

Improvement in Mechanical Properties Using High Velocity Oxyfuel Coating (HVOF): A Review

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Abstract

Surface modification plays a vital role in improving the service life of different machine parts used in number of industries. Due to daily routine operations at difficult environment conditions, most of machine components have failure in their operations. In these types of cases, only materials with superior wear resistance can be used or material surface can be modified by coating. High velocity oxyfuel coatings (HVOF) play a significant role in improving surface properties. Current research focuses on review of tribological properties as well as mechanical properties with application of HVOF coatings. In the last two decades, HVOF coatings have gained huge popularity because of development of thin layer having high hardness, proper adhesion to substrate irrespective of the geometry of the parts and keeping geometry unchanged. The major benefit of HVOF coatings is utilization of vast variety of coating powders on variety of substrates. HVOF coatings have wider applications in automobile industries, aerospace industries, and power plants for improvement of wear resistance. The information in this study is mainly taken from previously published research papers. So, this study is a compilation of data for researchers conducting their study in the area of HVOF coatings.

Keywords: High velocity oxyfuel coatings (HVOF), hardness, aerospace, power plant

INTRODUCTION

Expensive machine parts are utilized in different sectors such as automotive, mining, aeronautical, textile, food processing industries, and hydraulic machineries. The petrochemical industries are regularly exposed to high temperature, destructive environment and continuous relative motion [1–7]. Thus, these components are subjected to permanent failures or decrease in their utility [8]. The most common issue is to deal with friction, which causes wear failure of various automobile components such as bearings, mechanical seal, piston rings, piston rod, cylinder liner, gear axle, valve, and brake. This phenomenon reduces production efficiency, and increases maintenance cost and running cost [9–22]. Hence, various surface modification techniques have gained immense interest among researchers to find solutions for improving service life of these components [12, 17, 22]. Among numerous surface

modification techniques, thermal spray coatings are recommended not only for increasing abrasion resistance, adhesion resistance, erosion resistance, corrosion resistance, fatigue resistance but also for avoiding the wear failure [15]. According to various authors, amongst various thermal spray coatings, HVOF coating becomes better choice because of its unique characteristics such as excellent wear resistance, high corrosion resistance, superior bond strength, high surface hardness, better fracture toughness, fine surface finish, less residual stress, high deposition density, lower oxides, low porosity, reduced energy consumption, and less material used [1, 16, 17]. Microstructural properties of HVOF coating depend on various parameters such as fuel

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flow, spray distance, feedstock powder, combustion chamber pressure, powder feed rate, nozzle geometry, and oxygen flow rate. Beside this, there are some other micro influential factors such as existence of cracks, formation of various kinds of oxides, and availability of various kinds of boundary regions. Further, it is challenging to select suitable coating powder for wear resistance applications such as winders, roll surfaces, plate's valves, agitators, mixers, pumps etc. [1]. Figure 1 shows schematic diagram of HVOF set up.

LITERATURE REVIEW

In order to compare mechanical properties of different types of coating powders, research articles of leading journals were selected to cover up vast variety of coating powders, as shown in Figure 2. The categorization of published research articles was carried out from before year 2000 to year 2022 as shown in Figure 3. Majority of articles were based on carbide based coatings because of having high wear resistance. Maximum number of articles are after year 2020. It shows rising interest of researchers in the area of HVOF coatings in recent years.

MECHANICAL PROPERTIES OF HIGH VELOCITY OXYFUEL COATINGS

Various miscellaneous mechanical properties like micro hardness, density, porosity, fracture toughness, etc. were studied on many coating substrates.

Ksiazek *et al.* developed WC-Co+Cr coated ductile cast iron samples [5]. After characterization of microstructure of coated samples by light microscope, they observed proper adhesion of coating with substrate and very less number of pores with negligible cracks, and concluded that coated samples have high density, high hardness, low porosity, compact structure, and excellent fracture toughness.

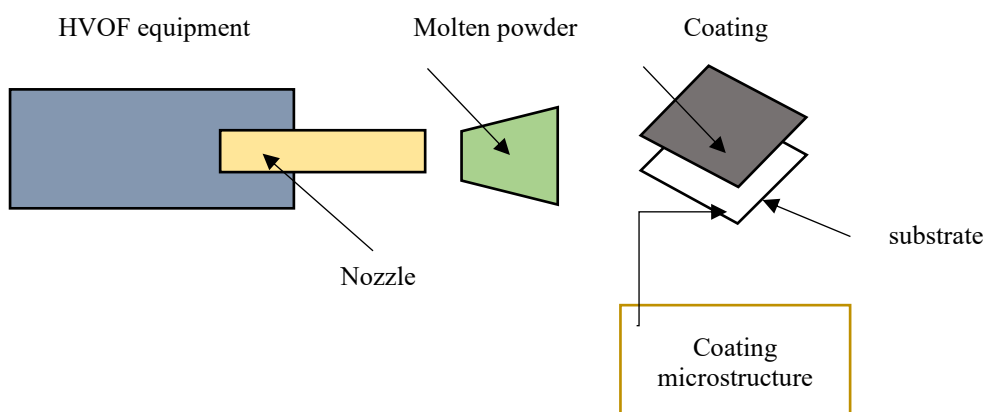


Figure 1. Schematic illustration of High velocity oxyfuel coating [1].

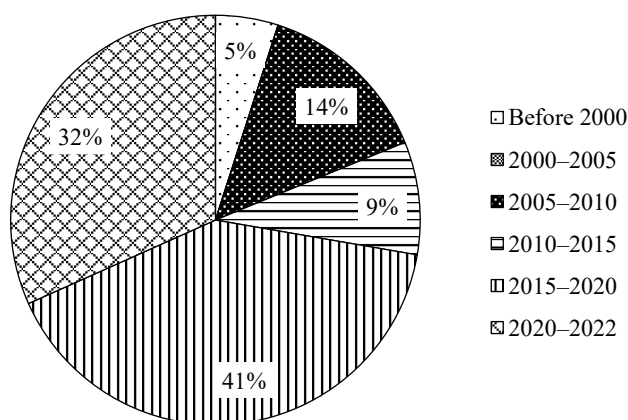


Figure 3. Yearly distribution of publication across the period of study (before 2000–2022).

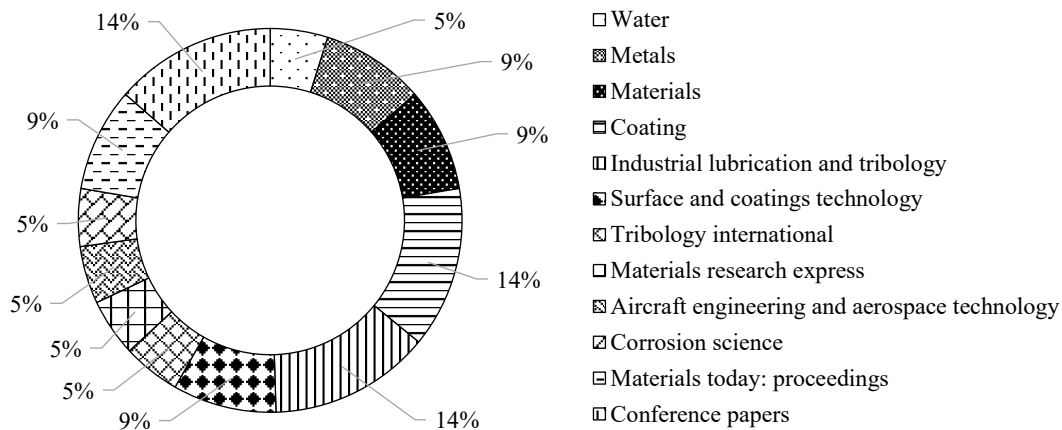


Figure 2. Publications journals details.

Table 1. A summary of surface roughness and microhardness of reported studies on HVOF coatings.

Coating powder	Substrate	Surface roughness (Ra)	Micro hardness (HV)	References
WC-Co + Cr	Ductile cast iron	5.36±0.6 µm	2523HV0.1±30	[5]
WC-FeCrAl	AISI 316L	4.32±0.28	1050 to 1069 HV 0.1	[6]
WC-WB-Co	AISI 316L	4.73±0.31	1221 to 1325 HV 0.1	[6]
Ni-Cr-O	SS316L	7.04	821±19	[11]
NiBCrSi-WC(Co)	SS316L	6.67	538±17	[11]
WC-10CoCr	SS316L	6.50±0.16	1156±8.13	[12]
WC-10CoCr + 3% Mo ₂ C	SS316L	3.74±0.51	1182	[12]
AlCoCrFeNiTi	S235 Steel	-	730±82 HV 0.1 kgf	[13]
Ni-Cr-W-MO-Cu-C-B-Fe	AISI 304 Steel	-	550–650 HV	[16]
WC-Cr ₃ C ₂ -Ni	SS 316L	4.8	1037±100	[17]
WC83-Co17	C45 steel	-	1024 HV0.2 kgf	[21]
WC88-Co12	C45 steel	-	1038 HV0.2 kgf	[21]
WC86-Co10Cr4	C45 steel	-	1154 HV0.2 kgf	[21]
Cr ₃ C ₂ 60-NiCr40	C45 steel	-	855 HV0.2 kgf	[21]
Cr ₃ C ₂ 75-NiCr25	C45 steel	-	918 HV0.2 kgf	[21]
CoMoCrSi-WC + 12Co	Titanium	-	1410±70	[22]
CoMoCrSi-WC + CrC+ Ni	Titanium	-	1290±35	[22]

They also found that compressive residual stresses were developed which leads to enhancement of adhesion of coating to the substrate. After coating, no change was observed in cast iron matrix. After characterization via scanning electron microscope (SEM), dark cobalt chrome matrix with bright carbide grains was observed. Mean porosity of coated samples was observed 4.1±0.2. Table 1 indicates microhardness and surface roughness values of different types of coatings. It can be seen from Table 1 that microhardness value of wide variety of coatings is in the range of 500 to 2600 HV.

Comparison of number of coating powders is shown in Figure 4. Among them, WC-Co+Cr coating powder has highest value of microhardness. Figure 5 represents surface roughness value of wide variety of coating powders, having lowest value of surface roughness for WC-10CoCr+3% Mo₂C.

Brezinová *et al.* evaluated the microhardness of WC-FeCrAl and WC-WB-Co coated samples in accordance with ISO 4516 using Vickers method and observed that both coatings have greater hardness than uncoated metal and found that WC-WB-Co have higher hardness. They discussed that WC-FeCrAl

was a green carbide coating which preserves the properties of WC based coatings and removes hazardous metals from the environment and human reach [6].

Hong *et al.* found that HVOF-sprayed WC-CoCr coated samples have superior mechanical strength and less oxidize rate due to formation of fcc-Co phase and high hardness, and low surface roughness [9].

Singh *et al.* characterized the Ni-Cr-O and NiBCrSi-WC(Co) coatings and evaluated that surfaces of both the coatings shows anisotropic microstructure and they observed excellent bonding strength with the substrate. They found greater average roughness in case of Ni-Cr-O coatings [11].

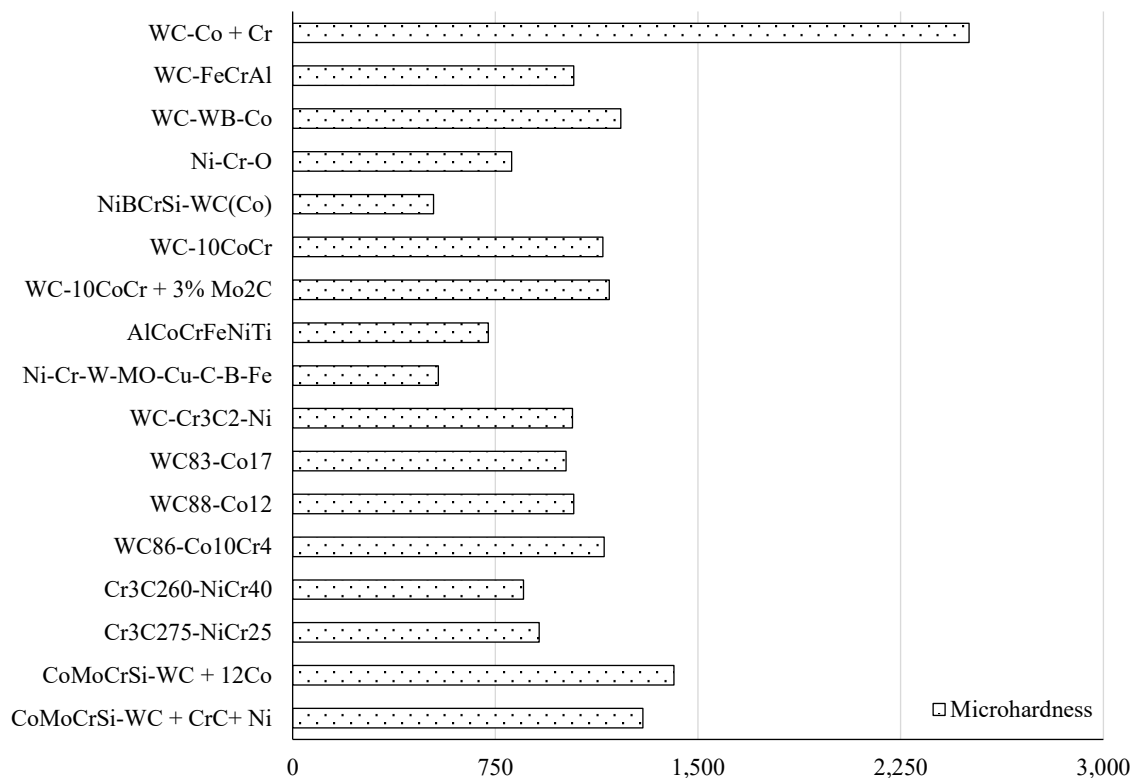


Figure 4. Details of microhardness values of various coatings.

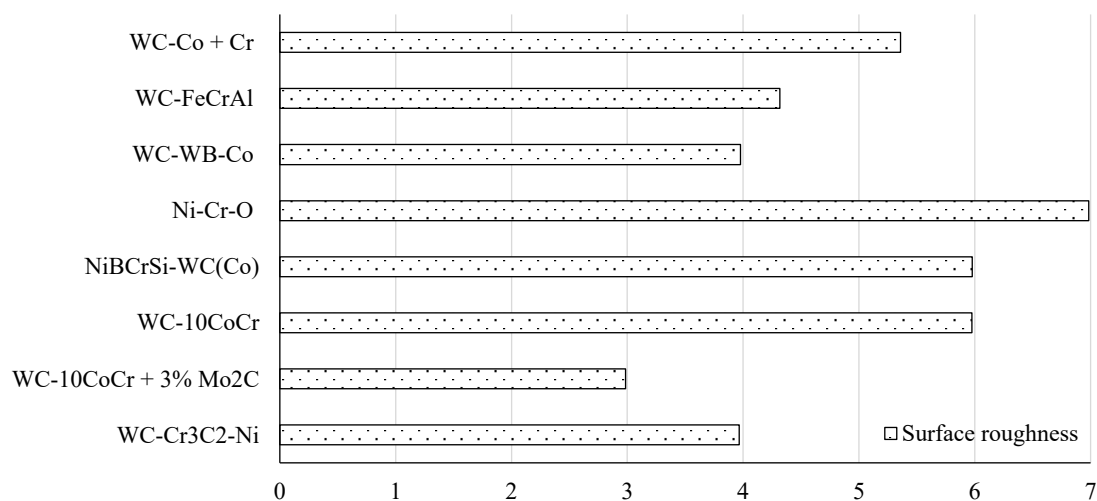


Figure 5. Details of surface roughness of various coatings.

Singh *et al.* concluded that HVOF sprayed Mo₂C-based WC-CoCr coatings have higher microhardness compared to WC-CoCr coatings, however newly developed reinforced coatings have less porosity compared to conventional WC-CoCr coatings and also newly developed coatings have enhanced fracture toughness compared to conventional one. They characterized both the coatings and observed the additional presence of carbide in the newly reinforced coatings [12].

Löbel *et al.* revealed that HVOF sprayed AlCoCrFeNiTi coatings have greater microhardness compared to S235 steel samples [13].

Fe based coatings such as Fe-Ni-Cr-B-C and Fe-Ni-Cr-Mo-B-C have dense microstructure, poor porosity, higher nano hardness, lower bond strength compared to Ni-Cr-Fe-Si-B-C and WC-CoCr coatings [15].

HVOF sprayed Ni-Cr-W-MO-Cu-C-B-Fe coatings consist of various phases, such as Cr₂O₃, MoNi₄ and Cr₂Ni₃ and have different bond strengths at various spraying distances; adhesive strength depends on thermal spray angle [16].

Goyal *et al.* developed HVOF sprayed WC-Cr₃C₂-Ni coating and observed the value of fracture toughness as 4.2±0.7 MPa/m. They observed mean porosity of coated samples as 1.4 [17].

Lekatou *et al.* compared HVOF sprayed nanostructured and conventional cermet coatings on Al 7075 and concluded that nanostructured coatings have superior microhardness, superior fracture toughness and less microporosity [18].

Ishikawa *et al.* performed pin on disc dry sliding wear test on HVOF sprayed WC: 20% Cr₃C₂-7%Ni cermet coatings against iron pin and concluded that specific wear rate of coating was smaller than that of iron pin because of oxidation of cermet coatings [19]. HVOF sprayed WC-Co coatings have higher microhardness and dense microstructure compared to Cr₃C₂-NiCr coatings [22].

TRIBOLOGICAL PROPERTIES

Williamson *et al.* performed dry sliding wear test on HVOF sprayed Cr₂O₃ and Cr₃C₂-NiCr, WC-(W, Cr)2C-Ni coatings and determined wear rate via mass loss method and optical microscopy method; they concluded that less wear occurred in case of WC-(W,Cr)2C-Ni coatings via mass loss method while according to microscopy method Cr₃C₂-NiCr coatings have least wear rate [2].

Singh *et al.* examined the effect of HVOF coated Chromium Nitride on the tribological properties under dry condition on reciprocating tribometer machine for the Cylinder Liner application at variable engine operating temperature and variable loads by keeping the fixed stroke length [4]. They found that chromium nitride has excellent bonding with base material and friction coefficient reduced with increase in temperature due to gradual formation of hard layer and wear rate decreased due to formation of chromium oxide thin layer and deposition of wear debris and observed that wear mechanism is abrasive wear, oxidation wear and adhesive wear.

Ksiazek *et al.* conducted abrasion resistance testing at 50 N applied load and 300 rpm rotational speed on WC-Co+Cr coated ductile cast iron substrate, and after characterization of worn surface by SEM, they observed that by coating, wear resistance was enhanced as compared to ductile cast iron and wear mechanism observed was mainly abrasive wear and adhesive wear and some cracks were found [5].

Brezinová *et al.* compared the wear resistance of WC-FeCrAl coating and WC-WB-Co coating on AISI 316L steel substrate by conducting sliding wear test on pin on disc tribometer under dry condition, and found higher wear resistance of both coated samples and WC-WB-Co coated sample have higher wear resistance compared to the other one [6].

Wei *et al.* performed high temperature wear test on a HT-1000 type ball-on disc tribometer of CoCrAlYTaNi-10% Al₂O₃ coated H13 Steel samples and analysed that average coefficient of friction of coated sample is lower than H13 Steel and the concluded that CoCrAlYTaNi-10%Al₂O₃ coated H13 Steel samples have superior wear resistance compared to H13 Steel [7].

Rukhande *et al.* conducted dry sliding wear test on NiCrBSiFe coated SS 316L samples on pin on disc tribometer and concluded that NiCrBSiFe coated SS 316L samples have superior wear resistance against alumina counter material than against the silicon nitride [8]. Wear mechanism found is abrasive wear, and it was revealed that as load increases, wear rate also increases, and found good sliding pair of HVOF coated NiCrBSiFe against alumina and silicon nitride because very low range of specific wear rate was observed.

Hong *et al.* analysed wear resistance of WC-CoCr HVOF sprayed WC-CoCr on Cr₁₂MoV cold work die steel substrates by performing dry sliding friction and wear tests on a pin-on-disk high-temperature tribometer, and concluded that wear mechanism is mainly abrasive wear and lower wear rates were obtained for HVOF coated samples [9].

Singh *et al.* compared tribological properties of Ni-Cr-O and NiCrBSiFe-WC(Co) composite coatings deposited on SS 316L and analysed that Ni-Cr-O coatings have high wear rate compared to NiBCrSi-WC(Co) coatings at an impact angle of 60° but both the coatings have improved wear resistance compared to SS316L metal and concluded that erosion wear depends on impact angle [11].

Löbel *et al.* performed ball-on-disk, oscillating wear, and scratch tests and concluded that HVOF sprayed AlCoCrFeNiTi coatings have excellent wear resistance, and in case of scratch test, brittle failure was not observed [13].

Navinsh *et al.* conducted dry sliding wear test for HVOF sprayed CrC-NiCrFeSiBCoC coatings with SS-316L substrate metal for two different compositions and found that CrC-NiCrFeSiBCoC (80–20%) coatings have improved wear resistance compared to CrC-NiCrFeSiBCoC (35–65%) coatings followed by SS-316L [14].

Milanti *et al.* compared tribological properties of HVOF sprayed Fe-Ni-Cr-B-C, Fe-Ni-Cr-Mo-B-C, Ni-Cr-Fe-Si-B-C, Ni-Cr-Fe-Si-B-C and WC-CoCr coatings by performing ball on disc dry sliding wear test, the rubber-wheel dry particle abrasion test, and the cavitation erosion test and concluded that abrasion wear resistance of WC-CoCr coatings is superior compared to Fe based and Nickle based coatings and Fe based coatings have lower wear rate, lower friction coefficient, and improved cavitation wear resistance compared to above mentioned reference coatings [15]. Goyal *et al.* performed pin on disc abrasive wear test on HVOF coated WC-Cr₃C₂-Ni samples and observed that coefficient of friction increases with increase in load and decreases with increase in sliding speed [17]. Lekatou *et al.* compared HVOF sprayed nanostructured and conventional cermet coatings on Al 7075 and concluded that nano WC-12Co coatings have superior wear resistance because of formation of carbide phase [18]. Ishikawa *et al.* performed pin on disc dry sliding wear test on HVOF sprayed WC-Cr₃C₂-Ni coatings against iron pin and concluded that specific wear rate of coating was smaller than that of iron pin because of oxidation of cermet coatings [19]. Sidhu *et al.* characterized HVOF sprayed Cr₃C₂-NiCr and WC-Co coatings and observed higher wear resistance of WC-CO coatings with adhesive wear mechanism [20]. Fedrizzi *et al.* analysed wear mechanism of HVOF coated WC-12Co, WC-17Co, WC-10Co-4Cr, Cr₃C₂-40NiCr and Cr₃C₂-25NiCr coatings and confirmed the presence of abrasive wear and adhesive wear, superior wear resistance was observed in case of WC based coatings [21]. Prasad *et al.* compared tribological properties of HVOF coated and microwave treated CoMoCrSi-WC-CrC-Ni and CoMoCrSi-WC-12Co coatings deposited on titanium substrate found abrasive wear mechanism [22].

CONCLUSION

To avoid catastrophic failure, wear failure should be avoided, and reduced at early stages. High velocity oxyfuel coating plays a significant role in improving wear resistance as well as other crucial mechanical properties (Such as high corrosion resistance, superior bond strength, high surface hardness, better fracture toughness, fine surface finish, less residual stress, high deposition density, lower oxides, low porosity). A large number of research has been done in the past to evaluate the assessment of these coatings by conducting various laboratory tests. It was observed in most of research studies that microhardness value of wide variety of coatings is in the range of 500 to 2600 HV. Lowest value of surface roughness was observed for WC-10CoCr+3% Mo₂C coatings. Highest value of microhardness was observed for WC-Co-Cr coatings. Though further research study is still required to analyse the performance of HVOF coatings in more aggressive environment particularly by using variety of lubrications in laboratory or in actual environmental conditions. More research is required to understand many types of wear mechanism in case of different types of HVOF coatings.

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