Mechanical and Tribological behaviour of velocity oxygen fuel thermal spray coating: A Review

Shivani Jha¹ and R.S. Mishra¹
¹Mechanical Engineering Department, Delhi Technological University, Delhi, India.

E-mail: shivanijha2@gmail.com

Abstract. For over decades thermal spraying has been present and optimized over the time and now it has become an effective method to thick coating deposition. Thermal spray coating especially high velocity oxygen fuel (HVOF) have served various industrial sector such as aerospace, defence and thermal electricity generation. To overcome disadvantages of traditional coating there was a need of smart coating process which could integrate new functionalities and coherent responses. The aim of this paper is to present a detailed review of current technological changes in HVOF thermal spray coatings. This paper gives insight view of different type of coatings on substrates, their mechanical and tribological properties. HVOF coating categorised according to various application sector has also been discussed in this paper.

Keywords: HVOF; Thermal spray coating; Wear; Hardness; SEM

1. Introduction
The thermal spray method is commonly used in manufacturing applications to improve material surface properties. As the HVOF processes imply the velocities at low temperature from the supersonic to hypersonic range resulting into high strength and bulk density coatings [1]. In past trends, the thermal spray processes are generally applicable to repair and maintenance purpose. Later on, the thermal spray process is used in manufacturing sectors to configure the components and equipment’s with high durability and performance. Regeneration of improperly and worn machined components, wear resistance against erosion, abrasion, adhesive wear, and corrosion protection against wet, high temperature, and atmospheric corrosion are all reasons for using HVOF in industrial sectors. In the emerging scenario, The HVOF thermal spray coatings have the applications in medical technology such as bioactive and bioinert surfaces in human implants. The versatility of thermal spray coatings finds in various industrial sectors such as paper and pulp industry, corrosion protection in infrastructure and steel substrates, gas turbines, power generation plants, textile, printing, electrical, steel and biomedical industries [2]. Moreover, the coatings are widely used in aerospace’s and mining sectors. Thermal spraying is characterized as a process in which a liquefied or semi-liquefied substance, either metallic or non-metallic, is deposited on the substrate's surface to improve various surface properties such as wear, corrosion, and so on. [3]. The molten material or the partially molten particles are sprayed with the application of high velocity on the substrate surface. Along with the gas stream, the material is heated and accelerated towards the substrate surface and hits the surface with high speed. The gas stream is generated by putting together and igniting fuel and oxygen in the combustion chamber, which confirms the flow of gas through the nozzle as shock wave. The velocity of the gas along with the particles results into the supersonic. The melting of powder particles results from the bursting of gases and imparts on the substrate surface on which the coating is deposited. The
substrate does not melt in the spraying action as well as attached with the coating adhesively attributed to metallurgical nature.

The semi-plastic state of the powder particle that are flattened also while falling on the substrate results in to the adhesive adherence with the substrate and with the consecutive layer of the coating, hence the coating is formed [4]. The microstructure, adherence, morphology, chemical composition etc. are examined by the union of the thermal spray coating parameters such as fuel/oxygen ratio, standoff distance, power feed rate, particle size distribution, number of passes and total gas flow [5].

2. Thermal spray coatings (TSC)

TSC is a long-established manufacturing method for treating engineered part surfaces. Metals, alloys, metal oxides, ceramics, carbides, wires, tubes, and a variety of composite materials may be coated on a different base material to create a special coating using this process. TSCs offered a functional surface that allowed the substrate material's properties to be preserved or modified. They are easy to use, cost-effective, and have features that support all industries. The benefits include reduced costs, improved efficiency, or a longer component lifespan, resistance to wear, regulation of dimensions and clearances, and improved electrical properties. Coatings have a much lower cost due to improved efficiency, a longer component lifespan, and less upkeep. The TSC method is used in a variety of industries for a variety of important applications. Restoration and maintenance, abatable adhesives, and decoration uses are the major application functions. The schematic diagram of TSC are shown in Figure 1.

![Figure 1. Schematic of thermal spray coating [6].](image)

3. Discussion

3.1. Mechanical and tribological properties

Jonda et al. [7] studied the HVOF sprayed Cr₃C₂–NiCr coatings on magnesium alloy AZ31 of 5mm thickness. With flow speeds of 350 l/min and 40 l/min, respectively, oxygen and kerosene were used as fuel gases. Furthermore, nitrogen was used as a carrier gas at a rate of 101 l/min. The powder feed rate was set at 25g/min. 280mm was used as the spray distance. The surface of the Cr₃C₂–NiCr had no cracks or discontinuities, according to the author. Moreover, the dense and homogeneous structure is obtained. The wear mechanism is the adhesive one. The two main phases of sprayed coatings were Cr₃C₂ and CrNi₃. The micro hardness of the coating was increased up to 790 HV. Ghadami et al. [8] prepared, characterized and then analyse the oxidized behaviour of NiCrAlY coatings and (0.5-2 wt%) CeO₂ gradient NiCrAlY coating. Fuel flow rate 55 l/min, oxygen flow rate 210 l/min, power feed rotation 430 rpm, power feed rate 430 g/min, carrier gas as nitrogen 20 l/min, and a standoff gap of
280 mm are the specifications used for traditional coating. Furthermore, the propane fuel flow rate is 55 l/min, oxygen flow rate is 200 l/min, powder feed rotation is 400 rpm, powder feed rate is 35 g/min, nitrogen as carrier gas flow rate is 20 l/min, and the standoff gap is 250 mm for nano-ceria updated coatings. The various techniques used to analyse the coatings are SEM, FESEM, TEM, XRD, EDS and Raman Spectroscopy. The nature of typically graded coating gradually increases the micro hardness.

Figure 2. Representation of functionally graded and monolayer coating [8].

Oladijo et al. [9] HVOF thermal spray method was used to investigate the wear resistance and residual stress of Inconel 625 coating on SS304 substrate. The process parameters of HVOF thermal spray of Inconel 625 coatings are O2 flow rate of 52.39 m3/h, kerosene flow rate, 80g/min of power feed rate of 0.03 m3/h and standoff distance of 375mm. The testing of the Inconel coating at 250, 300, 400 and 500 µm thickness are obtained. From the neutron diffraction technique, residual stress of Inconel 625 coating resulted into the compressive stress and prevents the coating cracking. This Inconel 625 coating presents the better tribometer performances on the substrate. By increasing the coating thickness decreases the wear rate. Adhesive and abrasive wear were the prominent wear mechanism. Pulsford et al. [10] hvoaf procedure was used to investigate the slipping wear mechanism of WC-Co reinforced NiCrFeSiB thermal spray coatings against WC-Co and Al2O3 counter bodies. The various techniques are SEM, XRD, EDS, micro hardness, indentation fracture toughness, porosity and dry sliding wear tests performed. At higher total gas flow rate, The NiSF_HF coating suffers less material removal than the NiSF_HF during the wear tests against the WC-Co and Al2O3 counter-bodies due to high hardness. The wear rate of the both coatings affected by the Al2O3 on the contrary of the WC counters bodies due to the abrasion mechanisms. Rukhande and Rathore [11] On the 316 SS substrate, the tribological activity of plasma and HVOF sprayed NiCrSiBFe coatings was studied. The effect of counter materials, coating methods, and regular loads were investigated. Wear resistance properties of HVOF sprayed and plasma sprayed NiCrSiBFe alloy powder in the 316 SS substrate sliding against AISI 52100 bearing steel were investigated in the experiment under dry sliding conditions at room temperature. The wear test performed on different load parameters such 10N, 15N and 20N along with the constant sliding velocity. The HVOF process enhances the wear resistance property when compared with plasma sprayed process. The dominant wear mechanism for coating is abrasive and adhesive one. Somasundaram et al. [12] under bio-lubricant conditions, he demonstrates tribological features of n-(GO/WC-10Co-4Cr) HVOF coatings. The substrate content is AA 6061 discs with thicknesses ranging from 50 to 150 m and a graphene oxide percentage weight of 0.75-1, as well as a nano mixture of WC-10Cr-4Co powder. The tribology test was performed on the
substrate by using pin on disc apparatus for the various values of load, disc rotational speed and percent value of jojoba oil. From the tribological test, the best results were obtained at 0.085 GO/WC-10Co-4Cr with coating thickness of 150µm imparts the lower frictional coefficient and lower wear rate also. SEM analysis shows the presence of IMCs that protects the boundary regime from oxidation wear. Davis et al. [13] analyse the tribological and mechanical properties of NiMoAl-Cr2AlC Composite Coatings by HVOF thermal spray process. Various percentage weight of Cr2AlC added to the NiMoAl at 10, 20, 50 and 100 wt%. Moreover, both were prepared by turbo-mixing and deposited by HVOF thermal spray process. The microstructure, chemical composition, phase composition, mechanical and tribological properties were analysed by using FESEM, EDAX, XRD, nano-hardness tester and pin on disk wear testing rig. The 20wt% of Cr2AlC MAX phase with that of NiMoAl enhanced the wear properties and increases the coating life by 7000 twist of fatigue cycles. Warda et al. [14] examined the Ni20Cr coating sprayed by HVOF process on the T24 steel pipes (refer to Figure 3). The various tests were performed are optical microscopy, XRD, SEM, EDX and adhesion test. On the application of Ni20Cr coating by HVOF process, the high temperature protection is assured for the external surface t-24 steel pipes. The uncoated steel samples were held at 550°C and 600°C, and the kinetic law appears to be parabolic. At 650°C, the oxidation kinetic law has modified to a linear one. The dense coating had a thickness of at least 260 µm, a Vickers micro-hardness of about 460 µm, a very low oxide content (4 ±1 vol%), and an adhesion strength of at least 29.7 MPa. There is no degradation observed on the coated substrate when subjected to cyclic thermal and isothermal treatments at 750°C. A 5µm thin layer of Cr2O3 NiCr2O4 was detected on the surface of coating. Moreover, the coating on T24 steels will sustained above its maximum service temperature.

Figure 3. HVOF thermal spray for high temperature protection [14].

Abbas et al. [15] studied the microstructural characterization of Polished and Oxidized Stainless AISI 316 stainless Steel Substrates by HVOF-Sprayed Nickel. The experiment is performed at the flow rate of kerosene and oxygen in l/h are 22.7 and 943, feed rate of Ni powder is 65g/min, Standoff distance 330 mm and two passes made torch travel speed at 1000 mm/sec. The various techniques were used to analyse the microstructures are SEM, FIB, TEM, STEM, EDS and XPS. The oxidized substrate results into the significant amount of desorbed species that have shown donuts shaped splats and microstructure. The microstructure shows the large size porosities, inconsistent splat-substrate interface and uniform grain orientations. The findings obtained from the FIB and TEM analysis results into the combination of mechanical and metallurgical bond between the splats formed and the substrate under consideration. Less splashing is observed in oxidized sample when compared to polished sample. Ham et al. [16] first fabricated, and then examined properties of novel Fe-Mo-Cr-C-B metallic glass coating by different thermal spray processes. The coating was done on SS400 substrate by plasma, VPS and HVOF thermal spray processes. The XRD results show that all the coatings sprayed by the three processes exhibit broad halo peaks. From the wear analysis, it can be concluded that samples prepared by VPS method enhance the wear resistance under all wear load conditions. Mayer et al. [17] evaluated the corrosion/cavitation synergy of the Cr3C2-25NiCr coating sprayed by the HVOF process. SAE 1020 carbon steel plates were used as a substrate material. The various techniques used for analysing are XRD, OM, Vickers hardness test, Fracture toughness, Cavitation erosion test and potenio-dynamic polarization test. The cavitation erosion test in 3.5%
NaCl water solution and distilled water shows the similar results which were measured by weight loss. Cavitation has a greater impact on corrosion kinetics than corrosion has on the cavitation resistance of the Cr3C2 25NiCr coating. The mechanical wear that occurs at the start of the cavitation experiments causes the majority of the corrosion properties to change. Venturi et al. [18] incorporated the graphene nanoplatelets to Cr2O3 coatings for the low wear coatings. The AISI 304 stainless steel was used as a substrate. The procedure was carried out with hydrogen and oxygen flow speeds of 462 slpm and 198 slpm, respectively, and a substrate surface velocity of 1.4 m/s for 26 spray passes. The SEM, micro hardness test and dry sliding wear test has been performed. From the inclusion of GNP, no delamination of the coating and substrate interface was found. Incorporating graphene nanoplatelets into composite coatings often improves mechanical properties. The basic wear rate by 20% (coating), and the overall wear rate by 70%. (counterbody). Zhou et al. [19] monitored the tensile behaviour of NiCoCrAlYCe coating deposited by HVOF thermal spray process. The NiCoCrAlYCe coating and NiCoCrAlY coating on K417G Ni-base superalloys has been analysed. β-NiAl and β-Ni phases make up the phase structure of the NiCoCrAlYCe coating. The NiCoCrAlYCe coating has a bonding strength of 56.54.8 MPa, which is considerably higher than the NiCoCrAlY coating (46.14.6 MPa) deposited using the HVOF thermal spray technique. Coating loss is caused by the expansion and progression of pre-existing horizontal cracks, which causes the initiation, propagation, intersection, and instability of new longitudinal and horizontal cracks. There is more wear testing and mechanical testing possible. Tillman et al. [20] The HVOF thermal spray method was used to analyse the adhesion of WC-Co Coatings on 316L Substrates. The substrate is treated using the SLM method in this process. The surface roughness and residual stress of the individually pre-treated SLM substrates were analysed. Vickers interfacial indentation experiments were used to analyse the coating adhesion. The findings demonstrate that the WC-Co coating has strong adhesion properties to the stainless-steel substrate that has been SLM treated. Thakur and Arora [21] HVOF sprayed nano-WC-CoCr coatings with chromium-MWCNTs transformed coatings were studied for production and wear efficiency. By enhancing the Cr factor (10 and 16 wt %) with the required proportion of MWCNTs (2 wt%), the Co-Cr binder matrix can be interchanged. EDS, XRD, and SEM were used to examine the elemental compositions, phases, and surface morphologies of feedstock powders of formed coatings. The established coatings were tested for percentage porosity, micro hardness, indentation fracturing stiffness, and surface roughness. Following erosion monitoring, material removal occurs through micro cutting and ploughing of the Co-Cr binder matrix, as well as pull-out and fracturing action on the WC-grains. With the high proportion of Cr content in MWCNTs, the fracture hardness has been increased. The wear resistance in test conditions enhanced with the proportion of 16 wt% WC-CoCr+2 wt% MWCNTs (refer to Figure 4).

Sivarajan et al. [22] analysed the melt profile and hardness of laser treated nanostructured WC-12Co mixed with Inconel 625 coatings sprayed by HVOF process on the application of different laser power and scan speed. The AISI 4140 carbon steel was used as a substrate. By keeping the other parameters fixed and speed 1000mm/min, the various laser power (200, 300, 400, 500 and 600 W) are analysed. The various scan speed levels are 750, 1000, 1250, 1500 and 2000 mm/min on the fixed laser power of 300 W. The final laser treated specimen was carried out on every composition with the overlap of 30% using a scan speed of 1000mm/min and laser power of 300W. Depending on the laser power and scanning speed, the maximum hardness is achieved on the surface. The increase in melt depth is obtained by decreasing the scanning speed. Bansal et al. [23] investigated the erosive behaviour of Ni-20Cr2O3 coating on pipeline materials by HVOF spray process on the mild steel, SS 202 and SS 304. The L16 orthogonal array was used. The various factors are velocity, concentration in wt% and test duration. The velocities in rpm were taken as 500,800,1100 and 1400 rpm. Some defects were observed on the eroded surface are signature of lips formation along with its fractures, ploughing, micro pores and wear marks. The most dominating mechanism is micro cutting on the eroded surface. Tuhari et al. [24] has optimized the NiAl/Cr2C3 thermally sprayed coating by the Taguchi method. The experiment was done AISI 316 substrate. The L9 orthogonal matrix was used.
The factors are current (820, 850 and 880A), voltage (35, 40 and 45V), spray distance (90, 100 and 110mm) and power feed rate (35, 40 and 45 gr/min). The Taguchi analysis shows the current was the most significant factor for the hardness and wear responses. Voltage shows the minimum effect on the properties. The adhesive wear is the dominant mechanism for the coating for the wear resistance. Singh and Kaur [25] investigated the high temperature wear behaviour (NiCrSiFeBC) and (WC–Co) coating by HVOF thermal spray process. The best wear resistance was obtained at 400°C of the composite coating. The dominant wear mechanism was abrasion and adhesion at the both loads. Zhu and Li [26] compared the microstructure evolution of TiB2–Ni Cermet Coating thermally sprayed by the APS and HVOF process. Low carbon steel (0.45wt%) was used as a substrate. The microstructure of the coating was analysed by TEM, scanning electron microscopy, XRD analysis and microprobe analysis. The both process exhibit the difference in the properties of coating such as hardness and fatigue strength. The microstructural phase of both the coatings was different.

![Figure 4. Micrographs of chromium based HVOF spray coatings [21].](image)

Khan et al. [27] analysed the operating parameters of HVOF coating quality for the application in aerospace. The AISI 4340 steel was used as a substrate. The 2^4 factorial design method was used for optimizing the four process parameters. The four operating parameters used were fuel/oxygen ratio (3 and 3.33), spraying distance (225 and 250mm), coating thickness (0.25 and 0.5 mm) and power injection rate (50 and 100 g/min). The roughness, contact angle and micro hardness were analysed. The optimized fuel/oxygen ratio, power injection rate, coating thickness and spray distance were 3, 100g/min, 0.25mm and 225mm respectively. The optimum micro hardness, surface roughness and contact angle were obtained optimum parameters were 1148 HV, 2.81µm and 105.3° respectively. The chrome coating exhibited the lower micro hardness and contact angle at optimum condition when compared to HVOF thermal spray coating. Hajare and gogte [28] has done the comparative analysis of wear behaviour of HVOF sprayed thermal coatings on the SS304 substrate. The chromium carbide and tungsten carbide coatings have been studied. Image analyser, X-ray diffractometer, SEM, pin-on disc wear testing machine and EDS were examined to analyse the mechanical and structural characterizations. At various loads and room temperature, the wear resistance of tungsten carbide is
higher than the chromium coatings. There is a considerable effect of thermal properties of both coatings on the wear behaviour of the coatings. Zhao et al. [29] investigated the tribological properties of TiB2-NiCr Coatings HVOF-Sprayed with agglomerated feedstocks. The mild steel samples were used as a substrate. The coating comprises of TiB2, Ni2B and CrB phases as well as displayed dense microstructure. The micro hardness and coating roughness of TiB2-40NiCr coating is lower as compared with Cr3C2-25NiCr. On the application of dry sliding wear test, the adhesive wear was the primary dominant factor for both coatings.

3.2. Erosion
Liu et al. [30] examined the performance analysis of corrosion behaviour and cavitation erosion resistance of WC-12Co, WC-10Co-4Cr and Cr3C2-NiCr Coatings by HVOF thermal spray process. The author has chosen the stainless steel 1Cr18Ni9Ti as substrate on which the HVOF thermal spay coatings to be sprayed. The parameters used are represented in table 1. The cavitation erosion test was performed in the deionised water and 3.5 wt% NaCl solution. The author analysed that the eroded surface of stainless steel 1Cr18Ni9Ti was more uniform as compared with the coatings in the deionised water due to the presence of benefit from dense structure. The passivation layer is formed on the surface of stainless steel when it is dissolved in the 3.5 wt% NaCl solution which is prone to breakdown later leads to the increased cavitation erosion damage. Micro stiffness, porosity, and fracture durability all have an effect on cavitation corrosion resistance in deionized water. Because of the porosity, crack nucleation occurs, resulting in further cavitation erosion harm. In both deionized water and corrosive solvent, the WC-10Co-4Cr coating provides the highest resistance to cavitation erosion. Zoel et al. [31] has done the experimental and simulation study of residual stress distribution of WC-10Co-4Cr Coating sprayed by HVOF process on the AISI 1010 steel. Authors indicated the effective way to analyse the critical points of coating is the simulation which is cost effective substitute also. Owoseni et al. [32] analysed the residual stress of suspension HVOF-Sprayed Alumina Coating on 304 stainless steel substrates via a Hole-Drilling Method and XRDFuel (hydrogen) flow rate (l/min)-612, Oxygen flow rate (l/min)-306, Flame capacity (kW)-101, Suspension flow rate (ml/min)-90, Spray distance (mm)-85, Number of passes-41, and Spray gun traverse speed (mm/s)-5 are the different parameters used. The coating's microstructure reveals separate building components called lamellae. Hong et al. [33] investigated the Microstructure and cavitation erosion behaviour of ceramic metal coatings by the HVOF thermal spray for the application in hydro turbines. According to the cavitation erosion test, the lesser volume rate removal is observed in WC-CoCr coating than Cr3C2-NiCr coating at each flow velocity. Gonzalez et al. [34] optimized the parameters in the development of New Ti coatings deposited by HVOF spraying process on the application of DOE and ANOVA. On applying DOE, various effects of spraying distance, gun speed, powder feed rate, type of combustion, number of layers and type of substrate has been analysed to examine the porosity, hardness, adhesion and thickness (refer to Figure 5). In this L16 (4^4) orthogonal array has been applied. The most influence spraying parameters (from high to low) are spraying distance, number of layers, gun speed, power feed rate, type of substrate followed by O2/H2 ratio.

Ding et al. [35] HVOF sprayed multi-modal WC-10Co4Cr coatings were studied for deposition and cavitation erosion. Two HVOF structures, classified by the types of fuels, used 304 SS as a substrate with multiscale WC-particles. Because of the low porosity, the cavitation process was slowed and the cavitation rate was reduced. The synergistic effect of corrosion on cavitation erosion leads to more vulnerability in NaCl solution than in fresh water. Hong et al. [36] analysed the effect of different flow velocity of HVOF sprayed WC-20Cr3C2–7Ni and WC-10Ni on the cavitation erosion behaviour. The various flow velocities 23.4, 33.5 and 41.9 m/s corresponding to the 1400, 2000 and 2500 rpm were used for the testing. As the flow velocities increases the volume loss rate also increases for both the coatings. Nascimento et al. [37] studied the effects of HVOF sprayed tungsten carbide coating and hard chromium electroplating on the AISI 4340 substrate. The fluoride-free hard chromium coatings enhance the properties when compared to the conventional ones. The higher wear weight loss is found with the chromium coatings. Before test, WC shows better results for corrosion
resistance after sealing application. When both of the hard chromium electroplated samples were tested, the higher salt spray resistance is attributed towards the accelerated hard chromium electroplated specimens. Bansal et al. [38] investigated the erosive behaviour of Ni-20Cr2O3 coating on pipeline materials by HVOF spray process on the mild steel, SS 202 and SS 304 (refer to Figure 6). The L16 orthogonal array was used. The various factors are velocity, concentration in wt% and test duration. The velocities in rpm were taken as 500, 800, 1100 and 1400 rpm. The various levels of wt% are 25 and 50. Some defects were observed on the eroded surface are signature of lips formation along with its fractures, ploughing, micro pores and wear marks. The most dominating mechanism is micro cutting on the eroded surface.

![Figure 5. SEM-BSE micrograph of the Ti powder [34].](image)

![Figure 6. Energy dispersive spectrum for Ni20Cr203 HVOF coating [38].](image)

Zhang et al. [39] fabricated Co-based coatings, WC-Co-4Cr coatings, Fe-based amorphous/nanocrystalline coatings and WC-Co-4Cr /Co-based coatings, and cavitation behaviour were analysed in deionised water. WC-Co-4Cr coatings give the better cavitation resistance in comparison with other coatings. As the volume loss rate was the highest at the start of the test and then there is decrement before stabilizing within eight hour for the WC-Co-4Cr coatings. Microstructural defects such as pores and cracks were the dominant for the cavitation erosion performance. Singh et al. [40] investigated the erosion wear of WC-12Co coating by HVOF spray using Taguchi approach. Mild steel, SS304 and SS202 were used as a substrate material. For the testing of coated and uncoated samples, slurry erosion pot tester was utilized. It is shown by the ANOVA validation, the most significant factor for erosion wear of uncoated and coated samples is speed of impacting particles
followed by erosion test duration and slurry concentration. Liu et al. [41] analysed the performance of WC-10Co-4Cr HVOF sprayed coatings under slurry erosion. 35CrMo steel was used as a substrate. WC-10Co-4Cr coatings with bimodal structure and composite coatings were deposited on the substrate respectively. The reason behind the spalling of coating was propagation and crack initiation under fatigue stress under all mechanism of erosion test. Praveen and Arjunan [42] investigated the influence of HVOF sprayed NiCrSiB /c coatings addition on the erosion wear and microstructure. The AISI 304 stainless steel was used as a substrate. The microstructure of the coating shows the presence of Cr3B2 phases with minor phases of NiO and alumina, Cr23C6 and Ni. There is very variation of adding 0.7 and 1.4wt% of nano Al2O3 in the properties like porosity, adhesion and surface roughness of NiCrSiB coatings. On the addition of 1.4wt% of nano Al2O3, the micro hardness of the NiCrSiB coatings increased significantly. At 90° erodent impact, the erosion resistance of the coatings is enhanced by 1.5 times with the addition of 1.4wt% of nano Al2O3. The ductile mechanism such as micro-cutting, ploughing, indentation and type 1 cutting were the most dominating in the erosion. Moreover, the influence of nano Al2O3 exhibits the brittle characteristics such as pull out of alumina hard phase and mild cracking. Vasudev et al. [43] analysed the erosion behaviour and high temperature oxidation of the alloy-718/NiCrAlY coating by the HVOF thermal spray process. As a substrate, the GCI material was used. The coating is thick and has a low porosity. The coated sample has a higher micro hardness and lower oxidation rate for a marginal weight gain than the bare sample. The coating was protected from the extreme oxidation condition by the formation of TiO2, Cr2O3, NiCr2O4, and Al2O3. The fatigue results into the formation of craters and micro cutting which is attributed towards the loss to the bilayer Alloy-718/NiCrAlY. The coated sample of GCI confirms the three times better erosion resistance performance at 30° and 1.7 times at 90° impact angles. 

Kiilakoski et al. [44] investigated the impact of process parameter of Cr2O3 Coatings. The coatings were deposited by HVOF thermal process on AISI 316 stainless steel. The parameters taken are flow rate of auxiliary air-cooling nozzles for cleaning surface, total combustion gas flow, suspension feed rate, spray distance and pressure of the air curtain that can remove the fine particles as well as excess load while keeping other parameters constant. Depositing efficiency of coatings was good but largely varied quality noticed. The need of auxiliary systems is clear due to the deposition of fine unmelted particles between the interfacial splats. The microstructure, hardness, cavitation erosion resistance and surface roughness have been evaluated. The optimal spray distance, the flow rate of air cooling nozzles and pressure level of air curtain are 90 mm, 400slpm and 0.4MPa respectively. 

Tailor et al. [45] fabricated the thin copper coatings deposited by thermal spray HVOF process. Cu coatings were deposited on the low carbon steel substrates. The author has analysed the HVOF thin wire material can be used copper wire instead of feedstock powder. Low porosity, uniform deposition, good adhesion strength, good conductivity and low roughness are achieved by the thin copper coatings. The optimized conditions have been shown in Table 1.

| Spray parameter | Values               |
|-----------------|----------------------|
| Oxygen flow     | 230 slpm             |
| Air flow        | 550-650 slpm         |
| LPG flow        | 55 slpm              |

Qiao et al. [46] analysed the cavitation erosion mechanism as well as mathematical model was developed based on the amorphous/nanocrystalline coatings sprayed by HVOF process. AISI 321 steel was used as a substrate. The better cavitation erosion results with Fe based was employed. The reason for improving the cavitation erosion resistance in regard with Fe based coating were the high fracture energy per unit area and small grain size which is analysed by the mathematical model. Ghosh et al. [47] investigated the high efficiency of chemical assisted nano-finishing WC-coating sprayed by HVOF process The Murakami’s reagent is used in this analysis to improve the surface roughness using
the chemical aided shape adaptive grinding technique. On top of the coating layer with the lowest hardness, a thin passivation layer forms. X-ray photoelectron spectroscopy experiments demonstrate the presence of WO3 in the passivation layer. The surface roughness was reduced significantly from nanometers to micrometers. Zheng et al. [48] experimented the erosion behaviour of HVOF sprayed WC coating. The AISI 4140 stainless steel was used as a substrate. The hardness of the WC coating has been increased to 1120 HV and coating thickness was 360µm. When compared with bare sample, the erosion coating has increased with the coating.

4. Conclusion

In recent years, various combinations of coating and substrate have been explored which results in exploring various industrial sectors. The hardness of the surface engineered materials has been enhanced resulting in the wider use of applications. Lot of work has been reported on the tribological behaviour of the material processed by HVOF thermal spray coating. The result for the same is encouraging to explore further in this field. Erosion of material is of main concern for researchers in the field of surface coatings, and over the years it has been improved by employing smart coating and substrate selection. Optimized input parameters have been worked using various techniques gives cost effective solution to industry.

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