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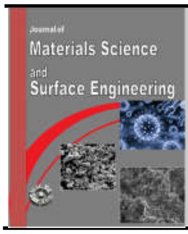

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Microstructure, Wear and Corrosion Properties of HVOF Sprayed Thermal Spray Coatings - A Review

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Abstract

Many industrial components failure due to wear and corrosion problems it may be protect in which used to deposit coatings by thermal spraying process. This process may be produced high quality coatings due to low porosity and low oxide content on surface reveals that dense deposits and hard coatings. Among, the thermal spraying process can be differentiate one the process mainly used to reduce failure of the components employed by High Velocity Oxygen Fuel (HVOF). This literature reviews especially of material degradation processes that are encountered in industrial components. It presents the effect of corrosion and wear on materials. Thermal spray technology to deposit metallic coatings is also presented in this review. It focused on the HVOF spraying technique due to its high flexibility and cost effectiveness. The HVOF process is used to improve the properties of substrates such as hardness, wear and corrosion. The microstructure and micro abrasive wear performance substrates were characterized by optical microscopy as well as by Scanning Electron Microscope (SEM). In addition, X-ray Diffraction (XRD) and Thermo Gravimentric Analyses (TGA) were undertaken in the partial characterization of the coating. A brief literature survey was carried out on the topic of wear resistant coatings and the literatures were grouped on the basis of different coating materials, different abrasive wear mechanisms, wear and corrosion behaviour of metallic based alloy powder coatings, characteristics of HVOF coating and applications of HVOF coating.

Introduction

The present literature survey was carried out on the topic of wear resistant coatings and the literatures were grouped on the basis of different coating materials, different abrasive wear mechanisms, and corrosion behaviour of metallic based powder coatings, characteristics of HVOF coating and applications of HVOF coating.

Coating properties based on used powder

Wielage et al [1], concluded that the WC-Co powders involved in HVOF thermal spray process were used for many applications to improve the properties on steel bars. Depending upon the structure, size and shape of carbide powders were used for spraying condition to vary the wear properties. The authors concluded that the HVOF sprayed cermet coatings exhibit higher wear resistance replacing the hard chrome plating. The wear behaviour depending upon on the carbide size in WC coatings was negligible with pure cobalt matrix.

Picas et al [2], analysed the efficiency of HVOF thermal spray coating of WC–Co powder on stainless steel and reported that the coating resulted in low porosity, better wear resistance, and superior hardness. Wang et al (2009), investigated the performance of the structure of WC-12Co coating that is deposited by HVOF process, moreover, authors found better wear resistance compared to other coating especially coating on mild steel.

Chen et al [3], coated WC-Co by HVOF on a stainless steel substrate. It was found that under conditions of micro-scale abrasion, the fine WC grain size in the nano structured material resulted in rapid pullout of the hard phase leading to high wear rates.

Yang et al [4], investigated the WC-Co carbide coating deposited by high velocity oxy-fuel spraying on JIS-SS400 steel substrates under controlled conditions. They reported that the effect of wear behaviour on WC carbide coating is based upon the grain size of the carbide. The coated surface showed very dense coating structure due to the formation of cobalt phase.

Tao et al [5], investigated the tribological properties of ceramic coating (Al_2O_3 and Cr_2O_3) using plasma spray on copper alloy and analysed the wear behaviour under dry sliding condition tested using block on ring method. They reported that Al_2O_3 coating exhibited lower co-efficient of friction because of the higher thermal conductivity of this material. The failure of Cr_2O_3 coating was predominantly due to the propagation of crack in the microstructure which is induced in the splat formation.

Ouyang & Sasaki [6], reported that the Cr_2O_3 coating on AISI 304 stainless steel exhibited a very low co-efficient of friction at room temperature, because of high hardness and better tribological behaviour of Cr_2O_3. Moreover, at higher temperature there is an increase in friction and wear because of the formation of small pores and voids.

Yin et al [7], analysed the debris particles formed during the wear test of stainless steel substrate which was coated with $Al/Al_2O_3$and reported that coarse particles and flakes were found in the microstructure, and the wear mechanism was dominated by adhesive wear, and fatigue-induced detachment of transfer film from the ceramic coating. They also reported that the bonding

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strength of this composite coating was higher than that of Al_2O_3 coating.

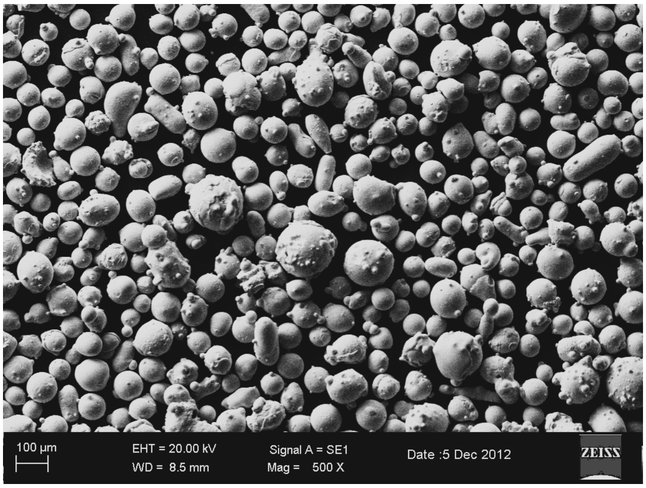
Atamert & Stekly [8], investigated the FeSiBCCr coated on duplex stainless steel by using hard facing method. The microstructure shown dispersed and present un-melted particles is determined by XRD characterization. Hardness at elevated temperatures is retained by the matrix. The principal alloying elements in Ni-based alloys are Si, B, C and Cr. The abrasion resistance can be attributed to the formation of extremely hard chromium borides. Besides carbides, Laves phase is also present in the matrix.

Moore [9], classified iron based alloys into pearlitic steels, austenitic steels, martensitic steels and high alloy irons. The principal alloying elements used are Mo, Ni, Cr and C. The softer materials, e.g., ferritic, are for rebuilding purpose. The harder materials, e.g., martensitic, on the other hand, provide wear resistance. Such alloys do not possess much corrosion, oxidation or creep resistance. Nickel aluminide is another example of coating material. The pre-alloyed Ni-Al powders, when sprayed, react exothermically to form nickel aluminide. This reaction improves the coating substrate adhesion. In addition to wear application, it is also used as bond coat for ceramic materials.

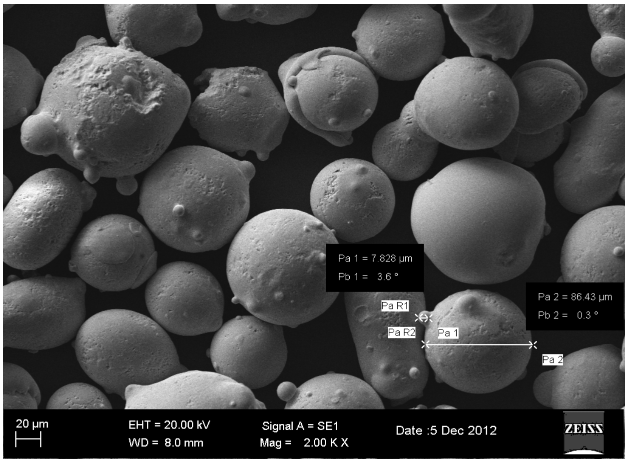
Hebsur & Miner [10], have identified that NiCoCrAlY alloy coating on stainless steel exhibits higher temperature corrosion resistance and hence, it finds application in gas turbine blades. The compositional flexibility of such coatings permits the tailoring of such coating composition for both property improvement and coating substrate compatibility. In addition, it serves as a bond coat for zirconia based thermal barrier coatings.

Alhelisten [11], found that the DIA-JET process involving a DC Ar/H2 plasma with methane gas supplied at the plasma jet is capable of depositing diamond films at a high rate. However, the oxy-acetylene torch produced from the combustion chamber is based on process parameters. Finally the coating build in the condition of surface is diamond film thickness. The diamond films are tested for the sliding wear against abrasive papers, where wear progresses by micro fracturing of protruding diamond grits. The processes continue till the surface becomes flat and thereafter, wear progresses by an interfacial spalling. Therefore, the life of the coating is limited by its thickness.

The SEM image of the Fe alloy feedstock powders. The satellite particles were typically size whereas spherical particles size ranged from 20-80 µm as shown in Figure 1.



(a)



(b)

Figure 1: SEM image of Fe based alloy powder [78]

Wear characteristics of the coatings

Sato et al [12], concluded that the wear-resistant coatings can be as vulnerable to oxidative wear as monolithic metal against copper substrates. For example, copper cutting tools coated with titanium nitride, titanium carbide or a combination of both compounds undergoes rapid wear because the titanium nitride and carbide coatings undergoes oxidation of the nitride and carbide to form titanium oxide which is then rapidly worn away.

Ahmed & Hadfield [13], found that the 100-200 µm thick plasma-sprayed tungsten carbide coatings on steel and ceramic balls fail by surface wear when lubrication is poor or by sub-surface delamination when there is effective lubrication.

Li et a1 [14], investigated that wear performance of the WC-Co powder coating on stainless steel by using HVOF process. It was identified that thermal spraying process coatings provide a very cost effective solution by protecting the operating components from wear damage. The coating material, mechanical properties and physical properties can determine coating performance in resisting wear damage. Moreover, composite based materials and HVOF sprayed small carbides exhibit excellent wear resistance. Operating components engaged in sliding wear applications usually experience accelerated material loss. Author reported that Near-nano-structured WC-18Co coatings on steel substrates by HVOF coating. In this thermally sprayed coating is associated with the coating microstructure, mechanical properties, physical properties, coating defects such as inclusion and porosity. Moreover, the tribological behaviour of the sprayed HVOF coating is significantly influenced by the microstructure properties. Therefore, thorough review and understanding of the coating microstructure features that control sliding friction and wear behaviour in thermally sprayed coatings is required.

The authors concluded that the HVOF deposited coatings on AISI 4140 alloy steels were used to improve the wear resistance of the substrate material. It also can be improved with increased coating hardness according to Mohanty et a1 (1996).

Chaudhury et al [15] investigated that wear performance of Al-2Mg-TiO_2 composites techniques used to deposit on copper substrate. The modes such as adhesion, abrasion, erosion, surface fatigue and tribo-chemical reaction. Each wear mode can also be divided additionally into various wear mechanisms. In studying the wear behaviour of materials, a specific mechanism of material removed may be dominant; however, several wear mechanisms operate at the same time.

Shrestha & Sturgeon [16], reported that microstructure investigate on samples were hard structure and dense structure is present by the HVOF sprayed coatings with alloy NiCrSiB on EN 10083-1 C40E carbon-steel. The mechanism of wear investigates on surface employed to the morphology of surface and behaviour of materials effectively. Moreover, the concentration of abrasive particles rolled over on surface revealed low wear and sever wear was carried out.

Mechanism of abrasive wear

Much of this more complex view of abrasive wear is relatively new since, like all forms of wear, the mechanisms of abrasive wear are hidden from view by the materials themselves. Until recently, direct demonstrations of abrasive wear mechanisms were virtually nonexistent. The development of the Scanning Electron Microscope (SEM) has provided a means of looking at some aspects of the abrasive wear in closer detail. In one study (Kayaba 1984)) a rounded stylus was made to traverse a surface while under observation by SEM.

Lim & Brunton [17], reported that the pin on disc wear rig was constructed to operate inside the SEM, and to allow direct observations of wear. Two basic mechanisms revealed: a cutting mechanism and a wedge build up mechanism with flake like debris Kayaba, 1984. This mechanism was later called 'ploughing', and was found to be a less efficient mode of metal removal than 'micro-cutting'. In a separate study by Bates et al. (1974) authors state that actual wear situation the effect of cutting alone is relatively small since much more material is lost by a process that has characteristics of both cutting and fatigue.

Dean & Doyle [18], reported that a stylus with a fractured surface containing many 'micro-cutting edges' removes far more material than un-fractured pyramidal or spheroidal styluses. Similarly, a grit originated from a freshly fractured material has many more micro-cutting edges than a worn grit which has only rounded edges. Beneath the surface of the abraded material, considerable plastic deformation occurs.

Rutherford & Hutchings [19], authors reported that the micro-scale abrasive wear test help to identify the wear performance of substrate materials as per ASTM G77 is being widely used in studies on abrasive wear of materials. The micro scale abrasion test (also known as the ball-cratering abrasion wear test), in which ball is rotated against a specimen in the presence of different volume concentration slurry fed in to the surface finally revealed wear performance at different loading conditions. Many of the industrial components were employed this test was carried out in the part of wear transition.

Trezona et al [20], studied the test conditions on the wear rates and mechanisms. Authors stated that wear transition relatively produced in the different regimes of particle motion at different loading condition. It also define the particle motion like to create two body grooving abrasion on coated surface and certain condition particle has to rotate between surface has been produced three body rolling abrasion was carried out. Since wear is a system response and is not a material property, the wear resistance of a material can vary over wide range if different mechanisms are induced by different test conditions Kato & Adachi (2000).

According to Cozza et al [21], wear mode map plot has to identify the mechanism of two body and three body condition on coated surface at different volume concentration. The result shown on the surface moving of slurry particles between the surfaces may be produced the modes, and based on the hardness of the abrasive particles. Apart from the slurry particles move on surfaces dynamically is withstand the toughness of coated surface. Moreover, the dominant wear modes in the micro-scale abrasion test have been reported to be influenced by the applied load and volume fraction of abrasive in the slurry.

Adachi & Hutchings [22], reported that in the micro scale abrasion wear test, a rotating ball is forced against the tested specimen, in the presence of abrasive slurry, and the abrasive particles rolled on soft and hard surface at different loading, and it's finally showed on surfaces is some crater formed at the condition of rolling or grooving abrasion.

Allsopp et al [23], determined the nature of the abrasive particle motion in the contact region between the ball and the specimen. If the particles do not move relative to the ball surface, but act as fixed indenters moving across the specimen, a series of fine parallel grooves is produced on the specimen surface. This leads to the so-called grooving wear or two body abrasion. If on the other hand, the abrasive particles roll between the two surfaces, indentations with no evident directionality are produced in a process known as rolling abrasion or three body abrasions.

The two-body abrasive wear corresponds closely to the 'cutting tool' model of material removal, whereas the three-body abrasive wear involves slower mechanisms of material removal, though very little is known about the mechanisms involved (Johnson 1968). The Figures 2 and 3 is showed that particle motion on surfaces at different loading aspects to produced different modes in the presence of volume of slurry concentration. Normally the slurry particles hardness is high is dominant against counter surface was performed with the use of Micro scale abrasion apparatus.

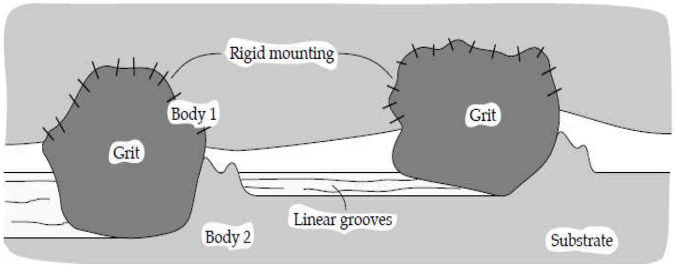


Figure 2: Two body mode abrasive wear [80]

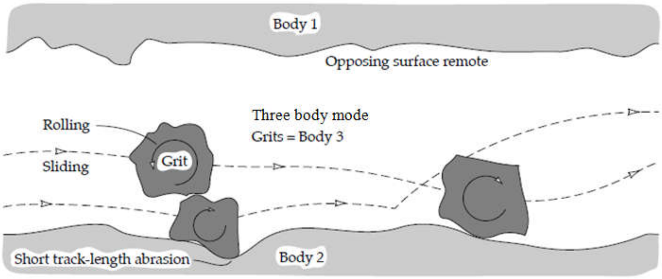


Figure 3: Two body and three body mode of abrasive wear [80]

Moore & Swanson [25], concluded that abrasive particle shape has an effect on the rate of wear. This is because it influences the transition load from elastic to plastic contact and the critical indentation size of fracture. If particle load and surface hardness are constant, the projected area of plastic contact will be constant, but the cross-sectional area of a groove resulting from such a contact will depend on the particle shape. The authors showed that the ratio of cross-sectional to projected area of contact for pyramidal, conical and spherical indenter increases as the included angle, cone angle and radius decreases respectively (Moore 1981).

Deuis [26], found that sharp crushed particles resulted in rates of wear typically two to five times higher than that produced by their rounded counter parts. It is expected that the wear rate will be higher for "sharp" pointed abrasives than for "blunt" round abrasives. The wear rate was obtained by using rounded and crushed silica sands against steel surface.

Swanson & Klann [27], reported the factor often in the volume loss of the plain carbon and low alloy steels and examined using the wet and dry sand rubber wheel abrasion tests with round and angular silica abrasives.

Avery [28], has concluded that the abrasive particle size also affects the wear rate of materials. When the materials and the abrasive type remain fixed, the wear rate increases with increasing particle size up to a certain size; above this critical size, the wear rate becomes almost independent of further size increases. This critical size is often cited as about 100 µm.

Larsen-Basse & Premaratne [29], have found that the abrasion under conditions where Ha/Hs less than 1.2 is sometimes termed soft abrasion, in contrast to hard abrasion when Ha/Hs greater than 1.2. The critical transition point between the hard and soft abrasion appears to be the point at which plastic deformation in the form of grooves and scratches occurs. Eyre (1979), has found that the microstructure of materials effects their wear properties. For ferrous materials, various factors like retained austenite, carbide content and size, heat treatment regime and alloy content impact on the wear properties.

Hutchings [30], has found the structural properties are important in abrasive particle contact. Parameters such as volume fraction and distribution of a dispersed phase, its coherency and hardness all affect abrasive particle indentation, strain hardening, strain distribution, fracture, and recovery processes.

Deuis et al [31], has reported that the worn surface will be strain-hardened by plastic flow, and that hardness will generally be greater than that of the bulk. Moreover, the micro cutting mechanism becomes more dominant as the hardness of the material increases. This was observed not only for abrasion with angular abrasives, but also for abrasives with a more rounded morphology.

Garcia et al [32], have reported that the temperature increase caused by plastic deformation during abrasion is associated with the speed of sliding. The abrasive hardness to metal hardness increases with increase in temperature leading to a higher wear rate. In addition, in the three-body abrasive wear, contact between an abrasive and the worn surface would be particularly short compared with that in the two-body abrasive mode.

Inman et al [33], found that the three-body abrasion, heat generated in the deformed material would not easily diffuse into the abrasive particles. This causes thermal softening of the surface material while the abrasive particles has strongly scratched on soft materials although it is not changed the characterization of surfaces during dry sliding conditions. Moreover, the surface hardness is not higher than the abrasive hardness of the slurry particles. The oxidation of steels in air is much more rapid at 600°C than at 20°C, and as temperature rises, the removal of steel as oxide becomes more significant.

The images of (Fig. 4) rolling and grooving abrasion was produced on steel materials at normal load with corresponding slurry concentration formed at normal conditions by using Micro scale abrasion performance.

Coating performance

Surface Preparation for Thermal Spraying

Varacalle et al [34], reported that high bond strength was most influenced by higher current, longer spraying distance and lower pressure. It was performed the surface roughness produced by grit blasting A36/1020 steel using different abrasives. The higher surface roughness and adhesion were produced by grit blasting under the spraying parameters. The effect of grit blasting on substrate material coating based on the parameters such as blast media, blast pressure and working distance was to improve the coating bond strength. The investigation of adhesion property testing of coated specimen based on the grit blasting thickness enhanced the bond strength.

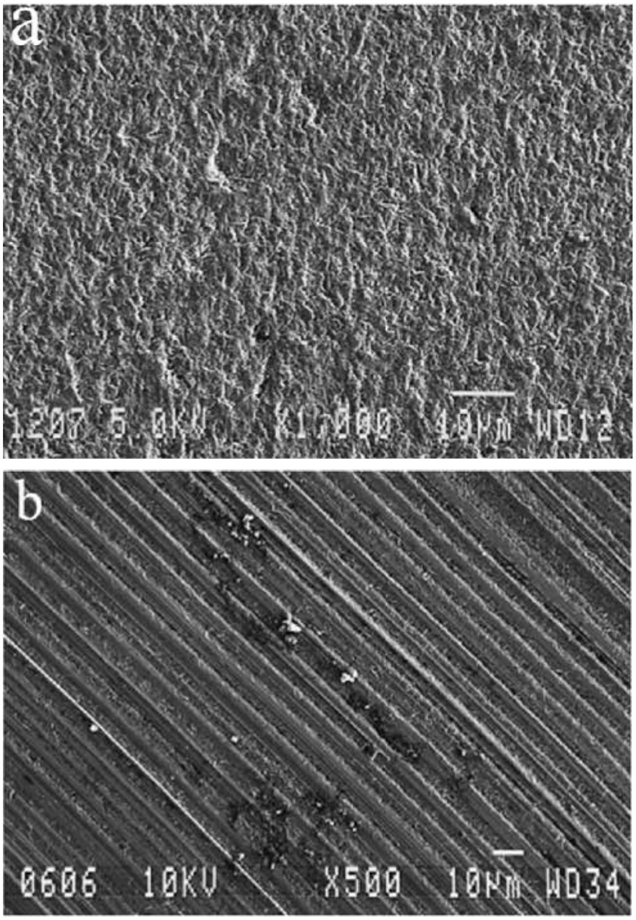


Figure 4: SEM imags of (a) Three body abrasion (b) Two body abrasion produced on steel materials at normal load with slurry concentration [79].

Tolpygo et al [35], concluded that the surface of platinum modified nickel aluminied bond coats on super alloys by grit blasting to deposition of thermal barrier coatings (TBCs). The oxidation of bond coat on the surface, cracking and spalling of the scale was formed in the surface. The results of this work suggested that the impurities introduced by grit blasting of the bond coat surface prior to TBC deposition, were expected to strongly affect the performance and durability of the coating.

According to the conclusion of the authors Shigeyasu Amada & Tohru Hirose (1998), influence of grit blasting (Al_2O_3) pre-treatment on mild steel to improve the adhesion strength and roughened surface was improved by plasma sprayed coatings. The authors reported that the properties of adhesive and roughness value were exhibited from coated surface at the maximum values of blasting angles. The surface topography of substrates and the fractal dimension was determined by the roughened surfaces. It is concluded that fractal dimension is a better measure than average surface roughness for the evaluation of the adhesive strength of ceramic coatings.

James et al [36], conducted the grit blasting process (Al_2O_3) prior to plasma spray coating and found that it affects the various properties of the steel substrate and coating. Investigation of the adhesion of thermally sprayed coatings depends on the condition of surface layer, and the grit blasting process provides the roughened surface. The authors concluded how the understandings of the process parameters contribute to the coating properties and a feasible method for process control to achieve manufacturing ability and zero defects. Moreover, the grit size and blasting thickness are based on the properties desired in the coated surface. Staia et al [37], found that thermal spray coating improved the adhesiveness properties of coated surface. The grit blasting process generated sufficient surface roughness, which ensured mechanical anchoring between the coating and the substrate. The authors concluded that WC-Co thermally sprayed coatings on AISI 1020 steel substrates are often used for their high hardness and resistance to abrasion wear. However, thus coating is more sensitive and could even predict.

Heat Treatment of HVOF Coatings to Improve Performance

Li et al [38], examined the effects of NiCrAlY powder coating on stainless steel substrate by HVOF method. The authors found improvement in adhesive strength, shear strength, young's modulus and micro hardness. The main reason for the increase in the properties of the materials is due to the presence of the additional crystallization of the calcium phosphate amorphous phase on the surface of coating.

Lee & Min [39], investigated the properties of NiCrWMoB alloys sprayed on AISI 316L stainless steel by HVOF method and reported low porosity (< 1%) due to the fine precipitates of the borides and carbides present in the coated substrates and also the residual stress in the as-sprayed coating. Rodriguez et al (2000), concluded that the effective approach to improve the coating performance of WC-NiCr alloy deposited on steel substrates is by applying post-coating heat-treatment.

Dent et al [40], found that the Fe based alloy coating on mild steel substrate by HVOF process has been used to produce better mechanical properties of the substrate materials. In these alloys of NiCrBC and FeCrBC better results such as micro-hardness, less porosity and increase in the wear resistance were reported. The amorphous phase is the main reason for the increase in the hardness seen initially. Moreover, the devitrification will lead to the formation of nanoscale Fe grains and nanoscale boride/carbide precipitates during the coating process.

According to Lee & Min (2000), the effect of annealing on hardness was improved in the sprayed surface and annealed surface at different temperature. The high micro hardness was exhibited in the coated surface in high temperature. The reason was associated with a substitutional solid solution hardening by super saturation, and fine precipitates such as borides and carbides in the sprayed coating. Moreover, the porosity was decreased with the annealing temperature. The coating structure was densified as the sintering due to the high treatment process filled up the voids.

Fatigue Performance of HVOF Coatings

Puchi-Cabrera et al (2006), reported the fatigue behaviour steel materials relatively both uncoated and coated with a Ni based alloy deposited by HVOF thermal spraying. It was found that the process of grit-blasted on samples mechanically sprayed or deposit on surface to create internal stress concentrators, inducing the nucleation of fatigue cracks propagate on surface, coating interface, which the reducing of fatigue life. However, reduction of failure in the surface is mainly identified in which the corrosion-fatigue failures, help to increased the performance of the coated surface and identify the corrosion morphology by various image techniques.

Al-Fadhli et a1 [41], investigated the corrosion–fatigue behaviour of Inconel-625 thermally sprayed using HVOF coating applied over plain and welded stainless steel substrate and found the pit formation at the surface. However, the presence of the un-melted alumina particles in the coating interface possibly caused localized corrosion, which took effect after a long period of exposure. As a result of interconnected porosity, corrosion media may penetrate the coating and attack the substrate, even though the coating itself is resistant to the particular corrosive environment. Padilla et a1 [42], evaluated the fatigue performance of 4140 steel substrate that was HVOF sprayed with NiMoAl kind of deposit either for improving some of its properties, such as wear and corrosion resistance, or achieving the required dimensions in order that the worn, undersized or ground components could fulfill properly their role in service. The different elevated alternative stresses exhibited in the low fatigue resistance due to the repeated operations of several cracks increase the fatigue life.

Voorwald et al [43], coated WC-17Co and WC-10Co-4Cr on AISI 4340 steel and reported a reduction in the axial fatigue strength of coated steel in comparison to base metal. The decrease in fatigue strength induced by the HVOF processes may be associated with the high density of porous and oxide inclusions into the coatings, which are possible crack nucleation/initiation sites.

Electrochemical and corrosion behaviour of HVOF coatings

Bakare et al [44], reported that the amorphous form of $Fe_{43}Cr_{16}Mo_{16}C_{15}B_{10}$ alloy coating on steel substrates good corrosion resistance which is resulted to the crystalline form in the conditions of 0.5M H_2SO_4 and 3.5% NaCl environment. The improved corrosion behaviour of the largely amorphous material is attributed to its homogeneity, and particularly to the elimination of the Mo-rich phase in form of crystalline resulted to more corrosion resistance at NaCl and H_2SO_4 environment condition.

Zhang et al [45], coated Fe-based amorphous coatings with the composition of $Fe_{48}Cr_{15}Mo_{14}C_{15}B_6Y_2$ on mild steel substrate by the high velocity oxygen fuel (HVOF) spraying process. The feedstock powders deposit on substrate relatively melted and un-melted particles were shown on morphology of the surface. In coating characteristics resulted better wear and corrosion resistance revealed on surface at NaCl environment. The coating prepared with coarser powders and larger porosity exhibits greater corrosion resistance than the coating prepared with finer powders and lower porosity.

Tang et al [46], investigated the performance of NiCrAlY alloy coating and oxide content on mild steel substrate. In this coating a duplex oxide layer was observed which had α-Al_2O_3 sub-layer and a $Ni(Al,Cr)_2O_4/Cr_2O_3$ upper layer. The oxide scale formation on the coatings can be significantly affected during HVOF process in the presence of oxidation is resulted increasing porosity. Low oxygen content in the coating is beneficial to the formation of a protective α-alumina scale.

Zhao et a1 [47], coated FeCrSiMoMn on austenitic steel using a high velocity oxy-fuel (HVOF) spraying process. The HVOF process coating used in the steel resulted in higher micro-hardness. Moreover, the coatings had improved corrosion resistant than the coatings deposited by the APS process, because the oxidation of the powder material during HVOF spraying was much lower than that during APS.

Neville & Hodgkiess [48], coated WC and Nickel based metallic alloy powders on steel materials investigated the HVOF thermal spray process on steel substrates and analysed their ability to resist corrosion due to salt water at different temperatures. Authors investigated the corrosion performance of inconel 625 coatings on carbon steel by HVOF sprayed method. The authors revealed that the low porosity present in the coated surface helps enhancing corrosion protection. The reasons for the improvement of corrosion resistance in the coating are due to better sealing of the pores and voids in the microstructure.

Sidhu et a1 [49], compared HVOF coating of two alloy powders such as NiCrBSi and Stellite-6 powders on Superni 75 and reported that Stellite-6 coating provided a better hot corrosion resistance than the NiCrBSi coating. The reasons are the oxides of chromium and nickel, and their spinels might have contributed to blocking the transport of degrading species through the NiCrBSi coating and provided hot corrosion resistance.

Zhao et al [50], coated NiCrBSi alloy powders on a low carbon steel substrate using high-velocity oxygen fuel (HVOF) thermal spraying, and carried out corrosion tests by immersing the specimens in 3.5% NaCl with pH adjusted to 3 by addition of acetic acid. It was found that the corrosion of the NiCrBSi coating first occurred around the particles that had not melted during spraying and the defects such as pores, inclusions and microcracks, resulting in exfoliation or laminar peeling off. The authors concluded that the thermal spraying parameters for reducing the electrochemical unevenness or sealing the pores can improve the corrosion resistance of the coating.

Microstructure of the Coatings

Edris et a1 [51], the study HVOF spraying was used to deposit coatings of the Ni-based alloy Inconel 625 onto mild steel substrates and the concluded that the structure of the sprayed coatings were related to the processing conditions employed. The as-sprayed microstructure was found to consist of Ni-based alloy coating is exhibited more $NiCr_2O_4$ crystal orientation present in the structure of the coated surface. The microstructure of these Inconel 625 exhibits a characteristic and layered appearance. The darkest rounded features were identified as pores.

Verdon et a1 [52], investigated the microstructures of two tungsten carbide–cobalt (WC–Co) coatings, deposited on stainless steel using high velocity oxy-fuel (HVOF) thermal spraying method in different conditions. The morphology of coated surface showed additional phases was identified by using XRD dispersed in tungsten and tungsten carbide in the coated surface. Moreover, the composition of the binder fluctuates through the microstructure and that the tungsten concentration in the binder increases at the expense of the volume fraction of the remaining WC grains. In addition, new crystalline phases appearing during the HVOF thermal spray process were also reported.

Dent et a1 [53], examined the micro structure of the HVOF sprayed NiCrBC powder coating on stainless steel substrate. It shows splat like microstructure which is a characteristic of thermally sprayed metals. The amorphous phase region is identified by using TEM. The formation of the amorphous phase was due to the high cooling rates of the splats combined with the alloy composition of the shown microstructure. The authors concluded that hydrogen fuel is believed to influence the coating microstructure during the HVOF process. Particle size is usually influenced by particle temperature during spraying where particle size and temperature are both inversely related. The presence of voids in the un-melted particles results in porosity.

He et a1 [54], found that the microstructure and property of the feed stock powder could be retained in the coating process under spraying parameters. The microstructure revealed that the un-melted particles were the reason behind the increase in density and micro-hardness of the materials. He et a1 (2000), reported that the particle size range is determined by the particle temperature during spraying, where the particle temperature reduces as the particle size increases. The powder characterization and the performance of the coatings was investigated by using various methods such as scanning electron microscope (SEM), X-ray, transmission electron microscope (TEM), thermogravimetric analyzer (TGA), and micro-hardness measurements. There is no evidence for the presence of an amorphous phase in the sintered WC-12 pct Co powder, and the binder phase in this powder is still crystalline form of Co.

Horlock et a1 [55], studied the high velocity thermal process coating of Ni(Cr)-TiB_2 particles on steel substrates and reported that the particles were uniformly distributed throughout the coating with little evidence of porosity or cracking. The microstructure exhibited in these multiphase coatings is multilayer that resulted in improved hardness, size distribution, wear resistance and ceramic/matrix bond strength.

Ji et a1 [56], revealed that NiAl intermetallic coatings deposited on AISI 4140 steel by HVOF process exhibit high hardness, improved modulus of elasticity and excellent carburization resistance at high temperature. The abrasive wear resistance is influenced by the microstructure parameters mainly carbide particle size, carbide content and the bonding of carbide particles. HVOF process produces dense coating structures with elevated hardness and bond strength and less residual stresses.

Wu et al [57], investigated FeCrSiBMn coatings prepared by high velocity oxy-fuel process on stainless steel. The different techniques normally used to determine the characterization of microstructures of the coating details investigated by OM, SEM, and XRD. The presence of Fe-Cr matrix and several kinds of borides was identified in form of particles may be melted and un-melted condition in the surface. The analysis of metallic powder particles may be form of amorphous and crystalline form exhibited in the structures in the shape of agglomerate or sintered conditions. The coating displayed excellent resistance to the cavitation erosion in fresh water to form complex microstructure.

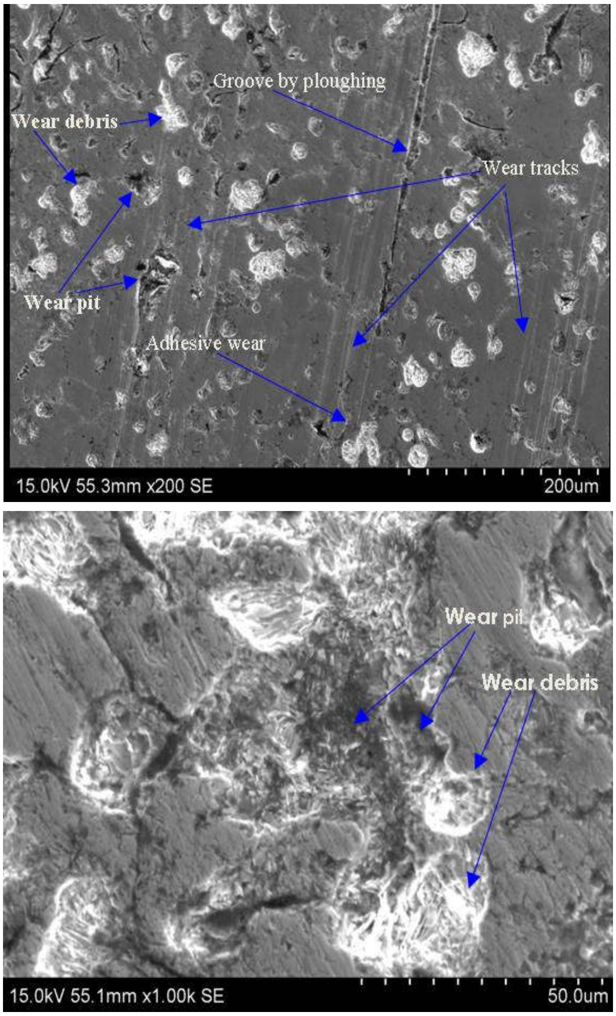


Figure 5: Fe based alloy coating surface morphology images by SEM [78]

Kim et al [58], reported that the FeCrB based gas atomized powders (Armacor M and 16), were thermally sprayed on a low carbon steel substrate, using the HVOF process. The microstructure of the cross-section of the coatings was examined by SEM. Using backscattered electron imaging, two different phases present were seen at different contrasting levels. Those phases were then identified as Fe-rich, FeCr solid solution (the bright contrast area) and Cr-rich, chromium-iron boride (the dark contrast area). The boride phase was homogeneously distributed in Fe-based matrix. The size of the boride phase in the coating was smaller than those found in the feed stock powder. This is explained by the authors as the same phenomenon in decarburizing during spraying. The contact area for individual abrasive particles is usually much larger than that of the surface particle, and wear occurs predominantly by plastic ploughing and cutting. Figure 5 SEM shows the global distribution of wear debris. Signs of 'adhesive wear' are also evident along the wear-tracks.

Influence of HVOF spraying parameters on coatings

Edris et a1 (1997), sprayed Ni-based alloy (Inconel 625) onto mild steel substrates and reported that HVOF process parameters influence coating microstructure and coating oxygen content.

Kim & Suhr [58], investigated the influence of fuel and oxygen ratio on the characterization of the HVOF sprayed Cr_3C_2 coatings on low carbon steel substrate. The authors concluded that the hardness was increased due to the formation of coating matrix densification during heat treatment.

Lih et al [59], found that the velocity of oxy-fuel is a coating process parameter for preparation of the CrC/NiCr coatings on stainless steel. The authors reported that the microstructure of the coating surface properties depends on the stand-off distance and oxygen flow rates.

Sartwell et a1 [60], observed that HVOF process is more used for cost effective and good bonding strength than hard chrome plating coating process. The performance of the coating process has been found exhibiting superior performance for protecting landing gear, hydraulic actuators and propeller components.

Reignier et a1 [61], reported that the cermet (WC-Co) coating deposited on landing gear substrate by HVOF process produced good adhesion property of surface. The authors concluded that the HVOF process produce better properties than the hard chrome coating. Tan et a1 (1999), reported that HVOF technique was used in the aerospace landing gear component to solve the problems faced in high temperature environment.

Taha-al et al [62], investigated the diamalloy 1005 containing WC particles on steel coating by laser melting process. In this research, the effect of WC percentage composed in the coated surface and based on the residual stress formed in the coating was studied. The residual stress in the coating was examined by XRD technique used to predict the stress in the material interface. The residual stress of the coating is based on WC content in the coating.

Giovanni Bolelli et al [63], investigated the surface stress by X-ray diffraction (XRD) technique. The stress measured in the ceramic coating contains compressive and tensile based thickness of the coating. The authors concluded that variation of experimental parameters and analytical techniques applied on surface influences the residual stresses on the surface.

Stokes & Looney [64], concluded that the selection of HVOF thermal spray process parameters has great contribution in limiting the rising of the residual stress in the coatings. The residual testing was carried out on samples build up in resulted from thick coating materials. The HVOF process is determined like residual stress on samples on testing help to identified internal cracks and failure. Authors reported internal failures due to internal stress or residual stress at HVOF spraying process at normal conditions.

Pinaa et al [65], investigated the residual stresses on HVOF thermally sprayed coated materials based on the two stages of stress generation: Quenching stress and secondary cooling stress during coating. The authors reported that superposition of residual stress in the coating results in elastic behaviour. Moreover, the cooling stress on the sprayed coating revealed little cracks formed during the stress concentration.

The purpose of table1shown the parameters involve coatings were performed on certain materials. These parameters may be helped to identify the quality of the coatings in which HVOF process is used on substrate at ambient conditions. Authors reported that different parameters on used on substrate materials to improve the coatings performance.

Table 1: Shown spraying parameters of HVOF coating.

Spraying Parameters	SUS 316L [81]	Hastelloy [81]	FeSiNiCr [78]	FeBCr [78]
Fuel flow rate (L/min)	0.322	0.379	0.552	0.552
Oxygen flow rate (L/min)	850	861	956	956
Barrel Length (mm)	0.7	0.82	0.93	0.93
Powder feed rate (g/min)	102	102	115	115
Torch velocity (mm/s)	70	59	47	47
Spray distance (mm)	380	380	200	200
Powder feed gas	Nitrogen	Nitrogen	LPG	LPG

Hardness of the coating

Mahesh et al [66], reported the hardness of coatings on superalloy substrates measured in the range of 210-272 HV. The hardness values slightly increase in the coating interference depth is attributed to the presence of oxides and the lower hardness values in the tested location and presence of porosities. However, Al has stronger tendency to dissolve in Ni to form solid solution increasing the hardness.

Fanga et al [67], investigated the coating of WC-CrC-Ni powder on Inconel 718 substrate by HVOF process. The author concluded that surface hardness depends on the parameters used in the coating process.

Wu et al [68], investigated the FeCrSiB alloy coating on stainless steel by HVOF process. Mostly, the hardness value determine in the cut section of the coated specimen at different levels. The properties of hardness testing on coated samples employed by SEM images and further values taken on surface after preparation samples was reported. The value of hardness exhibited is higher is to reasons for present molten and semi molten boride particle present in the microstructure and also due to the well flattened regions and un-molten particles (α-Fe (Cr, Si).

Alleg et al [69], coated partially amorphous $Fe_{75}Si_{15}B_{10}$ on carbon steel and reported that the micro hardness strongly depends on the material's microstructure. Moreover, the SEM images (Figure 6) was revealed severe abrasive grooving track is formed on coated surface due to diamond slurry medium environment reported by the author of shunmuga priyan et al [78].

Ak et al [70], studied NiCr coatings on stainless steel substrates and reported that the hardness values of the HVOF-sprayed coatings strongly depend on porosity, oxidized, un-melted/semi-melted particles, and inclusions.

Wear and corrosion properties on Fe-based alloy powder coating

Hyung-Jun Kim et al [71], investigated the coating of FeCrB based gas atomized powders, (Armacor M and Armacor 16), on steel substrates using the HVOF process. Authors stated that coating surface was improved all the basic properties such as wear resistance and good magnetic properties at low coat materials.

Liu et al [72], have reported that Fe-based amorphous metallic glasses are considered to be extremely viable candidates as surface protective coatings because of their high crystallization temperature, superior corrosion /wear resistance and relatively low material cost. For example FeCrB based amorphous coatings exhibited very high amorphous content, excellent corrosion resistance, extremely high hardness and prominent erosion resistance. Furthermore, thermal sprayed coatings with partially amorphous structure do not gave the anticipated excellent protection against wear/ corrosion due to the defects such as lamellar structure and pores, which are unique characters of thermal spray coating.

Kuroda et al [73], found that the Fe based alloy coating deposit on 316L stainless steel improved the corrosion resistance due to the proper proportion of porosity and amorphous fraction. The HVOF sprayed coatings have been widely used for industrial applications where good wear or corrosion resistance are needed, because the coatings exhibits low porosity, high hardness, and low oxide content.

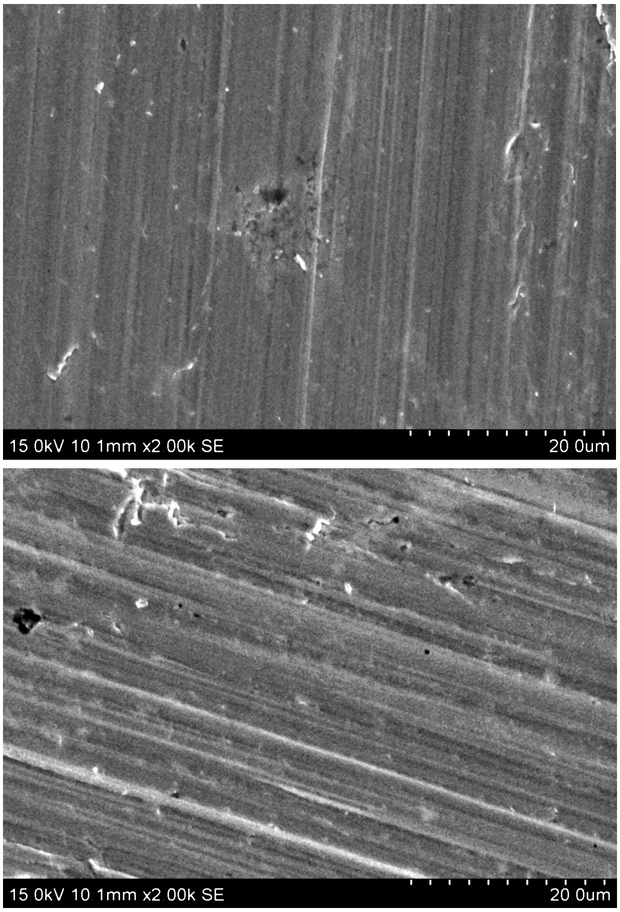


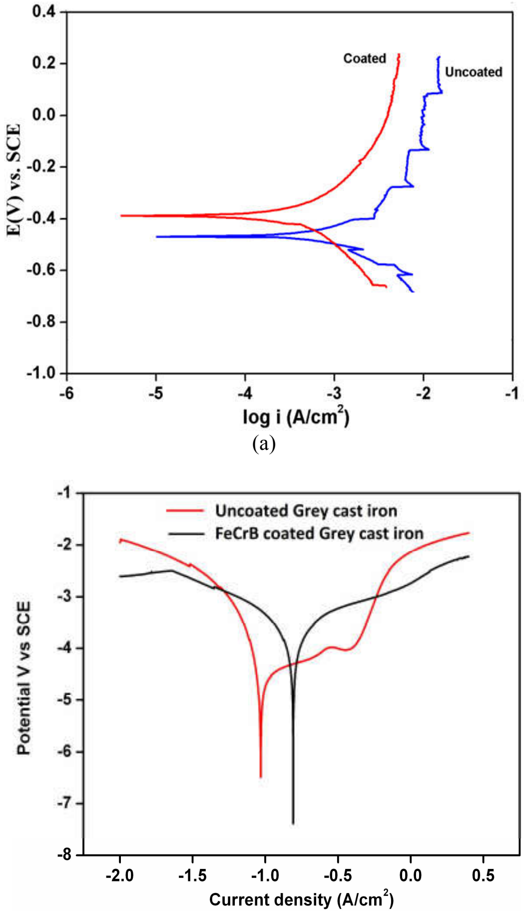
Figure 6: Fe based alloy coating wear scar morphology [78]

Zhou et al [74], concluded that the Fe-based amorphous metallic coatings on steel substrate can offer good corrosion resistance, mechanical properties improvements and increase the wear resistance revealed on coated surface. Mostly metallic coatings, especially Fe based coatings would affect on surface shown sever corrosive while hard chromium coatings process has been reported. Therefore, authors found that coating surface deposit by using thermal spraying process is resulted maximum corrosive resistance and protect the surface properties.

Huang et al [75], authors investigated the Fe based alloy coating on stainless steel substrate by HVOF coating and reported that the fully amorphous ribbons formed can produce good mechanical properties and wear resistance at ambient condition. The OCP test was monitored chemical stability on both uncoated and coated substrates were immersed in 20 Wt.% H2SO4 solution for about 45 minutes and the changes in OCP for these substrates were recorded as a function of the immersion time. Relevant plots are given in Figure 7.

Farmer et al [76], examined the corrosion behaviour of a series of amorphous alloys based on $Fe_{52.3}Cr_{19}Mn_2Mo_{2.5}W_{1.7}B_{16}C_4Si_{2.5}$ and showed that the corrosion resistance of these alloys could outperform that of wrought alloy 22 in seawater at temperatures up to 90°C.

Otsubo et al [77], compared the corrosion resistance of FeCrMo–(C, B, P) amorphous coatings made by HVOF and APS processes on stainless steel substrate and reported that the corrosion potential of the amorphous coatings sprayed by the HVOF process. Moreover, the density of the current moving to positive in which using HVOF process and authors found that APS with amorphous coating is not to move positive. Therefore the resulted thermal spray process withstands more corrosive resistance than APS process.



(a)

(b)

Figure 7: Corrosion plot (a) FeSiNiCr alloy coating (b) FeBCr alloy coating [78].

Conclusions

Many researchers have investigated the mechanical properties such as hardness, porosity, fatigue, and residual stress in iron-based alloy coating. The authors concluded that HVOF process has a potential for commercial applications, since it provides well bonded, wear resistant and corrosion resistant coatings, Moreover, the application of HVOF coating to the operating components will increase working life of these components. Additionally, the selection of optimized spray parameters and feed stock powder will certainly influence coating microstructure and performance. In the current scenario most of the surface coatings are the mixtures of different alloys has to improve the substrate based on coating parameters. As discussed above, it can be seen that coating performance was carried out based on microstructure, in which deposit on melted and un melted particles and spray process parameters employed. Thus, in terms of producing crystalline alloy coatings, it is, therefore, necessary to consider several factors including the presence of amorphous and/or crystalline structure in the original starting powder as well as the spraying parameters employed which influence the crystalline of amorphous phases in the coating due to reheating effects and cooling process is formed in the phases of coated substrates. The greater wear resistance was achieved of the coating was believed to be due to a combination of high hardness, high thermal stability and high corrosion resistance. Thus, improvements based on alloy coating in the present work will need to be further investigated in various wear conditions and environments in order to assess the suitability of applying crystalline/or amorphous coatings to parts of engineering surface applications requiring high wear resistance.

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