High-Velocity Oxygen Fuel (HVOF) Reinforcement of Amorphous Materials: A Pathway to Superior Wear and Corrosion Resistance

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Abstract: *The escalating demand for advanced structural materials with superior wear and corrosion resistance in aeronautical and military applications has spurred interest in amorphous alloys, particularly metallic glasses, due to their non-crystalline atomic configurations and exceptional mechanical properties. High-Velocity Oxygen Fuel (HVOF) spraying, a high-performance thermal spray technology, has emerged as a robust solution for enhancing the surface integrity of these materials by delivering dense, well-bonded coatings. This study investigates the integration of HVOF in reinforcing amorphous materials, with a specific focus on augmenting wear resistance under extreme mechanical stresses and improving corrosion protection in hostile environments. Key parameters such as particle velocity, flame temperature, and spray distance are analyzed to optimize coating quality while preserving the amorphous phase. The article delves into the microstructural evolution during deposition, assessing the resultant performance improvements through empirical data and computational models. Findings indicate that HVOF reinforcement significantly enhances the operational longevity of amorphous materials, positioning them as viable candidates for high-stress, corrosive conditions in military aviation, defense systems, and aerospace components.*

Key Words: *HVOF, amorphous materials, metallic glasses, wear resistance, corrosion resistance, thermal spray, coatings*

1. INTRODUCTION

Amorphous materials, particularly metallic glasses, have gained significant attention in recent decades due to their unique atomic arrangement and superior material properties. Unlike crystalline metals, metallic glasses possess a disordered atomic structure that lacks long-range periodicity, as can be seen in Fig. 1, which gives rise to their remarkable characteristics such as high strength, hardness, and excellent corrosion resistance.

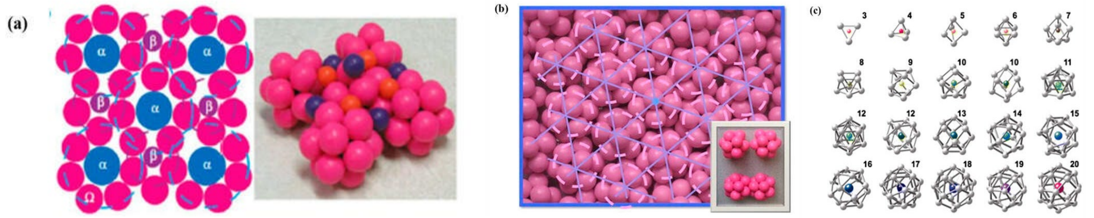

Fig. 1 The dense group structure model of amorphous alloys describes the arrangement of atoms in a non-crystalline solid. (a) The basic structural unit of this model is a tightly packed atomic cluster, often centered around a central atom, surrounded by other atoms in a specific geometric arrangement. (b) These groups may be organized into a tight hexagonal (HCP) structure. (c) Some clusters exhibit configurations that allow them to pack more efficiently, with coordination numbers indicated by numerical values [1]

These properties are particularly advantageous in demanding industrial applications, including aerospace, automotive, and biomedical sectors, where both mechanical performance and durability are critical (see Fig. 2). However, their inherent brittleness, which can lead to catastrophic failure under stress, presents a major challenge in broader industrial applications. Metallic glasses, formed via rapid solidification, exhibit a combination of metallic and glass-like properties, including high wear resistance, making them attractive for environments where materials are subjected to significant mechanical and corrosive stresses. For instance, aerospace components benefit from their lightweight and high-strength properties, while their corrosion resistance makes them ideal candidates for marine and biomedical applications where environmental durability is paramount [2].

Fig. 2 Practical applications of metallic glasses span a wide range of industries: (a) Guitar pins, (b) Earphones, (c) Solar Wind Collector, (d) Phone hinge, (e) Latch cover for TESLA doors, (f) Complex micro gears, (g) Coil springs [3, 4]

Despite these advantages, the practical adoption of metallic glasses has been somewhat limited due to their brittle nature at room temperature, leading to unpredictable failure modes under tensile loads. Overcoming this limitation remains a critical focus for advancing the technology. One pathway to mitigate these issues involves advanced processing techniques, such as High-Velocity Oxygen Fuel (HVOF) spraying, which can create robust coatings that preserve the unique properties of metallic glasses while enhancing their durability [5].
The goal of ongoing research is to optimize the balance between strength and toughness in metallic glasses, expanding their utility in more extreme environments, particularly in

aeronautical and military applications where failure can have severe consequences. This is vital for the development of next-generation materials for aircraft components, propulsion systems, and defense equipment, where high performance and reliability are non-negotiable.

One approach to overcoming these limitations is to apply protective coatings that enhance the surface properties of these materials. The High-Velocity Oxygen Fuel (HVOF) thermal spray technique has emerged as a promising method for this purpose. HVOF allows the deposition of dense coatings with low porosity and excellent adhesion, crucial for wear and corrosion resistance applications. This article reviews the potential of HVOF to reinforce amorphous materials, focusing on its impact on mechanical properties, wear behavior, and corrosion resistance.

2. METHODS AND MATERIALS: HIGH-VELOCITY OXYGEN FUEL (HVOF) SPRAYING

HVOF is a thermal spray process that utilizes a mixture of oxygen and fuel gases (e.g., hydrogen, kerosene, or propane) to produce a high-temperature, high-velocity flame. The material to be deposited, typically in powder form, is injected into this flame, where it partially melts and is accelerated toward the substrate at supersonic speeds, which can be seen in Figure 3. Upon impact, the particles form a coating layer through rapid solidification.

The key advantage of HVOF is its ability to produce coatings with superior bonding strength, low porosity, and high hardness due to the high particle velocities and relatively low flame temperature compared to other thermal spray processes. These characteristics make HVOF an attractive method for applying wear- and corrosion-resistant coatings, particularly on amorphous materials.

The High-Velocity Oxygen Fuel (HVOF) process is a thermal spray coating technique that uses a mixture of oxygen and fuel gases (such as propane, hydrogen, or kerosene) to produce a high-velocity, high-temperature flame. The coating material, typically in powder form, is injected into this flame, where it is partially melted and accelerated to supersonic speeds before being deposited onto a substrate. As these particles impact the substrate surface, they rapidly solidify, forming a dense, well-adhered coating.

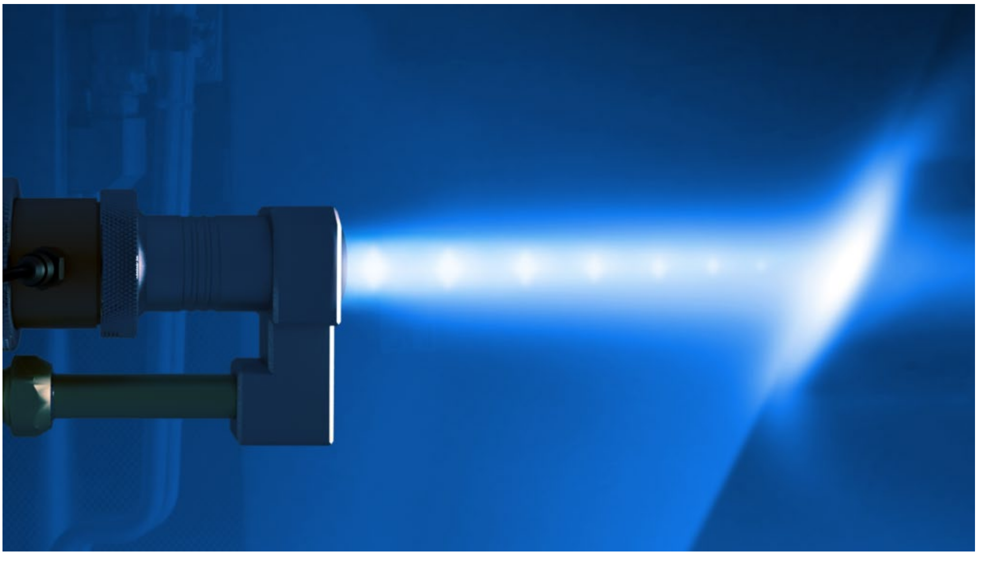

Fig. 3 The spray flame hits the substrate in the HVOF spraying process [6]

One of the primary advantages of the HVOF process is its ability to produce coatings with superior mechanical properties. The high particle velocities and relatively lower process temperatures, compared to other thermal spray methods, allow the formation of coatings with excellent bonding strength, low porosity, and high hardness. These attributes make HVOF coatings highly effective in enhancing wear and corrosion resistance, which is especially valuable in demanding applications such as aerospace, automotive, and military equipment.

HVOF is particularly beneficial when applied to amorphous materials, such as metallic glasses, which have unique disordered atomic structures. These materials offer high strength and corrosion resistance but are often brittle. The HVOF process can improve their surface properties by depositing a coating that enhances durability without significantly altering the substrate's thermal characteristics, making them suitable for environments that require extreme wear and corrosion protection, such as in turbine blades or engine components in aviation and defense sectors.

Furthermore, the low porosity of HVOF coatings reduces the likelihood of corrosive agents penetrating the surface, significantly improving corrosion resistance in harsh environments. This makes HVOF a preferred technique for applications where both mechanical durability and chemical resistance are critical.

Overall, the HVOF process is widely adopted in industries requiring high-performance materials, such as aerospace and defense, due to its ability to produce coatings that meet stringent operational demands. Studies have shown that coatings like tungsten carbide-cobalt and chrome carbide-nickel chrome, often applied using HVOF, deliver excellent wear resistance and protection in high-stress environments

3. HVOF REINFORCEMENT OF AMORPHOUS MATERIALS

The HVOF process facilitates the formation of an amorphous phase due to the rapid cooling rates (up to 10^7 K/s) that prevent crystallization. The resulting coatings primarily consist of an amorphous structure, which is crucial for achieving desirable properties such as high hardness and corrosion resistance [7, 8].

3.1 Processing Parameters and Their Impact

The HVOF process offers fine control over several critical parameters, including:

- Particle velocity: Higher velocities result in better coating adhesion and reduced porosity.
- Flame temperature: Lower flame temperatures help preserve the amorphous structure of the materials, which is essential for maintaining their desirable properties.
- Spray distance: Optimal distances prevent excessive heating or cooling, influencing the coating's microstructure.

In the case of amorphous materials, maintaining the disordered atomic structure during the HVOF process is crucial. Excessive heat during spraying can lead to crystallization, which would diminish the material's inherent advantages. By carefully tuning the HVOF parameters, it is possible to deposit coatings while preserving the amorphous state.

Influence of Spray Parameters: The optimization of spray parameters, such as kerosene flow, oxygen flow, and spray distance, plays a crucial role in enhancing the wear resistance of the coatings. The study indicated that the coatings prepared under optimal conditions not only had lower porosity but also demonstrated better mechanical properties, which are essential for wear resistance.

The study made by Han Zhang, Yong Hu, Guoliang Hou in article The effect of high-velocity oxy-fuel spraying parameters on microstructure, corrosion and wear resistance of Fe-based metallic glass coatings regarding the relationship between spraying power and amorphous phase content in the coatings are as follows [9]:

- Initial Increase and Subsequent Decrease: The amorphous phase content initially increases with spraying power but declines at higher levels due to the interplay between melting and oxidation degrees of the feedstock powder, along with thermal radiation effects.
- Melting State Dependency: Low spraying power results in inadequate melting of the feedstock, leading to lower amorphous phase content due to crystallization. Conversely, intermediate spraying power enhances melting, increasing the amorphous phase content.
- Impact of High Spraying Power: Very high spraying power can cause localized overheating and crystallization, reducing amorphous phase content. It may also lead to greater selective oxidation of the feedstock, further hindering amorphous phase formation [10, 11].

In conclusion, there exists an optimal spraying power range that maximizes amorphous phase content, which is essential for improving the coatings' properties. Overall, the findings suggest that there is an optimal range of spraying power that maximizes the amorphous phase content, which is crucial for enhancing the properties of the coatings.

3.2 Microstructural Evolution During HVOF Spraying

The microstructure of amorphous materials during HVOF processing is significantly influenced by the spray conditions. Studies have shown that rapid solidification following particle impact can help maintain the amorphous phase in the deposited layer. The high cooling rates associated with HVOF promote the formation of a fine microstructure with minimal crystallization.

The coatings typically exhibit a lamellar structure, where individual molten droplets (splats) are deposited and solidified upon impact with the substrate. The degree of splat stacking and the presence of defects, such as pores and oxides, are influenced by the spraying parameters. Higher spraying power results in better melting and more compact stacking of splats, enhancing the overall microstructure [12].

Oxide Formation: The interaction between the molten feedstock and the surrounding oxygen can lead to the formation of oxide strings around the splats. The number of these oxide strings tends to increase with higher spraying power, indicating a stronger interaction between the spraying powders and oxygen.

Microhardness: The microhardness of the coatings is also affected by the spraying parameters. Higher spraying power generally leads to increased microhardness due to improved splat-to-splat binding and reduced porosity, contributing to better wear resistance.

The microstructure of amorphous materials during HVOF spraying is characterized by an amorphous phase, reduced porosity, a lamellar splat structure, and variations in oxide formation, all of which are influenced by the spraying parameters. These microstructural features play a significant role in determining the mechanical and corrosion resistance properties of the coatings.

Moreover, the inherent high hardness of amorphous materials is further enhanced through the dense microstructure and low porosity achieved by the HVOF process. This contributes to improved wear resistance and durability, particularly in abrasive and erosive environments.

By optimizing HVOF spray parameters not only reduces porosity but also significantly enhances the corrosion resistance of iron-based amorphous coatings, making them a viable alternative to traditional coatings like hard chromium.

3.3 Wear Resistance

Wear resistance is one of the most critical factors for extending the lifespan of engineering components. Amorphous materials, due to their high hardness, already exhibit superior wear resistance compared to conventional crystalline alloys. The application of HVOF coatings further improves this property by providing a hard, dense, and well-adhered surface layer that can withstand mechanical stresses during operation.

The study on high-velocity oxygen-fuel (HVOF) sprayed iron-based amorphous coatings also addresses wear resistance, highlighting several important findings:

- Enhanced Wear Resistance: The iron-based amorphous coatings produced through optimized HVOF spray parameters exhibited improved wear resistance compared to traditional coatings. The dense structure and low porosity of the coatings contribute to their ability to withstand wear under mechanical stress.
- Comparison with Other Coatings: The wear resistance of the HVOF sprayed iron-based amorphous coatings was compared to that of other materials, such as cold work die steel. The results showed that the amorphous coatings outperformed these traditional materials in terms of wear resistance, making them suitable for applications where durability is critical.
- Mechanisms of Wear Resistance: The mechanisms contributing to the wear resistance of the coatings include their high hardness and the absence of microstructural defects that can lead to failure under wear conditions. The amorphous structure provides a uniform distribution of properties, which enhances the overall performance of the coatings in abrasive environments [13].

In summary, the research indicates that HVOF sprayed iron-based amorphous coatings possess superior wear resistance due to their optimized spray parameters, dense microstructure, and amorphous phase characteristics, making them advantageous for various industrial applications.

Experimental studies have demonstrated that HVOF coatings of amorphous materials exhibit significantly lower wear rates in dry sliding and abrasive conditions compared to bulk counterparts. The dense coating microstructure effectively resists material loss, while the inherent hardness prevents surface damage from wear mechanisms like plowing or micro-cutting.

3.4 Corrosion Resistance

The corrosion resistance of amorphous materials arises from their lack of grain boundaries and chemical homogeneity. When applied via HVOF, these materials form coatings that provide excellent protection against corrosive environments, particularly in aggressive industrial settings like marine and chemical processing industries.

Porosity and Corrosion Resistance: The study found that coatings with lower porosity demonstrated better corrosion resistance. This is because higher porosity can lead to increased pathways for corrosive agents to penetrate the coating, thereby compromising its protective qualities. The electrochemical tests indicated that the iron-based amorphous coatings prepared with optimal parameters outperformed hard chromium coatings in terms of corrosion resistance [14].

Electrochemical Evaluation: The corrosion resistance was assessed using potentiodynamic polarization and electrochemical impedance spectroscopy (EIS). The results showed that the iron-based amorphous coatings had superior electrochemical properties compared to hard chromium coatings, indicating their effectiveness in corrosive environments [15].

4. CHALLENGES AND FUTURE PERSPECTIVES

Despite the promising results of HVOF-reinforced amorphous materials, several challenges remain. The main challenge lies in controlling the thermal input during spraying to prevent crystallization while ensuring sufficient melting for good particle adhesion. Additionally, the optimization of process parameters for different amorphous material compositions is critical for maximizing performance.

Future research directions could focus on:

- Hybrid coating systems: Combining amorphous materials with other reinforcing phases, such as ceramics or carbides, to enhance toughness without compromising wear or corrosion resistance.
- Advanced modeling techniques: To predict the behavior of amorphous materials during the HVOF process and guide the optimization of parameters.
- In-situ diagnostics: To monitor the structural evolution during coating formation and provide real-time feedback for process control.

5. CONCLUSIONS

The High-Velocity Oxygen Fuel (HVOF) spraying technique offers a viable pathway for reinforcing amorphous materials, significantly improving their wear and corrosion resistance. By carefully controlling processing parameters, HVOF can deposit dense, well-adhered coatings while preserving the beneficial properties of amorphous materials. This opens up new opportunities for the application of these materials in demanding industrial environments. Further research is needed to fully unlock the potential of HVOF for amorphous materials, particularly in optimizing process parameters and exploring hybrid coatings.

Amorphous materials reinforced through the HVOF technique represent a significant advancement in material science, offering exceptional properties that are highly beneficial for aeronautical and military applications. Their ability to withstand extreme conditions, combined with the protective capabilities of HVOF coatings, makes them ideal for use in critical components and systems. Continued research and development in this field will likely lead to further enhancements in the performance and applicability of these advanced materials.

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