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Effects of Powder Particle Size, Post-Spray Treatment, and Wear Parameters on the Performance of HVOF Coatings: A Review

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Abstract - Thermal spraying is a coating technique applied to mechanical components to enhance their service life by improving erosion resistance, hardness, and corrosion resistance. Among the various thermal spraying processes, high-velocity oxy-fuel (HVOF) coating is a relatively recent development and widely used techniques in this category. This coating produced by HVOF are dense coatings and extends the lifespan of coated components by enhancing properties such as wear, erosion, and corrosion resistance. The purpose of this paper is to review the effects of heat treatment and particle size on the mechanical and wear properties of HVOF coatings, in addition to that the influence of impingement angles and temperature on wear behaviour of HVOF coatings.

Keywords: HVOF coatings, Post spray treatment, temperature, wear

1. INTRODUCTION

Surface degradation due to wear is a major cause of component failure in engineering systems such as turbines, boilers, automotive parts, cutting tools, mining, electric power, agricultural industries, hydraulic machinery and aerospace components [1-8]. Major industrial wear issues are caused by abrasion [9]. By improving the wear resistance of materials, parts can operate more reliably for longer periods, reducing maintenance needs and replacement costs. Thermal spraying is used to enhance the surface properties of components, by depositing coating material in molten or heated state is deposited on the substrate [6, 10, 11]. The coating composition generally includes oxides such as Al_2O_3, Cr_2O_3, TiO_2, ZrO_2 and carbides such as WC, SiC, ZrC, TiC etc [12-15].

A. HVOF Spraying

The HVOF system comprises a spray gun, a powder feed unit, a flow meter unit, and an air and gas supply unit. The required powder is conveyed from the powder feed unit to the gun by means of a carrier gas, where combustion occurs. HVOF produces stronger coatings with superior mechanical integrity. Also HVOF spraying adopted in industrial practice for producing hardmetal coatings better than to plasma-sprayed coatings [16-18]. This paper will review the effect of heat treatment, coating thickness, power size and impact angle on microstructure, mechanical properties and tribiological properties of coating produced by HVOF technique. The effect of impact angle, temperature during erosion test will be discussed in last part of the paper.

II. INFLUENCE OF POST-TREATMENTS AND PARTICLE SIZE ON HVOF SPRAY COATING PROPERTIES

Spray parameters strongly influence coating microstructure and performance. Higher particle velocities generally result in denser coatings with improved wear resistance. Excessive flame temperature, however, can increase oxidation and phase decomposition.

A. Post spray treatments

Post-spray treatments such as heat treatment, laser remelting, or sealing have been employed to enhance coating properties. Heat treatment decrease residual stresses, improve carbide–matrix bonding, and enhance wear and mechanical performance. Effect of heat treatment process on microhardness and wear resistance of coating are presented in Fig. 1 and Fig. 2. Zhou et al. studied the outcome of nitriding on AlxCoCrFeNi high-entropy alloy HVOF sprayed coatings. After nitriding microhardness of the coatings increases from 479 to 981 HV. The AL contents and nitride play excellent role in enhancing the wear resistance of coating [2]. Guo et al. examined the microstructure, mechanical performance, and tribological behavior of CoMoCrSi coatings produced by high-velocity oxygen fuel spraying, both in the as-sprayed condition and after annealing at 800 °C. Following heat treatment, the coating showed a 13.3% increase in surface microhardness and a 12.5% improvement in adhesive strength. The annealed coating also developed a dense oxide layer composed mainly of Cr_2O_3, Co_3O_4, MoO_3, and $CoMoO_4$. This compact oxide layer enhanced hardness and improved wear behavior. Overall, annealing at 800 °C was found to significantly enhance the HVOF-sprayed CoMoCrSi coatings performance [19]. Stewart and co-authors developed WC–17 wt% Co coatings on steel substrates using a spraying process and subsequently subjected them to heat treatments ranging from 250 to 1100 °C. Temperatures above 600 °C led to notable phase transformations within the coatings. Wear testing showed that heat-treated coatings exhibited improvements of up to 35% observed even after heat treatment at 250 °C [20].

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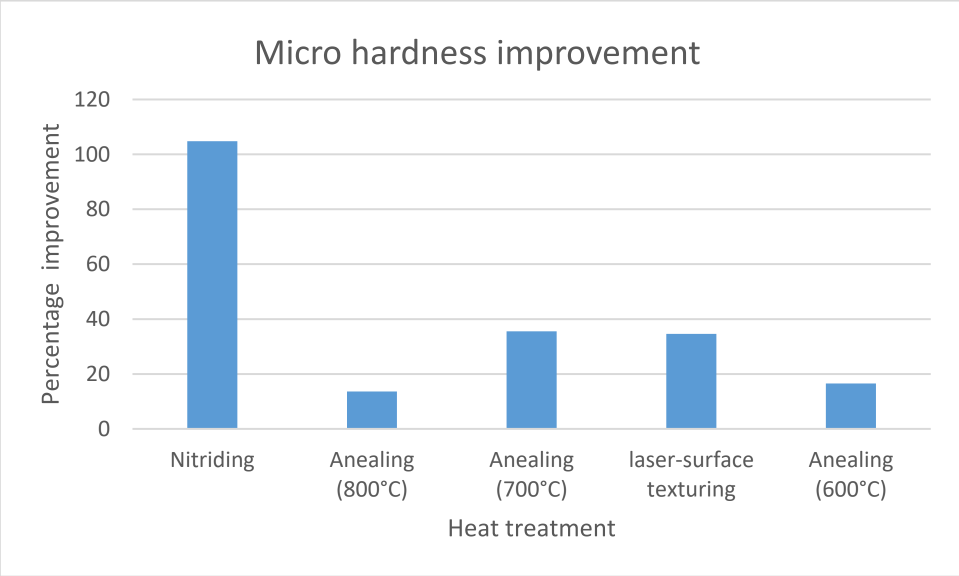

Fig. 1 Effect of heat treatment processes on micro hardness

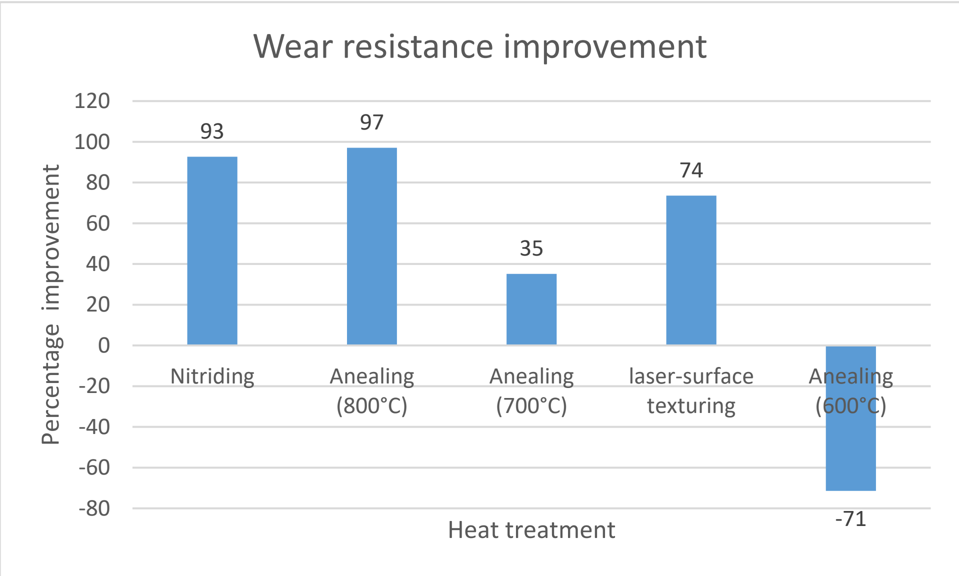

Fig. 2 Effect of heat treatment on wear resistance of coatings produced by HVOF [2, 19-22]

Daniel et al. applied HVOF-sprayed Cr_3C_2–25%NiCr coatings with different thicknesses onto VACO180 steel substrates and investigated their impact behaviour and impact lifetime. The coating thickness had a strong influence on impact lifetime, whereas surface roughness had no significant effect. Among the coatings studied, the one with a thickness of 220 µm exhibited the longest impact lifetime [23]. Sassatelli et al. deposited gas-fuelled HVOF-sprayed Stellite-6 coatings on AISI 304 stainless steel and showed that coating microstructure and phase composition depend on the fuel–oxygen equivalence ratio. Fuel- rich conditions produced dense coatings with low porosity, while oxygen-rich conditions resulted in more porous coatings with poor corrosion protection. During wear testing at 800 °C, a dense glaze tribofilm formed, which enhance coating tribiological strength [24]. Chen et al. investigated the wear behaviour of an $Al_{0.6}$TiCrFeCoNi high-entropy alloy coating deposited by high-velocity oxygen fuel spraying. The outcomes exhibited that the wear behaviour of the coating varied markedly with increasing test temperature. Abrasive wear was the dominant mechanism across all temperatures. At 500 °C, tribochemical reactions became significant, leading to the formation of a compact oxide layer on the wear track. This oxide layer acted as a solid lubricant, resulting in the lowest coefficient of friction at 500 °C [25]. Berger et al. investigated the effects of binder metal type (nickel or cobalt) and chromium addition on HVOF-sprayed WC-based hardmetal coatings. The coatings with cobalt as the binder exhibited improved resistance to erosive wear. However, the wear rate was found to be

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independent of the binder metal type, chromium content, and other coating characteristics such as porosity, hardness, and Young's modulus [17]. Bolelli and co-workers examined Co–28%Mo–17%Cr–3%Si and Ni–32%Mo–15%Cr–3%Si coatings deposited by HVOF, evaluating them in the as-sprayed state and after heat treatment at 600 °C for 1 hour. The heat-treated samples developed fine intermetallic phases at the submicron scale, resulting in increased hardness and elastic modulus. After heat treatment, both coatings demonstrated minimal wear against steel, although abrasive wear persisted when tested against alumina [26].

B. Effect of particle size

This section analysis the effect of power particle size effect on micro structure, mechanical properties and tribiological properties of coatings. Experimental studies analysis the effect of particle size are summarized in table 1. Saharkhiz studied the microstructure and high-temperature performance of NiCoCrAlYTa coatings produced by HVOF spraying, with particular emphasis on optimizing process parameters and evaluating the influence of particle size. The NiCoCrAlYTa powder contained a significant fraction of fine particles (5–38 µm). Due to their high surface-to-volume ratio, these fine particles possess greater surface energy, making them more susceptible to in-flight oxidation during spraying. The study concluded that increasing the particle size range from 5–38 µm to 25–38 µm reduced the oxide content from 7.8% to 1.8%. This reduction was attributed to the fact that smaller particles are exposed to higher temperatures and heat up more rapidly, leading to more severe oxidation while in flight [27].

TABLE 1: EXPERIMENTAL STUDIES REGARDING PARTICLE SIZE

Substrate	Coating	Particle size	Major findings	Ref.
Carbon steel (0.45% C)	WC–12 wt.% Co powders	0.2 to 7.0 µm	fracture toughness increases with increase in WC particle size	[28]
Hastelloy X Ni-based superalloy	NiCoCrAlYTa coating	5–38 μm	Coarse powders formed coatings with dense microstructure and particles with smaller fractions resulted into formation of small unmelted oxide areas in coating.	[27]
AISI 304 stainless steel	WC-CoCr cermet coatings	Micron size and nano size	WC-CoCr cermet coating deposited with nanosized WC grains showed better cavitation erosion resistance	[29]
AISI 304 stainless steels.	WC-10Co4Cr coatings	Micron size and nano size	Multimodal (composed of both micro- and nano-sized) coating has better properties, multimodal WC-10Co4Cr coating, have enhanced erosion resistance	[30]
Mild steel	WC–Co coatings	Micron size and nano size	Nano composite has poor wear resistance than the conventional coating	[31]

III. TEMPERATURE AND IMPINGEMENT ANGLES ON WEAR BEHAVIOR OF HVOF COATINGS

Temperature and impingement angles are the important parameters used test the performance of coating. The effect of heat treatment process on microhardness and wear resistance of coating are presented in Fig. 3 and Fig. 4. Medabalimi et al. examined the erosion behavior of HVOF-sprayed (NiCr) + 5% Si and (NiCr) + 2% C composite coatings under different impact angles and temperatures. The outcomes indicated that the NiCrC coating, containing hard carbide phases such as NiC, provided superior erosion resistance at elevated temperatures and at a normal impact angle (90°), due to its stable microstructure and improved thermal stability. Microhardness measurements exhibited that the NiCrSi coating exhibited higher hardness as a result of silicide phase formation, making it more appropriate for moderate erosive environments. In contrast, although the NiCrC coating had slightly lower hardness, it demonstrated better performance under severe erosive conditions. Notably, at 800 °C, the NiCrC coating outperformed the NiCrSi coating in terms of both thermal stability and erosion resistance, and it exhibited a lower erosion rate compared to that observed at 400 °C [32]. Behera et al. explored the effect of impact angle and temperature on the volumetric erosion loss of WC–Co–Cr coatings containing 10 wt% Mo. The WC–Co–Cr coating exhibited brittle erosion behavior up to 600 °C and transitioned to ductile erosion at 800 °C. In comparison, the WC–Co–Cr/Mo coating showed brittle erosion at 200 °C and a mixed brittle–ductile erosion mode in 400 °C to 800 °C. Across all tested temperatures and impact angles, the volumetric erosion loss of the WC–Co–Cr coating was lesser than WC–Co–Cr/Mo coating [33].

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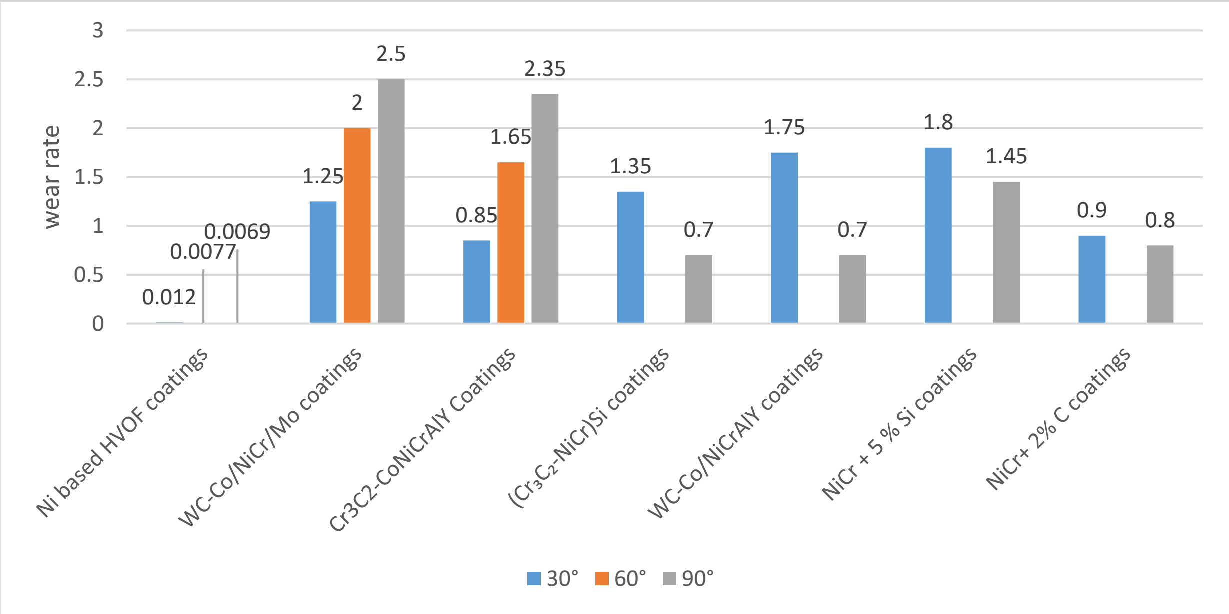

Fig.3 Impingement angles v/s wear rate chart for HVOF spray coatings [32, 34-36]

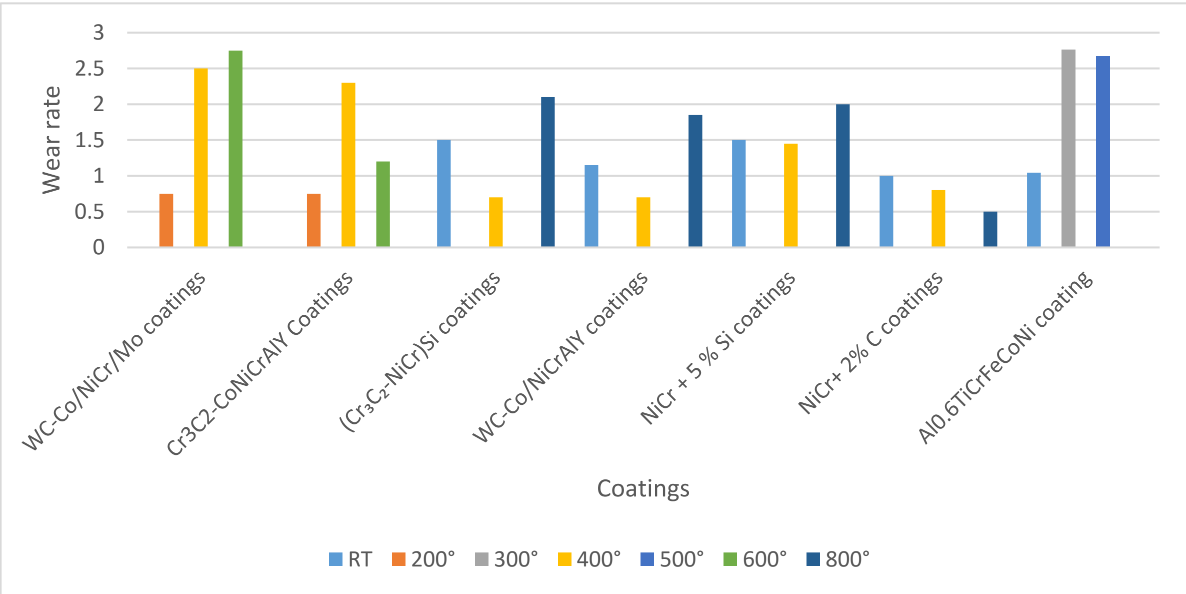

Fig.4 Temperature v/s wear rate chart for HVOF spray coatings [32, 34-36]

Singh et al. examined the erosion behavior of uncoated, HVOF-coated, and cold-sprayed T-91 steel under simulated coal-fired boiler conditions. Nickel powder coatings were deposited on the steel substrate, and erosion tests were performed at impingement angles of 30°, 60°, and 90° with alumina particles as the erodent. The highest weight loss occurred at a 30° impingement angle, decreased at 60°, and was lowest at 90°, which is characteristic of ductile erosion behavior. The results showed that cold-sprayed coatings reduced weight loss by approximately 40–60% [34]. Behera et al. investigated the high-temperature solid particle erosion behavior of WC–Co/NiCr/Mo and Cr_3C_2–CoNiCrAlY coatings deposited using the HVOF process. The outcomes showed that the Cr_3C_2–CoNiCrAlY coating exhibited brittle erosion behavior at temperatures between 200–400 °C and ductile erosion behavior at 600–800 °C. In contrast, the WC–Co/NiCr/Mo coating demonstrated predominantly brittle erosion behavior across both temperature ranges (200–400 °C and 600–800 °C). The as-sprayed Cr_3C_2–CoNiCrAlY coating showed superior erosion resistance compared to WC–Co/NiCr/Mo at all tested temperatures and at impact angles of 30°, 60°, and 90°, including at 800 °C. The brittle erosion behavior of WC–Co/NiCr/Mo at 200–400 °C was attributed to its microstructure consisting of hard particles embedded in a relatively soft binder. As the temperature increased beyond 400 °C, the Mo and Co binders experienced a reduction in strength, leading to a transition from purely brittle erosion to a mixed brittle–ductile erosion mode up to 800 °C [35]. Medabalimi et al. investigated the high-temperature erosion performance of HVOF-sprayed composite coatings on T11 steel substrates, specifically (Cr_3C_2–NiCr)Si and WC–Co/NiCrAlY coatings. The findings revealed that the WC–Co/NiCrAlY coating exhibited superior erosion resistance and oxidation stability across all tested temperatures and impact angles. This improved performance under high-temperature and erosive conditions was attributed to the formation of stable protective oxides, such as Al_2O_3 and Cr_2O_3, as well as intermetallic phases like Ni_3Al and Cr_3C_2. Although the (Cr_3C_2–NiCr)Si coating demonstrated higher microhardness due to the presence of silicide phases, it was more susceptible to direct impacts and showed lower oxidation resistance. Phase transformations occurring at elevated temperatures were beneficial for both coatings, contributing to enhanced erosion resistance. For both coatings, erosion was more severe at a perpendicular impact angle (90°) compared to an oblique angle (30°). Notably, the (Cr_3C_2–NiCr)Si coating experienced greater material loss at 90°[36].

IV. CONCLUSIONS

This paper reviewed the effect of particle size and post spray treatment on the mechanical and tribiological propertietiers of HVOF coating =s along with effect of impingement angles and temperature on the wear. Based on the literature following conclusions are made.

1. Nitriding is the most effective method for improvement in the micro hardness of HVOF coatings followed by annealing and laser surface texturing. Annealing is the most effective method to improve the ear resistance but performance depends upon the annealing temperature and composition of coating.

2. Coarse size particles produce dense coatings along with higher fracture strength. Whereas nano size particles coating generally have low wear resistance compared to micro size particles.

3. Wear rate of coating may increase or decrease with increase in the impingement angle depends upon the composition of coating.

4. Wear rate of coating may increase with increase in the temperature upto 400°C and decease with further increase in temperature.

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