientific Reports*, **14**, No. 1: 554: 1–15 (2024); <https://doi.org/10.1038/s41598-023-50592-5>
21. W. Wan, W. Li, D. Wu, Z. Zhang, and B. Ning, 3D analysis of gas flow behavior and particle acceleration characteristics in cold spray additive manufacturing based on non-axisymmetric numerical models, *Journal of Thermal Spray Technology*, **29**: 1335–1349 (2024); <https://doi.org/10.1016/j.jmrt.2024.01.204>
22. R. Horr, R. Rebhi, F. Didi, M. Kezrane, A. Alghamdi, Y.T. Zewdie, E. Ali, and S.S.M. Ghoneim, Numerical simulation of dynamic and thermal behavior of plasma jet interacting with substrate, *Results in Engineering*, **27**: 106125 (2025); <https://doi.org/10.1016/j.rineng.2025.106125>
23. S. Datta, D.K. Pratihari, and P.P. Bandyopadhyay, Modeling of plasma spray coating process using statistical regression analysis, *The International Journal of Advanced*

- Manufacturing Technology*, **65**, Nos. 5–8: 967–980 (2013);
<https://doi.org/10.1007/s00170-012-4232-y>
24. A. Fardan, C.C. Berndt and R. Ahmed, Numerical modelling of particle impact and residual stresses in cold sprayed coatings: A review, *Surface and Coatings Technology*, **409**: 126835 (2021);
<https://doi.org/10.1016/j.surfcoat.2021.126835>
25. K. Bobzin, W. Wietheger, H. Heinemann, and F. Wolf, Simulation of thermally sprayed coating properties considering the splat boundaries, *IOP Conference Series: Materials Science and Engineering*, **1147**: 012026 (2021);
<https://doi.org/10.1088/1757-899X/1147/1/012026>
26. S. Sampath and X. Jiang, Splat formation and microstructure development during plasma spraying: deposition temperature effects, *Materials Science and Engineering: A*, **304–306**: 144–150 (2011);
[https://doi.org/10.1016/S0921-5093\(00\)01464-7](https://doi.org/10.1016/S0921-5093(00)01464-7)
27. S.W. Yao, J.J. Tian, C.J. Li, and G.J. Yang, Understanding the formation of limited interlamellar bonding in plasma sprayed ceramic coatings based on the concept of intrinsic bonding temperature, *Journal of Thermal Spray Technology*, **25**: 1617–1630 (2016);
<https://doi.org/10.1007/s11666-016-0464-y>
28. G. Odhiambo, W. Li, Y. Zhao, and C. Li, Porosity and its significance in plasma-sprayed coatings, *Coatings*, **9**, No. 7: 460 (2019);
<https://doi.org/10.3390/coatings9070460>
29. W. Tillmann, O. Khalil, and M. Abdulgader, Porosity Characterization and its effect on thermal properties of aps-sprayed alumina coatings, *Coatings*, **9**, No. 10: 601 (2019);
<https://doi.org/10.3390/coatings9100601>
30. C.R.C. Lima, G. Clavé, V. Crespo, J. Nin, and S. Dosta, Microstructure evolution and oxidation behavior of thermal barrier coating systems with various cold-sprayed bond coats during isothermal high-temperature oxidation tests, *Journal of Thermal Spray Technology*, **35**: 170–182 (2026);
<https://doi.org/10.1007/s11666-025-02120-2>
31. D. Chicot, H. Ageorges, M. Voda, G. Louis, M.A. Ben Dhia, C.C. Palacio, and S. Kosman, Hardness of thermal sprayed coatings: Relevance of the scale of measurement, *Surface and Coatings Technology*, **268**: 173–179 (2015);
<https://doi.org/10.1016/j.surfcoat.2014.04.043>
32. P.M. Araujo, D. Chicot, M.H. Staia, and J. Lesage, Residual stresses and adhesion of thermal spray coatings, *Surface Engineering*, **21**, No. 1: 35–40 (2005);
<https://doi.org/10.1179/174329405X30020>
33. S. Kumar, G. Bae, and C. Lee, Influence of substrate roughness on bonding mechanism in cold spray, *Surface and Coatings Technology*, **304**, No. 2: 592–605 (2016);
<https://doi.org/10.1016/j.surfcoat.2016.07.082>
34. R. Khuengpukheiw, A. Wisitsoraat, and C. Saikaew, Wear behaviors of HVOF-sprayed NiSiCrFeB, WC–Co/NiSiCrFeB and WC–Co coatings evaluated using a pin-on-disc tester with C45 steel pins, *Wear*, **484–485**: 203699 (2021);
<https://doi.org/10.1016/j.wear.2021.203699>
35. I. Abizhanova, A. Kussainov, S. Abdulina, D. Buitkenov, and D. Kakimzhanov, Microstructure and dry-sliding tribology of thermal-spray coatings on Cu for continuous casting molds, *Processes*, **13**, No. 11: 3688 (2025);
<https://doi.org/10.3390/pr13113688>
36. V. Testa, S. Morelli, G. Bolelli, F. Bosi, P. Puddu, A. Colella, T. Manfredini, and L. Lusvardi, Corrosion and wear performances of alternative TiC-based thermal

- spray coatings, *Surface and Coatings Technology*, **438**: 128400 (2022);
<https://doi.org/10.1016/j.surfcoat.2022.128400>
37. A. Vackel and S. Sampath, Fatigue behavior of thermal sprayed WC-CoCr-steel systems: Role of process and deposition parameters, *Surface and Coatings Technology*, **315**: 408–416 (2017);
<https://doi.org/10.1016/j.surfcoat.2017.02.062>
38. N.H. Faisal, R. Ahmed, A.K. Prathuru, A. Paradowska, and T.L. Lee, Measuring Residual Strain and Stress in Thermal Spray Coatings Using Neutron Diffractometers, *Experimental Mechanics*, **62**: 369–392 (2022);
<https://doi.org/10.1007/s11340-021-00803-9>
39. M. Hadad, G. Marot, P. Dmarcaux, D. Chicot, J. Lesage, L. Rohr, and S. Siegmann, Adhesion tests for thermal spray coatings: Correlation of bond strength and interfacial toughness, *Surface Engineering*, **23**, No. 4: 279–283 (2007);
<https://doi.org/10.1179/174329407X215159>
40. G. Prashar and H. Vasudev, A comprehensive review on the analysis of adhesion strength of cold spray deposits, *Results in Surfaces and Interfaces*, **16**, No. 1: 100263 (2024);
<https://doi.org/10.1016/j.rsurfi.2024.100263>
41. T.C. Chen, C.C. Chou, H.E. Lin, T.Y. Yung, C.T. Yang, and Y.W. Tsai, Influence of coating microstructure on the corrosion behavior of Inconel 625 coatings fabricated by different thermal spraying processes, *Surface and Coatings Technology*, **484**: 130674 (2024);
<https://doi.org/10.1016/j.surfcoat.2024.130674>
42. M.D. Akhtar, R.M. Singari, and Q. Murtaza, A critical review of mechanical behavior, cavitation, and metallurgical properties of high-velocity oxygen fuel (HVOF) coating on different materials, *Journal of Adhesion Science and Technology*, **39**: 2577–2627 (2025);
<https://doi.org/10.1080/01694243.2025.2512981>
43. Y. Liu, L. Zhu, G. Ma, Y. Lu, A. Wei, W. Guo, Y. Huang, M. Liu, and H. Wang, Effects of Al₂O₃ content on the microstructure and performance of Inconel 625-xAl₂O₃ composite non-skid coatings by plasma enhanced high-velocity arc spraying, *Surface and Coatings Technology*, **485**: 130929 (2024);
<https://doi.org/10.1016/j.surfcoat.2024.130929>
44. L. Hua, J. Cheng, L. Xue, P. Song, and B. Zhang, Microstructure, wear properties and corrosion resistance of thermal sprayed FeCoCrNiBSi high-entropy amorphous coatings, *Surface and Coatings Technology*, **512**: 132341 (2025);
<https://doi.org/10.1016/j.surfcoat.2025.132341>
45. X. Feng, F. Guo, L. Luo, Y. Wang, Y. Long, X. Zhao, F. Pan, L. Guo, Q. Zeng, J. Feng, and C. Wan, Engineering design of feedstock powder and relevant thermal-mechanical performance of thermal/environmental barrier coatings, *Journal of Advanced Ceramics*, **14**, No. 2: 9221033 (2025);
<https://doi.org/10.26599/JAC.2025.9221033>
46. Yu. Zhou, J. Kang, M. Liu, G. Ma, Q. Zhang, J. Zhang, Q. Peng, R. Gao and H. Wang, Intelligent thermal spraying: A comprehensive review of innovation driven by AI and machine learning, *Materials Today Communications*, **49**: 113804 (2025);
<https://doi.org/10.1016/j.mtcomm.2025.113804>
47. D. Kumar, A.K. Ansari, S.K. Singh, R.S. Walia, P. Singh, and Q. Murtaza, Investigating the characterization and damping effects in thermally sprayed Al₂O₃–40%TiO₂ ceramic coating, *Proceedings of the Institution of Mechanical Engineers, Part E: Journal of Process Mechanical Engineering*, March 27 (2025);
<https://doi.org/10.1177/09544089251329708>

48. G. Jin, G. Chen, Z. Zhao, Z. Zhao, L. Liu, and J. Qian, Preparation of a superior damping coating and study on vibration damping properties, *SN Applied Sciences*, **5**, No. 8: 220 (2023);
<https://doi.org/10.1007/s42452-023-05451-3>
49. A.M. Limarga, T.L. Duong, G. Gregori, and D.R. Clarke, High-temperature vibration damping of thermal barrier coating materials, *Surface and Coatings Technology*, **202**, Nos. 4–7: 693–697 (2007);
<https://doi.org/10.1016/j.surfcoat.2007.07.021>
50. K. Xiao, H. Bai, X. Xue, and Y. Wu, Damping Characteristics of Metal Rubber in the Pipeline Coating System, *Shock and Vibration*, **7**: 1–11 (2018);
<https://doi.org/10.1155/2018/3974381>
51. G. Gupta, R.K. Tyagi, S.K. Rajput, and R. Maan, Review on thermal spray coating methods and properties of metal-based coatings, *Advances in Engineering Materials. Lecture Notes in Mechanical Engineering Advances in Engineering Materials. Select Proceedings of FLAME 2020* (Eds. B.P. Sharma, G.S. Rao, S. Gupta, P. Gupta, and A. Prasad) (Singapore: Springer: 2020), p. 427–439 (2020);
https://doi.org/10.1007/978-981-33-6029-7_40
52. A. Raj, Thermal spray technologies in additive manufacturing: a comprehensive review of techniques and industrial applications, *International Journal of Innovations in Science*, **4**, No. 2: 259–266 (2025);
<https://doi.org/10.69968/ijisem.2025v4i2259-266>
53. K. Anusha, A review on advancements in warm spraying and related thermal spray methods, *Materials Today: Proc. Springer*, **5**: 233 (2025);
<https://doi.org/10.1007/s43939-025-00416-2>

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СУЧАСНИЙ СТАН ТЕХНОЛОГІЇ ГАЗОПОЛУМЕНЕВОГО НАПИЛЕННЯ КОМПОЗИТНИХ ПОКРИТТІВ У СВІТОВІЙ ПРАКТИЦІ

В огляді наведено систематичний аналіз останніх досліджень (2019–2025 рр.) стосовно газополуменевого напилення композитних покриттів з акцентом на фізичні механізми, що лежать в основі формування структури та експлуатаційних властивостей. Газополуменево напилення розглядається як складний мультифізичний процес, що охоплює взаємопов'язані явища тепло- і масообміну, газодинаміки, фазових перетворень і механічної деформації частинок під час їх взаємодії з підкладкою. Аналіз показує, що фізичний стан частинок, а саме температура, швидкість і ступінь топлення, відіграє вирішальну роль в утворенні бризок, розвитку міжшарових меж і зміні пористості, які в сукупності визначають мікроструктуру покриттів, одержуваних методом полуменевого напилення. Показано, що мікроструктура є ключовою сполучною ланкою між технологічними параметрами і макроскопічними властивостями, такими як адгезійна міцність, механічна та трибологічна характеристика, демпфувальна здатність і втомна довговічність. Особливу увагу приділено функціональній ролі міжшарових меж і пор, які, крім того, що є структурними дефектами, слугують основними джерелами внутрішнього тертя і розсіювання механічної енергії під час циклічного і динамічного на-

вантаження. Висвітлено неминучі компроміси між твердістю, зносостійкістю, надійністю зчеплення, залишковими напругами і демпфувальними властивостями, що свідчить про необхідність фізично обґрунтованого компромісного підходу до проектування. Перспективи подальшого розвитку технології газополуменевого напилення розглянуто в контексті діагностики на місці, чисельного моделювання, багатомасштабного аналізу та управління процесами на основі фізичних даних. Ці підходи уможливають перехід від емпіричного вибору параметрів до прогнозованого проектування композитних і багатошарових покриттів з індивідуальними і відтворюваними властивостями, розширюючи область застосування покриттів, що наносяться методом полуменевого напилення, в сучасних інженерних системах з точки зору фізичної науки.

Ключові слова: газополуменеве напилення, композиційні покриття, формування мікроструктури, теплофізичні та кінетичні процеси, адгезійна міцність і пористість.