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Influence of Reinforcement on the Mechanical and tribiological behavior of HVOF-Sprayed Composite Coatings: A Review

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***Abstract*-Thermal spraying are popular to apply coatings on industrial machineries such as boilers, turbines, and marine equipment's with an aim to reduce wear and erosion. High-Velocity Oxygen Fuel (HVOF) spraying is a popular thermal spraying method recognized for its ability to produce dense, strongly bonded, and high-quality coatings. HVOF-fabricated composite coatings consist of hard reinforcing phases embedded within a tougher metallic matrix, which enhances resistance to wear, erosion, and mechanical damage in demanding service environments. This review discusses the effect of incorporating reinforcements such as ceramic particles (YSZ, Al_2O_3, TiO_2, SiC), carbides (WC, Cr_3C_2), and carbon-based materials (CNTs, graphene) on coating performance. The addition of these particles improved densification, lower porosity, refined microstructure, and stronger inter-splat cohesion, which resulted into superior mechanical and tribiological properties.**

Keywords: HVOF thermal spraying, composite coatings, mechanical properties, wear resistance.

I. INTRODUCTION

Major problem faced by mechanical components is the wear, which resulted in decline in the service life of components. Wear strength of surface can be enhanced by applying coatings, which acts as a protective obstacle between the component surface and the near environment, so decreasing material degradation and surface damage during operation. The HVOF technique is employed to improve the performace by applying the coatings the surface of engineering components. In comparison with plasma spraying, HVOF generally produces coatings with lower porosity and a denser, more compact microstructure. The compressed fuel–oxygen mixture is burned within a combustion chamber, producing a high-temperature, high-velocity gas stream. The required carbide, oxide, metal power or combination of these, introduced into stream of high velocity heated gas are heated to a molten or semi-molten condition and forced toward the substrate surface at supersonic speeds, where they impact, deform, and solidify to form a dense and strongly adherent coating [1, 2]. This technique is widely employed to deposit carbide, oxide, metal, and carbon-based materials and carbon nanotube-reinforced systems onto metallic substrates. Key advantages of HVOF coatings include low porosity, high microhardness, good surface finish, and good erosion–corrosion resistance [3].

II. EFFECT OF REINFORCEMENT ON POROSITY, HARDNESS, SURFACE ROUGHNESS AND WEAR RESISTANCE OF HVOF COATINGS

The mechanical and tribiological behaviour of the coatings are strongly depends upon the porosity, surface roughness, and hardness of the coating. This section will analyse in detail the role of different types of reinforcement in improving these parameters and enhancing coating performance. The incorporation of reinforcements into the coating matrix helps in refining the microstructure, reducing defects, and enhancing properties such as hardness and wear resistance.

A. Porosity

Porosity negatively influences the performance of HVOF coatings; therefore, it is essential to maintain it within an acceptable range. Although the HVOF process generally produces dense coatings, the incorporation of micro- and nano-sized particles can alter the porosity of the coating. This section reviews the influence of various reinforcements on coating porosity.The effect of different types of reinforcement on porosity is shown in Fig. 1. When titanium carbide (TiC) with cupronickel (70Cu–30Ni) and chromium (Cr) as binders was deposited onto SS316 steel specimens, the porosity of the TiC + 50% (70Cu–30Ni)–Cr coating increased from 1.34 to 1.87 related to the (70Cu–30Ni)–Cr coating. The presence of partially melted TiC particles and completely melted binder particles resulted into porosity increase. During spraying, the unmelted TiC core was retained in the splat by the molten binders, and subsequent splats formed over these partially melted particles, leading to higher porosity. In contrast, the (70Cu–30Ni)–Cr coating showed lower porosity because of the absence of unmelted or partially melted TiC particles, resulting in a denser coating [4]. The addition of Mo increased the porosity of WC-Co-Cr coating from 1.14 to 1.30 [5]. Reinforcement of NiCrSiB with Al_2O_3 nanoparticles produces a more uniform coating with less porosity, highlighting the

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improvement in packing density. The aluminum oxide nanoparticles are capable of absorbing sufficient heat during deposition, which promotes better melting and densification of the coating. As a result, a higher-density coating is formed. Furthermore, the number of pores witnessed in the nanoreinforced coating is considerably decrease associated to the unreinforced coating [6]. The WC–10Co–4Cr/Cr/MWCNTs coating exhibits the highest porosity compared to the WC–10Co–4Cr coating, primarily owing to micro-voids presence in the MWCNTs + Cr splats. Additionally, the higher chromium content reduces the melting and flattening of NWC powder particles [7]. The addition of SiC to TiO_2 coatings on a titanium substrate reduced porosity from 6.4% to 2.1%. The coating exhibited densely packed, well-flattened splats with minimal defects. This improved densification owing to optimized particle kinetic energy and controlled thermal input, which improved splat deformation, cohesion, and adhesion [8]. The incorporation of nano-CeO_2 into NiCoCrAlY coatings caused in a higher porosity level than the NiCoCrAlY coating. This was attributed to incomplete particle melting during HVOF spraying, leading to coarser pores and increased formation of interlamellar oxides, which ultimately reduced inter-splat cohesion within the coating structure [9].

The incorporation of nano yttria-stabilized zirconia (YSZ) into Cr_3C_2–25NiCr coatings led to a significant reduction in porosity. With the addition of 10 wt.% nano-YSZ, the porosity decreased from 2.01% to 1.09%, indicating improved coating densification. This improvement owing to the ability of nano-YSZ particles to occupy inter-splat gaps and microvoids within the coating matrix. The fine particles enhance packing density and promote better splat cohesion during deposition, resulting in a more compact and uniform microstructure. Consequently, the reduced porosity contributes to improved mechanical properties and overall coating performance [10]. The YSZ addition reduced the porosity from 1.89 % for Ni–20Cr coating to 1.38% with 10 wt.% YSZ. The reduction in porosity is attributed to improved melting and better heat absorption by nano-YSZ particles, resulting in enhanced densification and stronger inter-splat bonding [11]. The CNT reinforcement decreased the porosity by about 20% with 8 weight percentage compared to conventional chromium oxide coating, which attributed to the CNTs enhanced heat absorption and melting of chromium oxide particles, and their uniform distribution filled inter-splat gaps, leading to denser coating [12]. The incorporation of YSZ nano particles to WC–10Co–4Cr coating decrased the porosity from 3.040% to 0.853 %. Porosity decreased progressively with increasing YSZ nanoparticle content, as the nano-YSZ particles filled microvoids and promoted grain interlocking within the coating matrix. The 10% YSZ-reinforced nanocomposite coating showed lowest porosity [13].

B. Hardness

The primary objective of applying a coating to a substrate is to enhance surface hardness. An increase in surface hardness leads to improved wear and erosion resistance, thereby extending the service life of components subjected to severe wear or erosive conditions.The effect of different types of reinforcement on hardness is shown in Fig. 2. An increase in TiC content in the coating resulted in a corresponding increase in microhardness. The microhardness value rose from 407 HV for the (70Cu–30Ni)–Cr coating to 845 HV when the TiC content reached 50% [4]. The hardness value of WC-Co-Cr coating decreased with addition of molybdenum (Mo), which is mainly attributed to the lower value of Mo hardness [5]. The addition of Al_2O_3 nanoparticles resulted in a microhardness of 748 HV, compared to 928 HV for the NiCrSiB/WC–Co coating [6]. The WC–10Co–4Cr/Cr/MWCNTs coating exhibits the lowest hardness compared to the WC–10Co–4Cr coating [7]. The addition of SiC to TiO_2 coatings increased microhardness from 612 HV to 856 HV due to improved particle–substrate interaction, causing in a denser structure with fewer defects and enhanced resistance to localized plastic deformation [8]. An increase in nano-CeO_2 content in NiCoCrAlY coatings led to improved microhardness of the nanocomposite coating. This improvement is recognised to grain refinement and the purification of grain boundaries [9]. Previous studies indicate that coating microhardness is strongly influenced by factors such as grain size, porosity level, oxide content, presence of unmelted particles, and residual stresses [14]. The average microhardness of the Cr_3C_2–25NiCr coating was 1062 HV, which increased to 1251 HV with the addition of 10% nano yttria-stabilized zirconia (YSZ). This improvement is primarily attributed to reduced porosity, enhanced interfacial bond strength, and improved surface characteristics causing from the integration of nano-YSZ [10]. The microhardness of the Ni–20Cr conventional coating ranged from 712–759 HV, which increased to 1008–1055 HV with 10 wt.% YSZ reinforcement. The hardness of the nanocomposite coatings increased consistently with higher nano yttria-stabilized zirconia (YSZ) content. This improvement is due to the ability of nano-YSZ particles to fill pores in Ni–20Cr matrix, thereby reducing porosity and enhancing coating densification. The microhardness profiles also indicated a almost similar hardness in the coating cross-section for all samples [11]. The microhardness of the Cr_2O_3 coating ranged from 1312–1346 HV, while the 8 wt.% CNT-reinforced coating exhibited a higher hardness of 1678–1746 HV, representing an rise of about 30%. The ability of CNTs to fill pores within the chromium oxide matrix resulted into high hardness, thereby reducing porosity and improving densification. Additionally, CNT reinforcement suppresses crack formation and promotes dispersion strengthening, which together enhance resistance to indentation and penetration [12]. The average microhardness of the substrate, WC–10Co–4Cr conventional coating increased from 320 HV to 1278 HV with 10% YSZ addition. The increase in microhardness with YSZ reinforcement reduced the voids and porosity in the coating matrix, resulting in improved densification and enhanced mechanical properties of the nanocomposite coatings [13].

C. Surface Roughness

Surface roughness is an important parameter, as the wear rate of components is strongly influenced by it. Coatings with better surface finish values are generally preferred, as they tend to exhibit improved wear performance and superior mechanical properties. The effect of different types of reinforcement on surface roughness is presented in Fig. 3

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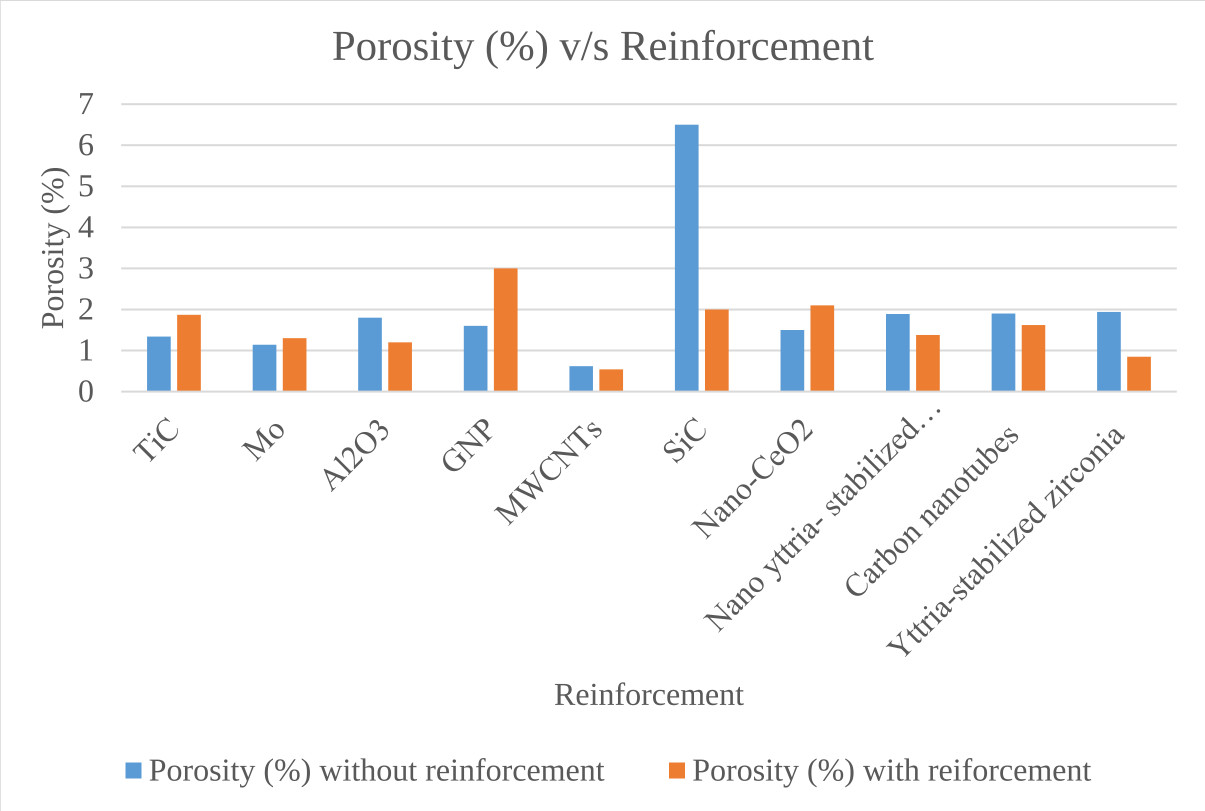

Fig. 1 Porosity v/s Reinforcement diagram for HVOF Nano composite coatings [4-13].

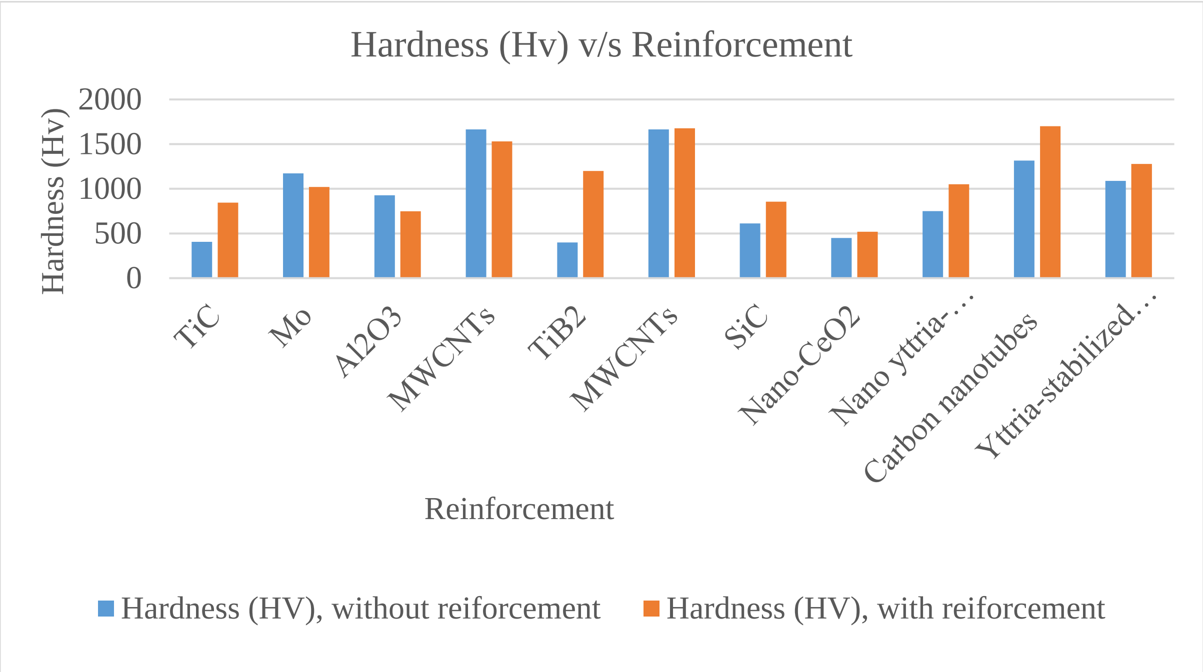

Fig. 2 Hardness v/s Reinforcement diagram for HVOF Nano composite coatings [4-14].

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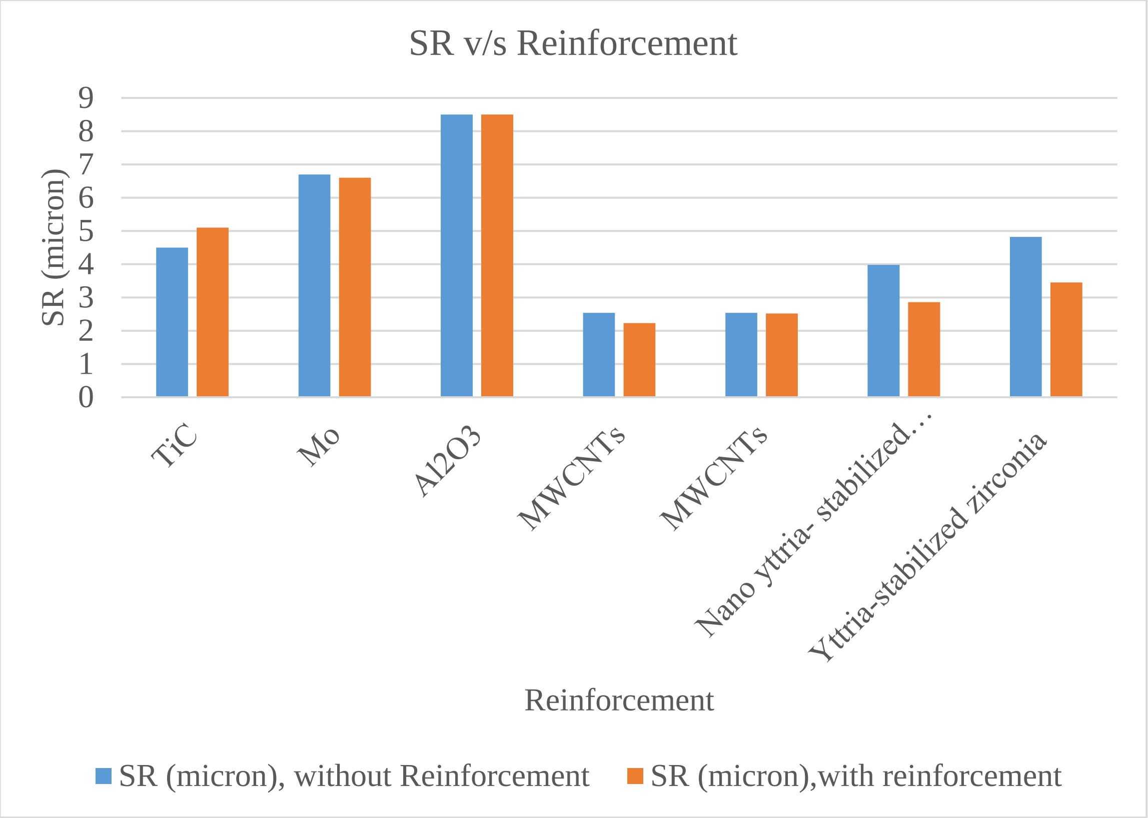

Fig. 3 Surface Roughness v/s Reinforcement diagram for HVOF Nano composite coatings [4-8, 11, 13, 15].

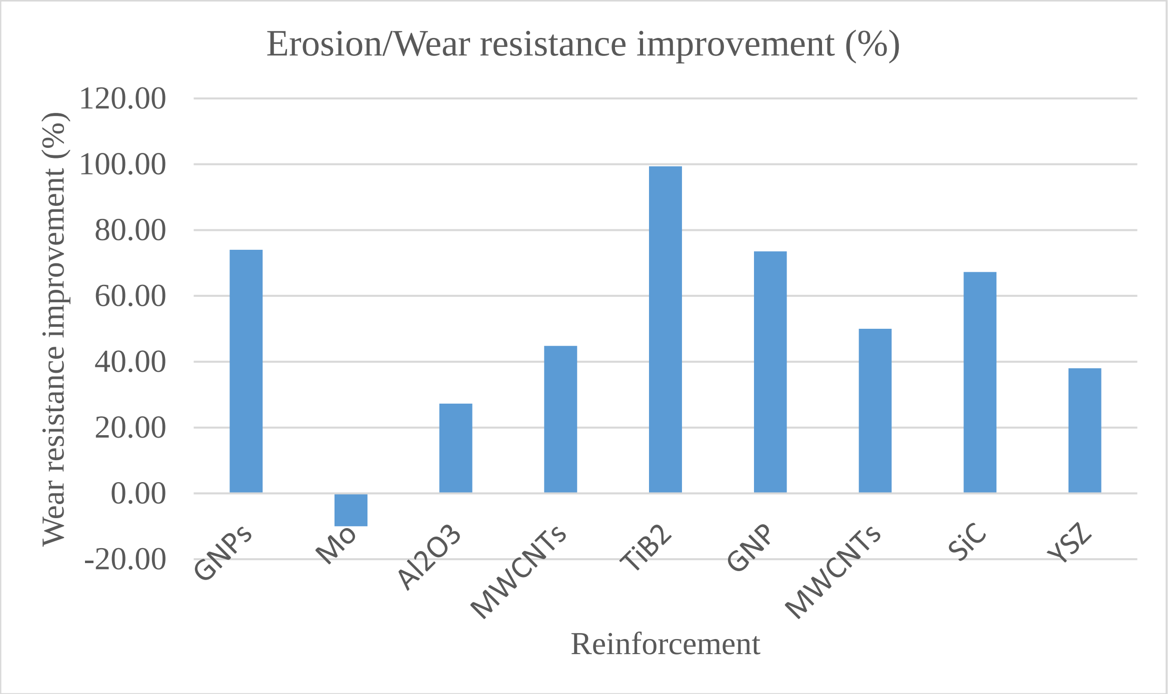

Fig. 4 Wear resistance improvement (%) v/s Reinforcement diagram for HVOF Nano composite coatings [5-8, 10, 15].

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The high surface roughness for the TiC-reinforced coating corresponds to the increased porosity value. A possible reason could be that porosity leads to non-uniform deposition of splats [4]. The surface roughness of WC-Co-Cr is less than that of WC-Co-Cr/Mo coating [5]. The incorporation of Al_2O_3 nanoparticles and WC–Co to NiCrSiB resulted in similar surface roughness values of approximately 8.5 µm [6]. The WC–10Co–4Cr/Cr/MWCNTs shows the least surface roughness in the as-sprayed condition compared to WC–10Co–4Cr coating. A consistent decrease in surface roughness is observed as the chromium content increases in the nanostructured coatings. This improvement in surface smoothness is owing to the higher fraction of molten CoCr binder phase [7]. The addition of SiC reduced surface roughness from 5.3 µm to 2.9 µm, owing to the formation of closely packed, well-flattened splats with minimal voids and microstructural defects [8]. The incorporation of nano yttria-stabilized zirconia (YSZ) significantly improved the surface characteristics of Cr_3C_2–25NiCr coatings. The surface roughness decreased from 5.03 µm for the conventional Cr_3C_2–25NiCr coating to 4.28 µm for the 90% (Cr_3C_2–25NiCr) + 10% nano-YSZ nanocomposite coating. This notable improvement in surface finish is attributed to the reinforcing effect of nano-YSZ particles, which enhance coating densification, reduce surface irregularities, and help the formation of a more uniform and compact microstructure [15]. The Ni–20Cr conventional coating roughness value decreased from 3.98 µm, to 2.86 µm with 10 wt.% YSZ reinforcement. The 10 wt.% YSZ–Ni–20Cr nanocomposite coating exhibited superior surface characteristics related to the conventional coating. The decrease in surface roughness is primarily attributed to decreased porosity and improved densification due to the adding of YSZ nanoparticles, which promote a more uniform and compact microstructure [11]. The incorporation of YSZ nanoparticles into WC–10Co–4Cr coatings improved surface characteristics. The surface roughness decreased from 4.82 µm for the conventional coating to 4.13 µm with 5% YSZ and further to 3.45 µm with 10% YSZ. The 10% YSZ nanocomposite coating exhibited the smoothest surface, primarily due to reduced porosity and enhanced densification resulting from nanoparticle reinforcement [13].

D. Wear/Erosion resistance

Numerous studies have examined the wear behavior of HVOF-based coatings and reported that reinforced composite coatings exhibit significantly higher wear resistance compared to conventional, unreinforced coatings. The effect of reinforcement on wear resistance is shown in Fig. 4. The volumetric erosion loss of WC–Co–Cr is inferior than that of WC–Co–Cr/Mo at all temperatures and impact angles, indicating that the addition of Mo does not improve the coating properties [5]. The NiCrSiB/WC–Co coating outperformed both the NiCrSiB/Al_2O_3 and NiCrSiB/n-Al_2O_3 coatings by exhibiting the highest erosion resistance. The superior performance was attributed to the higher fracture toughness and hardness of WC–Co compared to Al_2O_3 [6]. The incorporation of graphene nanoplatelets (GNPs) into WC–10Co–4Cr coatings markedly reduced the erosion rate. This improvement is attributed to enhanced coating densification, as GNPs filled microvoids within the matrix and increased surface hardness. With increasing GNP content, surface cracks were minimized and a smoother surface morphology was observed. Additionally, GNPs acted as solid lubricants at the contact interface, lowering the coefficient of friction. The reduced friction consequently led to a decrease in wear rate, further improving the overall tribological performance of the coating [15]. The incorporation of TiB_2 particles into Fe_3Al coatings significantly enhanced wear resistance. This improvement is primarily attributed to the increase in Vickers hardness resulting from the presence of hard TiB_2 reinforcements within the coating matrix [16]. The WC–10Co–4Cr/Cr/MWCNTs coating exhibits the high wear resistance compared to the WC–10Co–4Cr coating, which is mainly attributed to high fracture toughness [7]. The addition of SiC enhanced erosion resistance by more than 60%, primarily due to the formation of a uniform and dense microstructure that reduced crack initiation and limited material removal under impact loading [8]. The YSZ-reinforced nanocomposite coatings showed better erosion resistance than conventional Cr_3C_2–25NiCr coatings, owing to their enhanced mechanical properties and improved microstructural characteristics achieved through the HVOF spraying process [10].

III. CONCLUSIONS

The incorporation of different reinforcements into thermally sprayed coatings significantly enhances their microstructural and mechanical performance. The addition of SiC to TiO_2 coatings deposited on titanium substrates reduced porosity and produced densely packed, well-flattened splats with minimal defects. This improved densification was achieved through optimized particle kinetic energy and controlled thermal input, which enhanced splat deformation, cohesion, and adhesion. Similarly, the introduction of nano-YSZ particles progressively decreased porosity by filling microvoids and promoting grain interlocking within the coating matrix. Nano-YSZ also improved surface quality, reducing surface roughness from 5.03 µm to 4.28 µm due to enhanced densification and a more uniform microstructure. CNT reinforcement in Cr_2O_3 coatings increased microhardness to 1678–1746 HV, representing an improvement of about 30%. This improvement is resulted to pore filling, reduced crack propagation, and dispersion strengthening, which collectively improved resistance to indentation and penetration. The integration of TiB_2 particles further improved wear resistance owing to the increased Vickers hardness imparted by the hard ceramic phase. Likewise, graphene nanoplatelets (GNPs) reduced erosion rates by improving coating density and hardness. GNPs also minimized surface cracking and acted as solid lubricants, lowering the coefficient of friction and consequently reducing wear. Overall, reinforced HVOF composite coatings exhibit better mechanical strength and wear resistance compared to conventional coatings, making them suitable for applications in turbines, boilers, aerospace, and other high-temperature and high-wear environments.

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REFERENCES

[1] 1. Sidhu, T., S. Prakash, and R. Agrawal, State of the art of HVOF coating investigations—A review. Marine Technology Society Journal, 2005. **39**(2): p. 53-64.

[2] 2. Milanti, A., et al., Microstructural characteristics and tribological behavior of HVOF-sprayed novel Fe-based alloy coatings. Coatings, 2014. **4**(1): p. 98-120.

[3] 3. Voorwald, H.J.C., et al., Investigation of HVOF-sprayed WC-and NiCr-based coatings to improve corrosion and wear performance of high-strength steel. Journal of the Brazilian Society of Mechanical Sciences and Engineering, 2022. **44**(3): p. 96.

[4] 4. Rampal, et al., Development, characterization, and cavitation erosion analysis of high velocity oxy-fuel (HVOF) sprayed TiC and (70Cu-30Ni)-Cr based composite coatings on SS316 steel. Tribology International, 2023. **186**: p. 108621.

[5] 5. Behera, N., S.R. Medabalimi, and M. Ramesh, Elevated temperatures erosion wear behavior of HVOF sprayed WC-Co-Cr/Mo coatings on Ti6Al4V substrate. Surface and Coatings Technology, 2023. **470**: p. 129809.

[6] 6. Praveen, A.S. and A. Arjunan, High-temperature oxidation and erosion of HVOF sprayed NiCrSiB/Al2O3 and NiCrSiB/WCCo coatings. Applied surface science advances, 2022. **7**: p. 100191.

[7] 7. Thakur, L. and N. Arora, An investigation on the development and wear performance of chromium-MWCNTs transformed HVOF sprayed nano-WC-CoCr coatings. Surface and Coatings Technology, 2020. **388**: p. 125610.

[8] 8. Sathiyamoorthy, R., T. Duraisamy, and A. Mohankumar, HVOF-Sprayed Silicon Carbide-Enhanced TiO_2 Cermet Coatings for Titanium Alloys: A Study on Solid Particle Erosion Behavior. Silicon, 2025. **17**(14): p. 3333-3354.

[9] 9. Ghadami, F., et al., Structural characteristics and high-temperature oxidation behavior of HVOF sprayed nano-CeO2 reinforced NiCoCrAlY nanocomposite coatings. Surface and Coatings Technology, 2019. **373**: p. 7-16.

[10] 10. Kumar, R., K. Goyal, and D. Bhandari, Slurry erosion behavior of thermally sprayed ceramic nanocomposite coatings on turbine steel. International Journal of Applied Ceramic Technology, 2022. **19**(6): p. 3049-3061.

[11] 11. Singh, S., K. Goyal, and R. Bhatia, Effect of nano yttria-stabilized zirconia on properties of Ni-20Cr composite coatings. Journal of Electrochemical Science and Engineering, 2022. **12**(5): p. 901-909.

[12] 12. Goyal, K., H. Singh, and R. Bhatia, Experimental investigations of carbon nanotubes reinforcement on properties of ceramic-based composite coating. Journal of the Australian Ceramic Society, 2019. **55**(2): p. 315-322.

[13] 13. Kumar, R., D. Bhandari, and K. Goyal, Mechanical and microstructural characterization of yttria-stabilized zirconia (Y2O3/ZrO2; YSZ) nanoparticles reinforced WC-10Co-4Cr coated turbine steel. Journal of Electrochemical Science and Engineering, 2022. **12**(4): p. 651-666.

[14] 14. He, J., M. Ice, and E. Lavernia, Particle melting behavior during high-velocity oxygen fuel thermal spraying. Journal of Thermal Spray Technology, 2001. **10**(1): p. 83-93.

[15] 15. Kumar, V. and R. Verma, Effect of GNP and laser-surface texturing on HVOF sprayed WC10Co4Cr coatings for high-wear resistance. Tribology International, 2023. **178**: p. 108057.

[16] 16. Amiriyan, M., et al., Tribo-mechanical properties of HVOF deposited Fe3Al coatings reinforced with TiB2 particles for wear-resistant applications. Materials, 2016. **9**(2): p. 117.