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Novel HVAF Coatings for Tribological Behaviour – A Review

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Abstract

The future scope of work lies in the development and comprehensive assessment of advanced coatings to resist wear, corrosion and abrasion of engineering components in harsh environments. Among them, thermal spray especially HVAF coatings occupy an important place in coating huge and complex parts which become techno-economically viable. Such exercise may not be possible in the traditional coating procedures including the powder metallurgy route. In general, a choice of the spray process, material selection, and design is as significant to benchmark thermal spray coatings. In most cases, thermally sprayed hard metal coatings are mechanically attached to substrates with thicknesses ranging from 100 to 500 microns. The current study gives an overview of the literature concerning HVAF coatings for tribological applications. It comprises HVAF coating developments and mechanisms followed by their application to different types of tribological performance such as sliding wear, erosion, abrasion, fretting and corrosion. HVAF coatings override other thermal spray coatings including HVOF and offer distinct advantages with respect to adherence and strength coupled with hardness so as to have strong resistance to wear, and corrosion integrated with deformation. The ingredients used in the process like metal carbides and metal alloys coated with combustible powders have a particle size in the range of a few nanometers to 60 microns. The researchers are now concentrating on the development and recognition of dense HVAF coatings so that they perform reliably and suitably in the field with good attributes. This article covers in-depth the deployed materials which are suitable for the HVAF process followed by an evaluation of physical, chemical, mechanical, and metallurgical characterization with the main focus on adhesive, abrasive, erosive, fretting and corrosive wear phenomena.

Keywords: *Wear, High Velocity Air Fuel (HVAF), Scanning Electron Microscope, Surface roughness, Hardness.*

1.0 Introduction

The term 'Thermal Spray' refers to a range of coating methods applied to metals or nonmetallic surfaces. In the engineering field, coatings and surface modification technologies can be used to extend the life, improve the performance, and improve the aesthetics of materials used to make engineering components. Several technologies have been created to prevent components from degrading or failing as a result of exposure to other components, liquids and/or gaseous environment. Technology to apply coatings selectively improve component performance by conducting certain

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functions without compromising the benefits of the underlying material. The three main approaches are flame sprays, electric arcs and plasma arcs. These energy sources are used to heat thin film substances (in powdered, wire or rod form) to a melted or semi-molten state. Atomization jets or process gases accelerate and propel the hot particles toward the prepared surface. The bond forms with the surface as a result of impact, increasing the thickness and producing a lamellar structure. The thin "splats" are cooled at extremely fast rates, usually in excess of 106 K/s for metals[1]. In recent years, several researchers have explored an improved thermal spray coating on metals, ceramics, metallic amorphous and cermets to protect various components (mechanical, electrical and civil) where the emphasis is on surface contact scenarios such as severe erosion, corrosion and wear. High Velocity Air-Fuel, sometimes known as HVAF, is a thermal spray method used to coat components, vessels and structures to protect them against, erosion and abrasion. HVAF coatings are similar to and usually comparable to HVOF and Cold Spray coatings. The HVAF technique is a "warm spray," making it hotter than the cold spray, but cooler than a HVOF. HVAF cannons fire an air-fuel jet with axial powdered infusion at a rate of roughly 1900-1950ºC. As a result, HVAF can be effectively used in the application of carbide-based materials, but because air-fuel jets produce almost no oxides compared to high-temperature oxy-fuel jets, it can also be used in the application of metals with almost no oxidation, similar to cold spray. All conventional thermal spray powder materials can be applied using HVAF except ceramics. It is appropriate to gradually heat metal and cemented carbide feedstock particles up to or slightly over the melting point of the metal at the lower temperature. When compared to any other HVOF coating process, HVAF technique has a 5-fold lower starting oxygen percentage in the combustion gas mixture. Both variables prevent oxidation of metals and decomposition of carbides. Spraying affects the chemical composition, phase composition, coating formation, and microstructure. In order to meet the European Commission's standard for particle emissions of matter less than 10 microns, coatings that are resistant to sliding wear are particularly important for brake disc applications[2]. Recent years have seen a great deal of attention and interest focused on the development of innovative Fe-based amorphous coatings that have low friction and excellent wear resistance. In terms of wear resistance, crystalline steels (CSs), hard Cr and Al_2O_3 coatings fail to compare with Fe-based amorphous coatings because of their high hardness and reduced Young's modulus[3,4]. Wear in high-temperature conditions is an inevitable and intricate process that affects a large number of sectors, as some of the moving components[5,6]. Temperature affects three key tribological characteristics in general: bulk properties, reactivity and the tendency to create tribo-layers[7]. In addition to producing highly adherent coatings with minimal porosity, HVAF spraying produces minimal thermal 'damage' via oxidation, decarburization, when compared to other thermal spraying processes[8]. As a result of the higher particle velocity on impact, supersonic HVAF spray coating produces coatings with low porosity (<1%) and offers alternatives to current state-of-the-art approaches[9,10]. There is a significant economic impact of wear failures on the engineering sector worldwide[11]. In order to reduce the operating cost, overhaul frequency and/or component replacement can be reduced. In most cases, wear of components is closely correlated to cost of operation. There is a constant interest in alternative coatings for this purpose because efforts are being made to find better solutions for extending the durability and improving the performance of wear-prone components[12]. Currently, thermal spray coating technologies are used in production to reduce mechanical wear effects and increase product life, and will be used in the future for more demanding applications. If a material is required for an automotive piston ring, its main purpose should be to enhance or prolong the lifespan of an uncoated ring. The most typical wear functions and samples of thermal spray coating applications are shown in Table 1. It is necessary to examine other considerations when determining the optimal material for a specified task. The material cost, deposition rate, finishing specifications, coating thickness, component shape and equipment accessibility are the more crucial aspects to consider. Thermal spray solutions are used in a variety of industries, including aviation, agriculture, maritime, metalworking, papermaking, publishing, compressors, actuators, electronic parts, computer systems, petrochemical products, geothermal power, nuclear power, utility services, sport, armed services, offshore drilling platforms, refineries, railroad, motorcars and diesel. Thermal spray coatings properties are determined by their microstructure, which is impacted both by the materials and the deposition method.

Despite using materials with the same chemistry, coatings may have profoundly different properties. A large variety of distinct products with "identical chemistry" can be attributed to the varying design requirements enforced by original equipment manufacturers. Size of the particles, homogeneity, crystalline structure and morphology are all elements that affect material quality in relation to the manufacturing technique. As well as affecting application performance, these distinctions can influence the overall product price. Powders with restricted or extremely fine particle distributions, are typically more expensive due to limited manufacturing yields. An application must be selected based on the most relevant attributes, and the business side of coating application should be weighed against the technical benefits. Because of this, large producers have a variety of thermal spray substances in stock. Several methods can be used to create thermal spray materials. In some cases, the techniques are combined with one another. An ideal approach would involve finding a way to deposit materials economically while retaining performance consistency and reliability. Thermal spray technology, a representation of the thermal spray technique derivative is as shown in the Figure 1.

Table 1: [13]

Coating Function	Application	Materials
Abrasive Wear	Cutting Blades Glass Mold Plungers Pump Volute	WC- Co, NiCr, CrC, Cobalt-based Hard facing Alloy, Ni/Co Self-Fluxing Alloy
Sliding Wear	Piston Rings Impeller Shafts Cylinder Bores	Cast Iron-Mo, Mo-based Self-Fluxing Al-TiBabbittCo, Cr, Mo
Impact, Vibratory Fretting Wear	Mid-span Dampers Sucker Rods	WC-Co
Erosion/Cavitation Wear Chrome	Steam Turbine Blades (SPE) Turbine Applications	WC-Co, NiC-Chrome Carbide

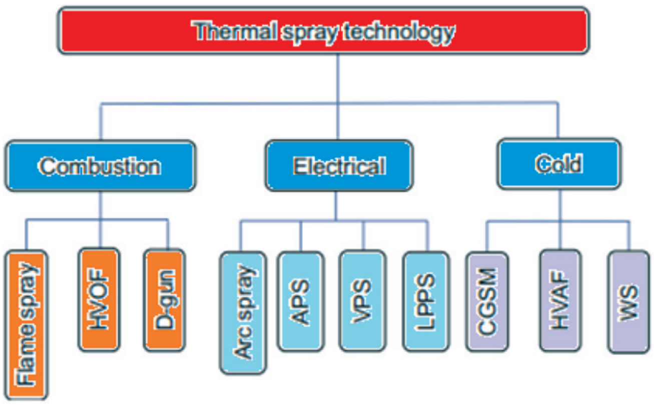

Figure 1: Lineage of the thermal spray technology
*Acronyms stand for HVOF (high-velocity oxygen fuel), D-gun (detonation gun), APS (atmospheric plasma spray), VPS (vacuum plasma spray), LPPS (low-pressure plasma spray), CGSM (cold gas spraying method), HVAF (high-velocity air fuel) and WS (warm spray)

2.0 Literature Review

Dandan Liang[14], examined the microstructure, mechanical characteristics and tribological performance of Fe-Cr-Mo-W-C-B-Y amorphous coatings (ACs) sprayed by active combustion using high velocity air fuel (AC–HVAFs). As the temperature rose from 293K to 673K in vacuum, the Fe-based AC's enhanced hardness encouraged wear resistance. The splat-to-splat link at 673K was weakened by the oxidation reaction, which raised the wear rate of Fe-based AC. In addition, elevated-temperature wear failures were due to delamination, adhesion and intensified oxidation. In addition, AC based on Fe showed improved wear resistance at increased temperatures, indicating that it could be applied as a wear-resistant coating material for high temperatures. Hui Guo[15] investigated the wear characteristics of high-velocity air-fuel sprayed both crystalline and amorphous metal coatings (ASC and SSC, accordingly). In general, the coefficient of friction (COF) of ASC decreased as the load increased from 0.78 to 0.69. With varied normal loads, the COF of SSC showed a modest difference, but it grows with sliding time with high fluctuations. Shear stress and flash temperature may both contribute to such a wide variation in friction behaviour. There is a significant difference in wear rates between SSC and ASC, indicating ASC is more durable. The proportions of Hardness/Young's modulus (H/Er) and Hardness/Young's modulus/Er_2 correlate with wear resistance. Fan Zishuan[16] reported the AC-HVAF spray system (acukote high velocity air-fuel), wear-resistant coatings made of WC-12Co powder with nano WC grains were deposited. Microstructures and phase compositions of the coatings were investigated. Materials were studied for their micro hardness, fracture toughness and wear resistance. X-ray diffraction (XRD) results indicate the predominant phase is WC, and its breakdown products are not present. As a result, the coatings have a solid-state micro hardness ($HV_{0.3}$) of 19 403 MPa on the surface, and a solid-state micro hardness ($HV_{0.4}$) of 17 410 MPa in the cross-section. With a 15 N load and a 1198 r/min rotating of the WC counter body in dry conditions, nano-sized coatings indicate a 40% decrease in average mass loss and a stable friction coefficient of 0.26-0.28 (micron–sized coatings: 0.25–0.4). According to the findings, coatings sprayed with nano-structure WC-12Co have higher wear resistance. Giovanni Bolelli[17] examined Fe-31Cr-12Ni-3.6B-0.6C (wt. %) coatings sprayed with high velocity air-fuel for their tribological characteristics in relation to deposition conditions. In all cases, coatings formed using a higher powder feed rate perform poorly due to reduced interlamellar cohesion. Abrasive grooving causes wear rates to be even off and significantly greater than at room temperature at 700ºC due to extreme abrasion. G. Bolelli[18] provided a detailed analysis of Cr_3C_2–25 wt. % HVOF and HVAF are used to spray NiCr hard metal coatings. In order to prepare two different particle sizes of commercial powder, five HVOF and HVAF thermal spray systems were utilized. Due to the fact that certain Cr_3C_2-rich particles rebound following high-velocity impacts into the substrate, the coatings do not contain as much Cr_3C_2 as that of the feedstock powder. On a dry sand rubber wheel, abrasive wear tests revealed groves and the pull-out of splat fragments. Coatings with coarser feedstock powder or using a specific HVAF torch had increased mass losses in around (70mg) as a result of inter and intra-lamellar cohesion. The degree of intralamellar cohesiveness in alumina sliding wear at room temperature was regulated, leading to shallower abrasive groves, small-scale delamination, and carbide pull – outs. The lowest wear rates ($5x10^{-6}$ $mm^3/(Nm)$) are found in coatings produced from fine feedstock powder[17]. Based on evaluations of the morphology, porosity, hardness and phases, particular spray conditions produce materials with low non-deformed particle contents, high levels of hardness, low porosities and high levels of feedstock phase retention. As-deposited coatings differ significantly in microstructural properties based on processing settings. Tests were conducted on the coatings. The coatings' performance in terms of friction and wear under various load circumstances was tested using a ball-on-disc tribometer. The frictional coefficients of the investigated coatings were similar based on their microstructures. In order to determine the wear mechanisms and material transfer, SEM/EDS analysis was performed on worn coating surfaces, mating alumina ball surfaces, and the wear debris. The paper contributed towards understanding of HVAF processing parameters can be optimized for the creation of acceptable microstructural features and phases in Fe-based coatings for enhanced wear performance. Liu[20] to improve the wear resistance of the Fe-TiB_2 cermet coating, better carbon nanotubes (CNTs) were used for the first time. Initially, a composite feedstock that was composed of TiB_2 and homogenous CNTs could be produced, with each particle being highly dense, spherical, and dense. In order to evaluate the impact of CNTs on coating microstructure and wear behaviour, Fe-based metallic and Fe-TiB_2-cermet coatings were later coated using high velocity air fuel (HVAF). Adding CNTs to the coatings led to a denser coating microstructure, and increasing micro hardness and fracture toughness by 32% and 44%, respectively. This material had the best wear resistance due to its increased tribological properties, low porosity, and fewest wear cracks, with a specific wear rate of $2.47X10^{-6}$ mm^3/N-m. CNTs enhanced coating wear through oxidative and mild abrasive mechanisms rather than severe adhesive wear. Mathiyalagan[21] experimented generating significant large-area tribological coatings on cubic boron nitride (c-BN) particulates in nickel-phosphorus. According to the authors, this is the first time that c-BN (NBN) has been used as an additive to Ni-P coatings. In order to demonstrate the importance of processing properly, two different nozzle designs with significant changes in microstructure, phase analysis, and hardness data were used. To evaluate the coatings' friction and wear characteristics, sliding wear experiments were also performed. The corresponding wear mechanisms are revealed by SEM analysis after wear. Kenneth Holmberg[22] describes the tribological mechanisms of thin coatings in sliding contacts using a systematic approach. Materials transport and macro mechanical, micro mechanical and tribo chemical changes are explored separately. Four primary parameters can be used to systematically study the mechanical interactions that govern tribological: coating-to-substrate hardness, coating thickness, surface roughness, and debris in the contact. According to Holmberg[23], there have been several instances of excellent performance in industrial establishments when friction and wear are controlled. The co-efficient of friction has been decreased in the most effective methods by at least two orders of magnitude, by applying a thin diamond or MoS_2 coating on steel substrate. Usually, a number of orders of magnitude's worth of wear have been concurrently decreased. The best outcomes are typically the product of a trial-and-error process that takes into account both the material choice and coating properties such as penetration depth, toughness and surface roughness. The present wear and friction dynamics of coated surfaces cannot be fully described by an all-encompassing theoretical paradigm at this time. It is possible to design parts and tools using a significant portion of experimental knowledge regarding how coated surfaces respond in tribological interactions.

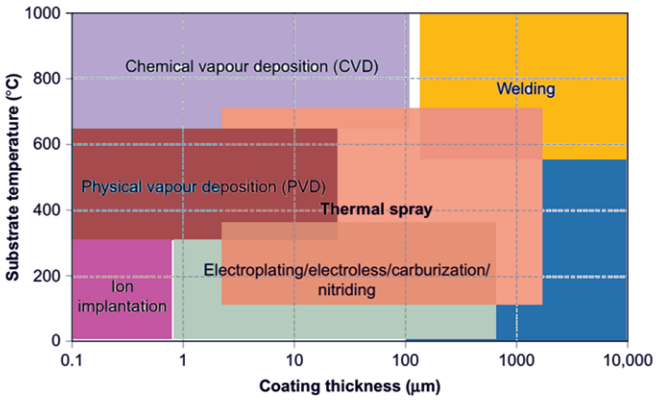

Figure 2: Comparison of the different coating processes in the Commercial market. Adapted from Davis and Davis & Associates (2005)

3.0 Conclusions

A number of researchers have investigated the tribological properties of metallic coatings, such as hardness, porosity, fatigue and residual stress. HVAF is said to be commercially viable since it produces coatings that are well-bonded, wear-resistant and corrosion-resistant. Furthermore, the application of HVAF coating on operating components will prolong their service lives. Additionally, the choice of optimal spray parameters and feedstock powder will influence coating microstructure and performance. Most surface coatings today are alloy mixes that need to improve the substrate according to the characteristics of the coating. As mentioned earlier, coating performance is determined by microstructure, which includes deposits on melted and non-melted particles as well as spray process parameters. This means that when producing crystalline alloy coatings, several factors must be considered, such as the beginning powder's crystalline /amorphous structure, as well as spraying conditions, which have an impact on the amorphous/crystalline phases, a result of heating and cooling processes during the coating process. A combination of the coating's high hardness, high thermal stability, and high corrosion resistance is thought to account for its increased wear resistance. Therefore, in order to determine whether crystallized/ or amorphous coatings are suitable for engineering surface applications requiring high wear resistance, improvements based on alloy coatings need further testing in different wear conditions and environments. A review of the literature and these investigations have lead to the conclusion that thermal spray coating is one of the most important methods of surface modification. The HVAF coating outperforms all other thermal spray coatings such as detonation gun spray, plasma spray, arc spray and flame spray. In the SEM and microstructure analysis, the coating produced by this method was found to have a uniform coating thickness and a continuous layer of coating as it is beneficial.

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