State of the Art of HVOF Coating Investigations—A Review

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PAPER

State of the Art of HVOF Coating Investigations—A Review

AUTHORS

T.S. Sidhu
S. Prakash
R.D. Agrawal
Metallurgical and Materials Engineering
Department, Indian Institute of
Technology Roorkee

ABSTRACT

Corrosion, erosion and abrasion, or combinations of these mechanisms, are the main cause of degradation of materials used in marine, aircraft, waste incinerators, power generation, chemical, and paper and pulp industries. One possible way to address these problems is by applying a thin layer of wear and corrosion resistant coatings. Due to the continuously rising cost of materials as well as increased material requirements, coating techniques have been given more importance in recent times. Among the different coatings techniques, high velocity oxy-fuel (HVOF) spraying process is a new and rapidly developing technology, which can yield high density coatings with porosity less than 1%, having high hardness and adhesion values, and good erosion, corrosion and wear resistance properties. The very high kinetic energy of the powder particles in the HVOF process results in the deposition of high quality coatings. It is possible to obtain a coating thickness of more than 1.5 mm with careful control of cooling to reduce residual stresses. The purpose of this paper is to review the physical, mechanical, erosion-corrosion and wear properties of the HVOF coatings and effects of deposition parameters of the process on the properties of the coatings.

INTRODUCTION

Structural steels used in marine applications, energy conversion and utilization systems, and in chemical and petroleum industries are often required to have a long service life because environmental regulations and labor costs of repairs are expected to become increasingly severe and high hereafter. In order to obtain a long lifetime, erosion-corrosion and abrasion of these materials are the main problems to be solved.

In the marine environment, structural steels are subject to severe corrosion damage due to the abundant presence of sea salts and water. Up to now, cathodic protection, thick anticorrosion paint and cladding, have been mostly used for corrosion protection for marine corrosion. However, it is questionable whether these methods can provide long service life, over 100 years, without any maintenance.

One possible way to attack these problems is the use of thin anti-wear and anti-corrosion coatings. However, the coatings to be used in a marine environment require an impermeable nature above all. If such coatings have even a small amount of pores connecting to the substrate, seawater may permeate them and reach the interface between the coating and the substrate. When a conductive solution contacts different conductive materials, it forms a galvanic cell. A combination of noble coating and less-noble substrate accelerates substrate corrosion more than a bare substrate with the same surface area.

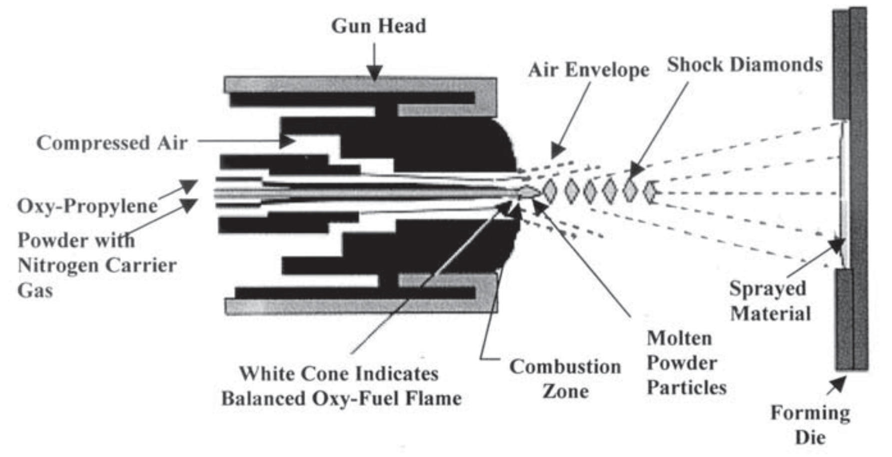
The high velocity oxy-fuel (HVOF) process belongs to a family of thermal spraying technologies being used to enhance the surface properties of base materials. HVOF coatings have comparatively less porosity as compared to plasma spray coatings. As porosities of the coatings play a significant role in the corrosion resistance of thermal spray coatings, HVOF coatings are being studied extensively for their corrosion resistant properties. Moreover, the composition of HVOF coatings is nearly the same as that of spraying powder.

The HVOF sprayed coatings have found wide application in marine, aircraft, automotive and other industries. For reclaiming a wide range of petrochemical-process components such as storage vessels, heat exchangers, pipe end fittings and valves, which are subjected to severe erosive, wear and corrosive conditions, Amoco Oil Company routinely employs the HVOF process by applying AISI 316 L and Hastalloy C-276 coatings (Moskowitz, 1992).

HVOF thermal spraying is a technique whereby powder material is melted and propelled at high velocity, with the use of oxygen and fuel gas mixtures, towards a surface. Propylene, propane, hydrogen, acetylene, methane, ethylene, crylene, SPRAL 29 kerosene, MAPP (methyleacetylene-propadiene-stabilised gas), LPG etc. are used as combustion fuels. The HVOF system consists of a spray gun, powder feed unit, flow meter unit, and an air and gas supply unit. The powder feed unit comprises a hopper assembly, air vibrator, feed rate meter and control cabinet. The desired powder is fed from the powder feed unit by means of a carrier gas to the gun, where combustion occurs. The amount of powder required for deposition may be regulated using the powder feed-rate meter. In the combustion zone, the powder material enters the flame, where it becomes molten or semi-molten, depending on the melting temperature and the feed rate of the

FIGURE 1

Schematic cross-section of HVOF gun (Stokes & Looney, 2001)



material. The flame temperature for the HVOF process is around 3000^0 C (Sobolev et al., 2004). The molten or semi-molten particles are then propelled out of the gun nozzle at supersonic velocities towards the target/substrate, where the material is deposited. Powder particles, typically in the range 10-63 µm, attain velocities of 300-800 ms^{-1} at the substrate to be coated (Kowalsky et al., 1991; Irving et al., 1993; Knight et al., 1994; Smith & Knight, 1995; Herman et al., 2000). The basic scheme of the HVOF spray system is shown in Figure 1 using the Diamond Jet gun as an example (Stokes & Looney, 2001).

Due to high velocity and high impact of the sprayed powder particles, the coatings produced by HVOF spraying process are less porous and have higher bond strength than produced by other methods such as plasma spraying, flame spraying, and electric arc spraying (Roa et al., 1986; Crawmer et al., 1992; Jarosinski et al., 1993; Provot et al., 1993). Particle speed, flame temperature and spray atmosphere are the main parameters which differentiate the various spraying techniques. Coating porosity, bond strength and oxide content are typical properties influenced by the coating procedure. Table 1 shows the characteristics of the WC-Co coatings sprayed by different spray techniques

FIGURE 2

Characteristics of HVOF and standard plasma process coatings (Helali & Hashmi, 1992)

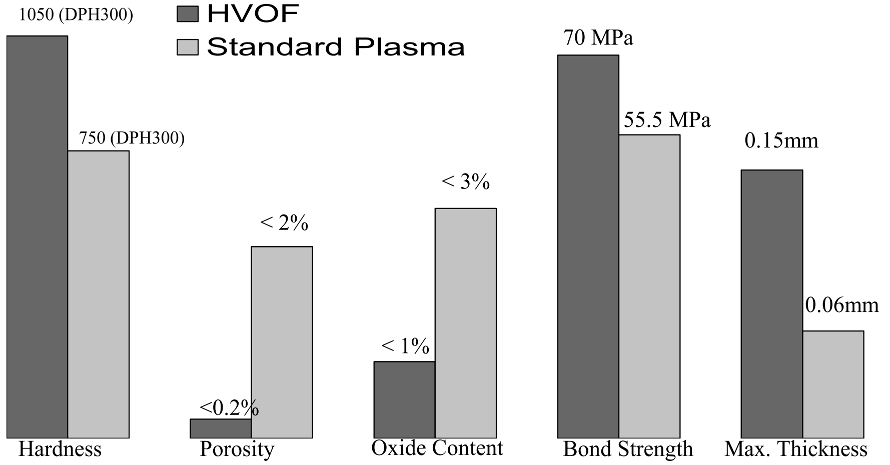


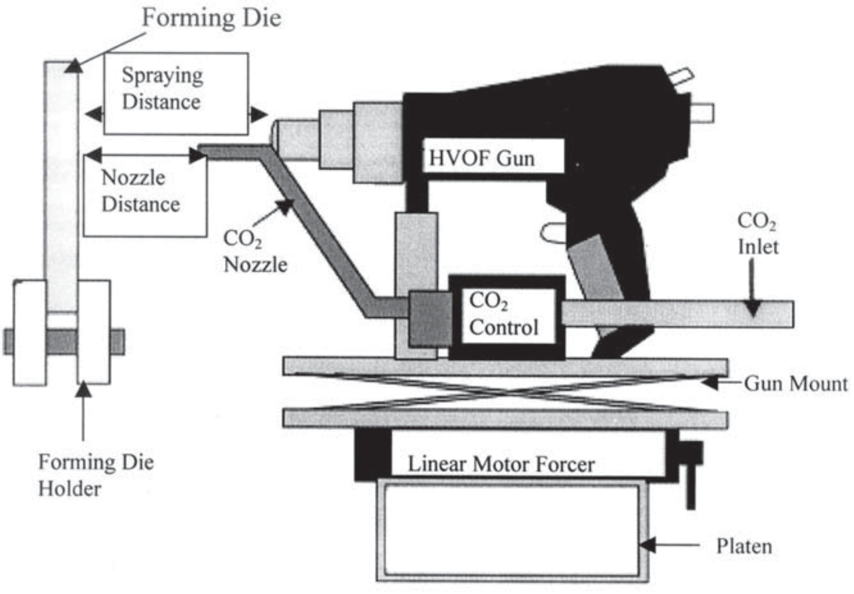
TABLE 1

Thermal spraying processes

Deposition Technique	Heat Source	Propellant	Typical Temperature(°C)	Typical Particle Velocity (m s-1)	Average Spray Rate (kg h^{-1})	Coating Porosity (%by Volume)	Relative Bond Strength
Flame Spraying	Oxyacetylene/ Oxyhydrogen	Air	3000	30-120	2-6	10-20	Fair
Plasma Spraying	Plasma Arc	Inert Gas	16000	120-600	4-9	2-5	Very Good to Excellent
Low Pressure Plasma Spraying	Plasma Arc	Inert Gas	16000	Up to 900	-	<5	Excellent
Detonation Gun Spraying	Oxygen/ Acetylene/ Nitrogen Gas Detonation	Detonation Shock Waves	4500	800	0.5	0.1-1	Excellent
High Velocity Oxy-fuel (HVOF)	Fuel Gases	CombustionJet	3000	800	2-4	0.1-2	Excellent

FIGURE 3

End-view schematic of HVOF gun, traverse unit and carbon dioxide cooling system (Stokes & Looney, 2001)



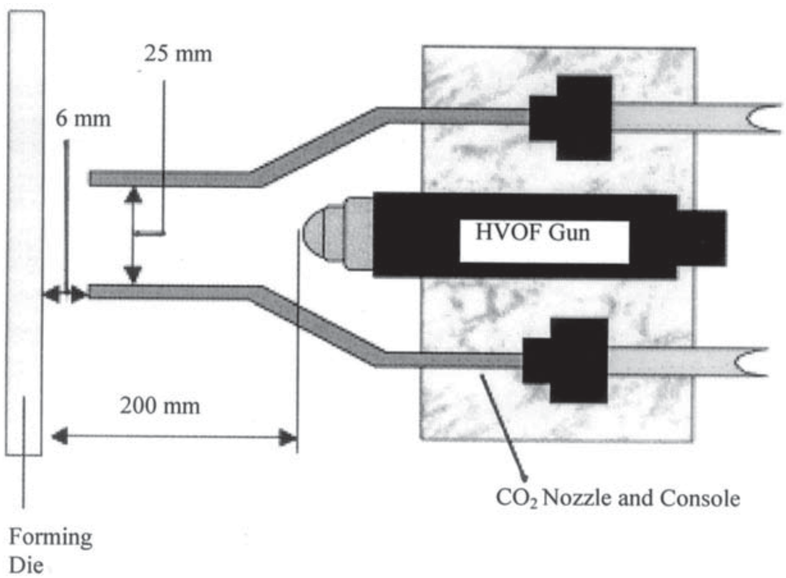
(Sobolev et al., 2004). In comparison with air or vacuum plasma spraying, the HVOF has the advantage of being a continuous process. Figure 2 indicates the characteristics of HVOF coating compared with those produced using the standard plasma spraying process (Helali & Hashmi, 1992).

Quality of the coatings depends significantly on the velocity and temperature of the powder particles impinging onto the substrate surface, which in turn is associated with the gas pressure developed in the combustion chamber. In the HVOF spray systems of the first and second generations (Continuous Detonation Spraying, Top Gun, Jet-Kote and Diamond Jet) combustion occurs at pressures in the range of 3-5 bar and the flame attains a supersonic velocity in the process of expansion at the nozzle exit. These systems produce comparable particle velocities with the standard spray parameters and the same fuel gases and powders. For instance, during spraying of the WC-17%Co powder with the particle size distribution of -45+10 µm using propane the particle velocities are about 450 m/s (Kreye, 1997).

HVOF systems of the third generation (Diamond Jet Hybrid 2600 and 2700, JP-5000, OSU Carbide jet, and TOP Gun K) operate at higher combustion pressures in the range of 6-10 bar. These systems permit higher particle velocities and higher spray rates. For examples, in the case of the WC-Co powder the velocities are about 600-650 m/s and the spray rates increase up to 10 kg/h and in JP-5000 system even up to 18 kg/h without any deterioration of the coating quality (Kreye, 1997).

FIGURE 4

Schematic of carbon dioxide nozzle layout and distances used (Stokes & Looney, 2001)



Stokes & Looney (2001) have modified the HVOF spraying gun by incorporating a traverse unit to traverse the spray gun back and forth, thermocouple to measure the spraying temperature of the sprayed surface and a carbon dioxide cooling system to cool the sprayed region, to reduce and control the spraying temperature. These additional features reduce the residual stresses caused by interruption of the spraying process for controlling the spraying temperature to a set value. Figure 3 shows the end-view schematic of a HVOF gun, traverse unit and carbon dioxide cooling system and Figure 4 shows a schematic of a carbon dioxide nozzle layout and distances.

In the HVOF spraying process, some in-flight powder particles get oxidized. This problem can be minimized by shielding the in-flight particles from the atmosphere by inert gas. Recently, Kawakita et al. (2003) have conducted studies on the HVOF spraying process, in which an inert gas shroud system is attached. In this system, a pipe is attached to one end of the barrel of a commercial HVOF gun and inert gas is injected from both the ends of this pipe. They termed this mechanism as the 'gas shroud mechanism' or the 'shroud mechanism'. Nitrogen gas is injected into the shroud at the flow rates of 1.5–2.5 $m^3 min^{-1}$ from upstream and at 0.3 $m^3 min^{-1}$ from downstream. This attachment enabled in-flight spray particles to be accelerated over 750 ms^{-1} and suppressed oxidation significantly. The coating of HastelloyC nickel base alloy by HVOF spraying with the gas shroud attachment has zero through-porosity and 0.2 mass% of oxygen content. The laboratory corrosion tests showed that the on-shroud HastelloyC coating is comparable to the bulk material of HastelloyC in terms of corrosion resistance.

Vacuum plasma spraying (VPS) is still a frequently used thermal spray process for deposition of corrosion and oxidation resistant materials and is recognized for providing reasonably density and relatively less oxidization under thermal and oxidation load. However, it is a very expensive process since equipment costs are greater than \$2 million US. Furthermore, the chamber process requires time-consuming evacuation and flooding cycles, which inhibits its efficiency. Additionally, an online process control by optical diagnostic means such as in-flight particle or substrate pyrometry is difficult in the vacuum chamber. In contrast, HVOF spray systems are operated in the atmosphere, investment costs are roughly a tenth compared to VPS, and process monitoring is easier (Irons & Zanchuk, 1993; Yamasaki et al., 1995; Meyer, 1995).

The electrochemical behaviour of HVOF sprayed WC-12%Co coatings applied on low alloyed Cr-Mo steel has been studied in artificial seawater using Zero Resistance Ammetry techniques. The electrolyte artificial seawater used in this study was prepared according to ASTM D-1141 (Collazo et al., 1999). Similarly HVOF sprayed stainless steel coatings have been subjected to the corrosion test in 3.4% NaCl + saturated $Ca(OH)_2$ solution. The corrosion performance of the coatings has been evaluated using linear polarization, AC impedance, and salt spray techniques (Gu et al., 1998). These studies concluded that the HVOF sprayed coatings have high corrosion resistance.

2. Physical and Mechanical Properties of the Coatings

Coatings used in marine structure must be strong, hard and adherent. Immersion coatings must have good impact and abrasion resistance and must be able to flex well enough to maintain contact with the steel substrate when it is bent.

The high kinetic energy of the particles in the HVOF process leads to the formation of dense and hard coatings due to the deformation of the particles in a plastic state rather than a molten state. As a result, oxidation of spray metal during flight and flattening is relatively less, since oxidation can occur only by a relatively slow diffusion mechanism. In spite of the plastic state, the high kinetic energy of the particles still allows flattening by deformation and leads to dense and pore-free coating with low oxygen content. This characteristic of the HVOF process is of high importance for spraying mechanically alloyed material (Provot et al., 1993; Nestler et al., 1994; Voggenreiter, 1996; Lugscheider et al., 1998; Zhao et al., 2001; Zhao & Lugscheider, 2002).

Detailed microstructural examination of HVOF sprayed powders shows that coatings exhibit characteristic splatlike, layered morphologies due to the deposition and resolidification of molten or semi-molten powder particles. During HVOF spraying, powder particles are generally comprised of three separate zones; fully melted regions, partially melted zones, and an unmelted core. However, the relative proportion formed in an individual powder depends on its particle size, trajectory through the gun, the gas dynamics (velocity/temperature) of the thermal spray gun and the type of gun employed (Dent et al., 2001; Kong et al., 2003; Zhang et al., 2003).

HVOF sprayed carbide dispersed Ni-based alloy (Cr_3C_2- NiCr) can have hardness of 1150 Hv and adhesion strength of 200 MPa. Further, by using the smaller primary powder size and NiCr of 20 mass %, adhesion strength of Cr_3C_2- NiCr coating can be improved to 250 MPa. In the case of NiCr< 20 mass%, due to the high carbide rate, the strength of the coating declines. On the other hand, if NiCr> 20 mass%, the softer particles could derive a decrease of adhesion strength. Further, in case of using smaller particles, the relatively extensive surface area, causing effective kinetic momentum and heat transfer from the gas flame to the particles attributes superior acceleration and heat, which result in better adhesion strength of the coatings (Hamatani et al., 2002). Through porosity of HVOF sprayed HastelloyC coating has been chemically detected using ICP atomic emission spectrometry of dissolved substances permeating via connecting pores in such coatings. It is found that through porosity depends on coating thickness and on the sprayed-particles stacking structure. Coating with zero through porosity has been prepared under a higher combustion pressure (0.86 MPa) than the standard (0.68 MPa) and was approximately 400 µm thick (Kawakita et al., 2003a). HVOF sprayed Al_2O_3-dispersion-strengthened NiCr powder results in dense coating with homogenous microstructure. The microstructure of powder is retained in the coating after spraying. However, the coating showed lower hardness than the powder after spraying. Wear resistance of the coatings is found to be dependent on the properties of powders. Homogeneous and higher volume fraction of Al_2O_3 powder (50 Vol. %) produced more wear resistant coatings (Zhao et al., 2004).

Addition of CeO_2 and Cr in the HVOF thermal sprayed NiAl intermetallic-based coatings improves the wetting and bond strength of the coatings to the substrate, which decreases the tendency of brittle peeling during thermal spraying. These coatings layers have higher hardness, improved elastic modulus with less cracks and pores as compared with pure NiAl coatings. The NiAl base intermetallic alloy coatings exhibited excellent carburization resistance at high temperature. This may result from the diffusion barrier role of the NiAl coatings, as after carburizing, oxide films such as Al_2O_3 and rare earth compound, $CeAlO_3$, are formed in the intermetallic-based alloy coatings. These oxides may obstruct the inward diffusion of carbon during high-temperature carburization, resulting in low carbon concentrations in the NiAl coatings, and prevent the formation of carbides in the substrate (Wang & Chen, 2004).

3. Wear Resistance Properties

High velocity oxy-fuel thermal spraying is one of the most versatile processes of deposition of coating materials to enhance wear performances. It is a process with almost no limitation of materials and has the ability to deposit coatings on a great variety of shapes and sizes, with thicknesses ranging from several micrometers to tens of millimeters.

HVOF sprayed carbides based cermets coatings are widely used against wear and corrosion in gas and oil industries. Their wear resistance is three to five times that of electroplated chromium, and their manufacturing costs are low. These coatings can be used as a possible replacement for hard chromium plating in gas turbine shaft repair. HVOF sprayed Cr_3C_2–NiCr and WC–Co coatings exhibit high hardness with a high volume fraction of carbides being preserved during the spraying process. Wear tests of HVOF sprayed Cr_3C_2–25NiCr and WC–12Co coatings have been carried out without lubrication and under extreme loading conditions. The hardness (Figure 5) and wear resistance (Figure 6) of the WC-Co coatings are better and porosity (Figure 7) is less as compared with Cr_3C_2-NiCr coatings. Micrographs reveal that on the HVOF sprayed Cr_3C_2–25NiCr coatings there is evidence of particle pull-out or scratching which supports the wear by abrasion. Damaged surfaces contain craters whose rate and dimension are more significant than those caused in WC–Co deposits (Sahraoui et al., 2003). Considering the economical and ecological requirements, HVOF sprayed Tribaloy©-400, Cr_3C_2-25%NiCr, WC-12%Co coatings can possibly replace electrodeposited hard chromium (EHC) in a gas turbine shaft repair. The friction coefficients of HVOF coatings are found to be close to that of chromium electroplated deposits (Sahraoui et al., 2004).

Chromium carbide/nickel chromium coating can be deposited by various thermal spraying processes i.e. detonation gun process (Tucker et al., 1998), plasma spray process (Hwang & Seong, 1995), and a variety of HVOF processes (Li et al., 1998). Among these thermal spray processes, the HVOF process has a relatively lower temperature

FIGURE 5

SEM observations of worn region of samples coated with: (a) Cr_3C_2–25NiCr; (b) WC–Co (Sahraoui et al., 2003)

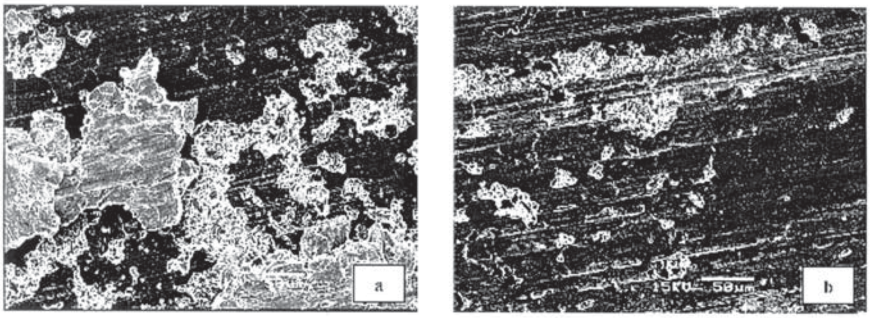


FIGURE 6

Evolution of the weight loss of HVOF coated samples vs. the applied loads (Sahraoui et al., 2003)

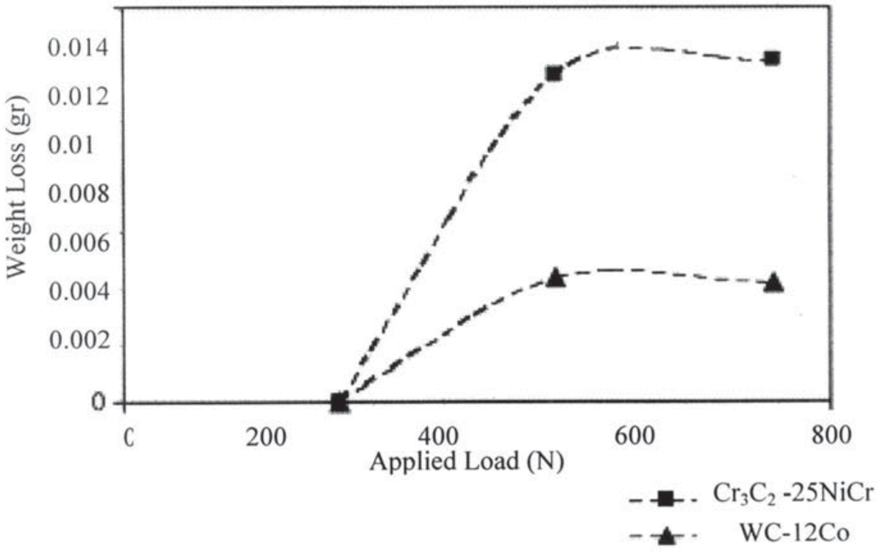
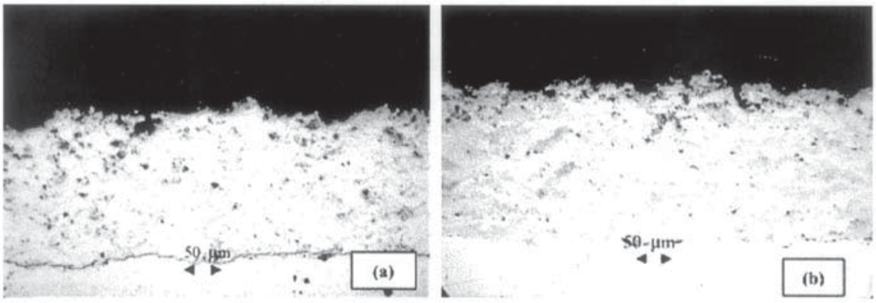


FIGURE 7

Optical micrographs of the as-sprayed coatings: (a) Cr_3C_2–25NiCr; (b) WC–Co (Sahraoui et al., 2003)



and supersonic gas jet for the deposition of heat sensitive materials in the atmosphere. Supersonic gas jet which ultimately forms diamond shock waves, is due to the nozzle which is of convergent divergent type. At the exit of the gun, pressure exceeds atmospheric pressure, so the gas jet expands with a corresponding increase of the Mach number above 1 and the so-called diamonds shock are formed. These benefits enable HVOF to be a promising and most popular process for the preparation of wear resistant cermet coatings.

Sudaprasert et al.(2003) have studied the sliding wear behavior of HVOF sprayed WC-Co coatings deposited using both gas-fuelled (HVOGF) and liquid-fuelled (HVOLF) systems and reported that with a dense powder feedstock, the HVOGF deposited coating was superior to the HVOLF deposited coating, as the HVOLF sprayed coating was associated with a mechanical damage to the WC-Co powder particles as they impact with the substrate resulting in carbide cracking, and a reduction in the integrity of the bond between the carbide particles and the matrix phase.

Triobological study of NiCrBSi coating shows that HVOF sprayed coatings had a higher value of micro hardness and wear resistance than the fused process as well as the plasma spraying process. Plasma sprayed NiCrBSi had the worst sliding wear resistance (Miguel et al., 2003).

4. Erosion and Corrosion Behavior of the Coatings

Marine corrosion includes the deterioration of structures and vessels immersed in seawater, the corrosion of machinery and piping systems that use seawater for cooling and other industrial purposes, and corrosion in the marine atmosphere. Erosion corrosion is acceleration in the rate of corrosion attack in metal due to the relative motion of a corrosive fluid and a metal surface.

The corrosion resistance of the HVOF sprayed HastelloyC deposit was found to be comparatively high under the seawater environment. Its corrosion rate was estimated to be in the order of 10 µm year^{-1} from the result of the electrochemical AC impedance measurement. The primary corrosion reaction of the deposit was uniform formation of the oxide or the hydroxide on its whole surface. When pores existed between the sprayed particles of the deposits, such places were subject to the predominant corrosion reaction and the corrosion rate there was considerably faster than that in the normal sprayed parts. As the result, the local corrosion seemed to take place there (Kawakita et al., 2003).

Erosion corrosion tests of HVOF NiAl-40Al$_2$O$_3$ intermetallic-ceramic coating using bed ash and fly ash retrieved from an operating boiler as erodent materials revealed that the coating exhibited excellent thermal shock resistance and high erosion resistance, especially at a steep impact angle and high temperature (Wang & Lee, 2000).The corrosion behavior of HVOF-sprayed Inconel 625 coatings showed that the coatings produced with the liquid-fueled gun exhibited reduced interconnected porosity and increased corrosion resistance compared with deposits obtained from the gas-fueled system (Zhang et al., 2003).

Wang (1996) conducted erosion tests on a proprietary HVOF Cr$_3$C$_2$-NiCr cermet coating (DenSys DS-200) at a temperature of 450^{0}C and impact angle30^0 and 90^{0}C under generally oxidizing conditions using bed ash and fly ash retrieved from over 60 CFBC units in North America and Europe. They observed that HVOF Cr$_3$C$_2$-NiCr coatings showed excellent erosion-corrosion behavior as compared with 1018 steel, A213-T22 steel, and other thermal sprayed coatings tested under both shallow and steep angles. The high erosion-corrosion resistance of HVOF Cr$_3$C$_2$-NiCr coating is attributed to its high compactness, fine grain size structure, and a homogeneous distribution of the skeletal network of hard carbide within a ductile, corrosive-resistant metal binder.

Corrosion and wear behavior of HVOF sprayed nano-powder Cr$_3$C$_2$-25%NiCr coatings on AISI 1045 steel substrate displayed a markedly smaller weight loss value with respect to hard chromium and HVOF sprayed 45µm grain sizes coatings (Figure 8). This behaviour can be related to the lower surface roughness and to the better distribution of carbides in the metal matrix and also to the lowest porosity of the coating. Micrographs of the morphology of the coatings surfaces are shown in Figure 9. The finer microstructure of the coating obtained using nano-sized powder is well evident, whereas some pores can be observed in the coating obtained using standard powders of grain sizes 45 µm. The research involves substantial benefits for the environment, as the proposed HVOF technique can replace some highly polluting surface treatment techniques, such as chromium-plating, with a perfectly clean process (Fedrizzi et al., 2004).

In an electrochemical test, HVOF sprayed NiCrBSi coatings exhibited an excellent corrosion resistance in alkali solutions, as the surface can form protective film and keep in a self-passivation condition. The corrosion current of the coating in sour solutions is greater than that in 3.5% NaCl. Corrosion of HVOF NiCrBSi coating first occurred around the particles that had not melted during spraying and the defects such as pores, inclusions and microcracks, then followed by the development along the paths formed by pores, microcracks and lamellar structure, resulting in exfoliation or laminar peeling off. Adjusting the thermal spraying parameters to reduce the electrochemical unevenness or sealing the pores can improve the corrosion resistance of the coating [Zhao et al., 2004a; Zhao et al., 2005).

The effects of inclusion and porosities on the corrosion behaviour of HVOF sprayed NiCrBSi coating has been reported by Zhao et al. The results revealed that if the inclusion were big enough, local corrosion would occur. The effects of porosities on the early corrosion of the coating are not serious unless there are penetrating porosities. However, porosities can do harm to the persistent corrosion resistance of the coating and the presence of porosities may weaken the cohesive strength within the coating (Zhao et al., 2004a).

Investigation of HVOF sprayed Ni-base alloy coating (N160JH and Delelo) revealed that corrosion weight loss rate of N160 JH and Delelo 50 coating was 1/30 and 1/16 that of substrate, respectively, and erosion corrosion resistance of N 160 JH

FIGURE 8

Volume loss of the HVOF coatings under different tribo-corrosion conditions (Fedrizzi et al., 2004).

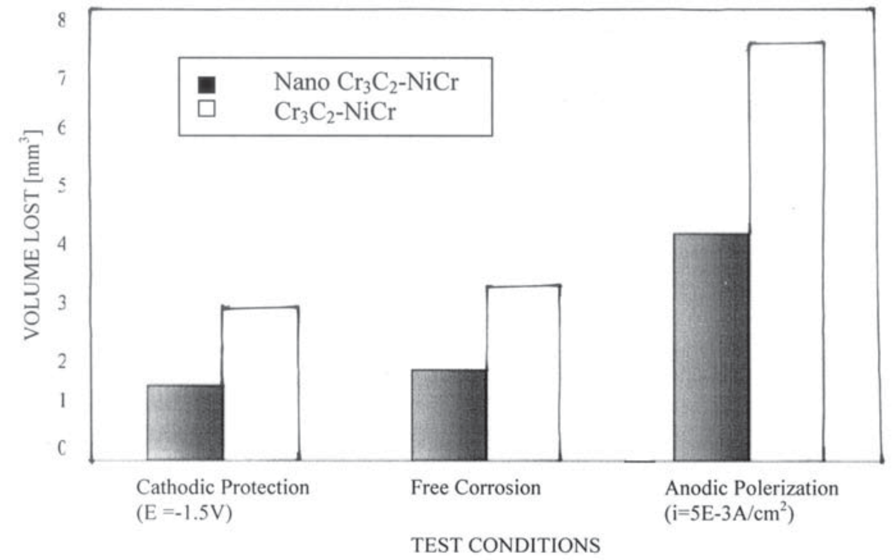
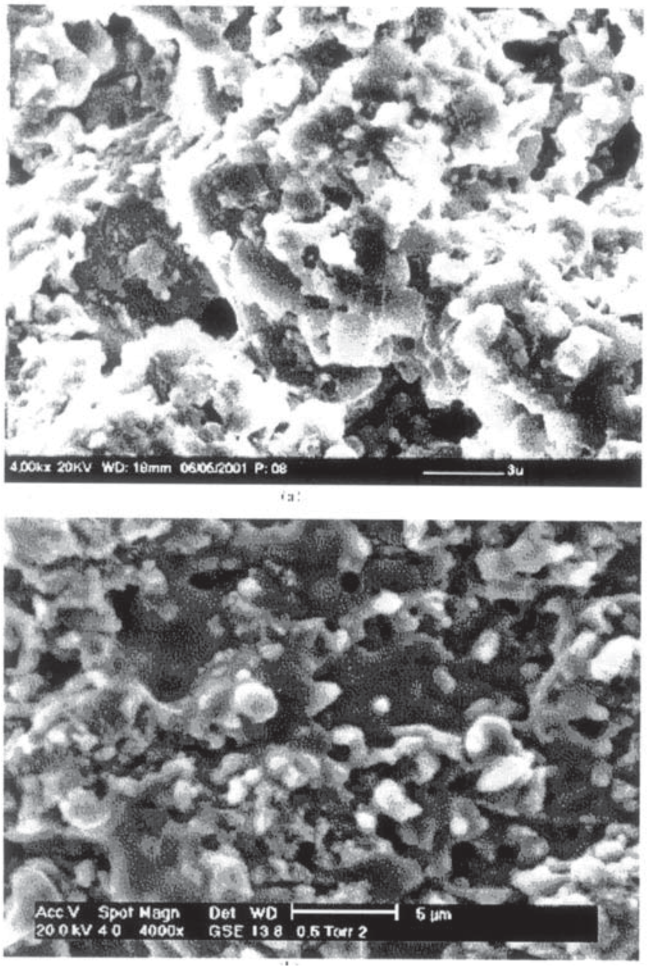


FIGURE 9

(a) Top view of the surface morphology of the HVOF sprayed Cr_3C_2-NiCr standard coating (b) Top view of the surface morphology of the HVOF sprayed nano-sized Cr_3C_2-NiCr coating (Fedrizzi et al. 2004).



and Delelo 50 coating was 15 and 5 times higher than that of substrate, respectively (Anfeng et al., 2003).

For some years, the hydraulic pistons in need of repair are also coated with the high pressure-high velocity oxygen fuel (HP-HVOF) process. The coatings used are mainly chromium carbide in a nickel chromium metal matrix. The applied thickness of the coating, as sprayed, is usually about 150 µm thick and may reduce to around 100 µm after polishing with diamond grinding to remove the surface oxide layer. The coatings obtained in this way show a much longer life combined with a better corrosion resistance than the usual galvanic chromium-plating (Barbezat et al., 1993; Russo & Dorfmann, 1995; Zimmermann & Kreye, 1996; Stein et al., 1999).

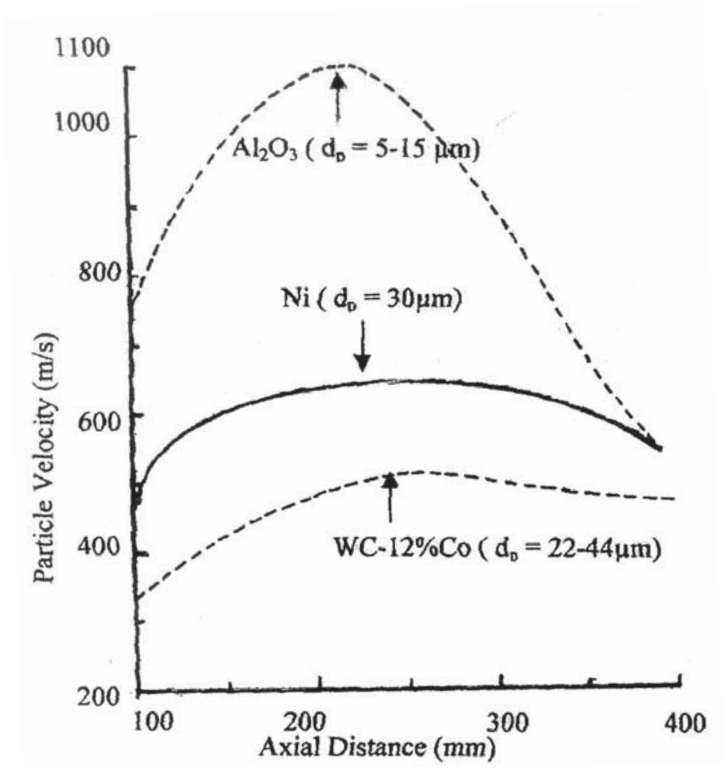
5. Effects of Deposition Parameters on the Performance of Coatings

Spraying distance, fuel/oxygen ratio and powder feed rate exert a significant influence on the porosity and corrosion resistance of the coating. The higher the total gas flow rate, lower powder feed rate and shorter the spray distance, the higher the particle velocity and temperature. The particle velocity is more sensitive to the spray parameters than particle temperature. In general, the coating hardness increased with increasing the particle temperature and velocity and coating porosity decreased (Lugscheider et al., 1998; Gil & Statia, 2002; Zhao et al., 2004b). With a high temperature, powder particles will be more in a molten state before striking the substrate surface. Thus, they flow more easily and may fill the voids formed across the boundaries of splats effectively. However, in the case of tungsten carbide coating, hardness decreases with an increase in temperature.

Significant melting of spray particles does not contribute to the increase in the adhesion of HVOF metallic coatings. On the other hand, the deposition of partially melted large particles contributes to the substantial improvement of adhesive strength of HVOF coatings and yields an adhesive

FIGURE 10

Variation in particle velocity with spraying distance



strength of over 76MPa, double the coating deposited with completely molten particles. These coatings adhere to the substrate by the mechanism of mechanical interlocking on the peaks of valleys of substrate, which is roughened by grit blasting. Semi-molten particles may have better mechanical interlocking with the substrate than the molten particles. Spraying distance is an important parameter in the HVOF process and it affects the velocities of spraying particles and therefore the porosity of the coating. The higher the velocity of spraying particles, the less the porosity (Gil & Statia, 1999; Li et al., 2000). Sobolev et al. (1994) have studied the effect of increase in spraying distance on velocities of Al_2O_3, WC-12%Co and pure Ni particles and results are reported in Figure 10. It is observed from the graphs that with an increase in spraying distance, the powder particle velocities increase, attain maximum values, and then decrease in the direction of the substrate. They further observed that the maximum velocity of the particle decreases and its axial position is displaced in the substrate direction as the particle diameter increases.

Hearley et al., while studying the effect of spray parameters on the properties of HVOF NiAl intermetallic coatings, found that gas mixing ratio and powder size were critical in determining coating properties. The best quality coatings can be obtained with an 80% stoichiometry gas ratio, a spherical inert gas atomized powder with a narrow particle size range between 15-45 µm and a small percentage of particles > 50 µm. With this optimized gas mixing ratio and powder size, it is possible to deposit a high quality NIAl coating with porosity levels of 2 vol%, low oxygen content (0.93 wt%), high Young's Modulus (281 Gpa) and hardness (420 Hv) (Hearley et al., 1999; Hearley et al., 2000).

Lih et al (2000) have studied the affects of HVOF process parameters such as oxygen flow rate, fuel gas flow rate, powder carrier gas flow rate, powder feed rate, gun barrel length, stand-off distance substrate surface speed as given in Table 2 and Table 3, on the coating quality and their results are reported in Table 4. Particle speed and

TABLE 2

Spraying parameters used for design of experiments (DOE)

Label	Parameters	Unit	Level1	Level 2
OF	O_2 flow rate	l/min	300	450
FF	C_3H_6 flow rate	l/min	55	75
CF	N_2 carrier gas flow rate	l/min	20	35
PF	Powder feed rate	g/min	25	50
GB	Gun barrel length	inch	4	5
SD	Stand-off distance	mm	200	300
SS	Substrate surface speed	m/min	63	126

TABLE 3

DOE matrix for coating deposition

Trial no.	OF	FF	CF	PR	GB	SD	SS
Run-1	1	1	1	1	1	1	1
Run-2	1	1	1	2	2	2	2
Run-3	1	2	2	1	1	2	2
Run-4	1	2	2	2	2	1	1
Run-5	2	1	2	1	2	1	2
Run-6	2	1	2	2	1	2	1
Run-7	2	2	1	1	2	2	1
Run-8	2	2	1	2	1	1	2
Run-9	1	2	1	2	1	1	1
Run-A	2	2	2	2	2	1	1
Run-10	2	2	2	2	1	1	1

TABLE 4

Properties of HVOF sprayed CrC/20NiCr coatings

Coating Properties	Run-1	Run-2	Run-3	Run-4	Run-5	Run-6	Run-7
Particle temperature (^{0}C)	1590 (984)	1674 (591)	1580 (1407)	1693 (684)	1710 (612)	1746 (614)	1668 (1286)
Particle Speed (m/s)	475	385	453	525	609	432	481
Deposition rate (µm/pass)	9.03	7.34	3.87	20.86	3.9	14.37	7.75
Porosity Content (%)	0.85	0.55	0.99	0.49	o.51	0.80	0.44
Roughness (µm, Ra)	6.71	4.67	4.6	8.3	5.86	4.09	3.83
Microhardness (GPa)	7.47	7.51	7.66	8.43	8.08	7.56	8.03
Tensile bond Strength (MPa)	79.6	99.4	87.7	90.8	86.6	85.2	93.4

temperature data have been generated from the average of detected good particles within 30 s accumulation measuring. The value in parentheses under temperature data is the total detected good particles of each measurement. It is observed that coatings deposited by higher kinetic energy and adequate surface temperature of molten particles are dense and hard.

The oxidation of powder during HVOF spraying results in the formation of metal oxides on the splat boundaries. The presence of these oxides in the HVOF coatings will degrade the resistance of the coatings to corrosion and also affect mechanical properties. To analyse the affect of the oxidation during HVOF coatings, Feng et al. prepared HVOF NiCrAlY coatings with oxygen contents ranging from 3 to 21 at.% introduced during spraying. Isothermal oxidation tests conducted at 1000^0 C up to 1000h on HVOF sprayed NiCrAlY coatings with various oxygen contents introduced during the thermal spraying process showed that a dense oxide scale consisting mainly of μ-Al_2O_3 formed on the coating with the lowest oxygen content (3 at.%). A duplex oxide scale with an μ-Al_2O_3 sub-layer and a $Ni(Al, Cr)_2O_4/Cr_2O_3$ upper layer formed on the coating with medium oxygen content (11 at.%). Porous $Cr_2O_3/NiCr_2O_4$ oxide scale formed on the coatings with the highest oxygen content (21 at.%). These results show that the oxide scale formation on the coatings can be affected significantly by the degree of oxidation that occurs in the coatings during the HVOF spraying process. Low oxygen (3 at.%) content in the coating is beneficial to the formation of a protective α-alumina scale (Feng et al., 2004).

6. Effects of Pre- and Post-treatments of Coatings

Residual stresses are developed in HVOF sprayed coating and in the coated material. The developed stresses have been measured with the hole-drilling strain-gauge method. The measured strains are found to be negative, indicating that the residual stresses are tensile stresses as per ASTM standards. Preheating of the specimen surface reduces the residual tensile stresses. Residual stresses can be reduced by selecting a coating material with matching properties to the substrate surface, and macro roughening of the substrate surface. Pre-heat the surface slightly, usually with a single pass of the torch without powder flowing, to remove any adsorbed gases or condensate and to cause some expansion of the part. The part surface temperature should be pre-heated to 79–93°C. The pre-heating should be done carefully to avoid contamination of the surface. For many applications, the maximum allowed temperatures are related to the component shape and the specimen material. When any restrictions are present, it is recommended that the maximum working temperature should be about 150°C. However, the preheating temperature may not be increased beyond 200°C because there may be a change in the structure of the steel beyond this temperature (Hashmi et al., 1998).

Kinos et al. (1994) had reported that corrosion resistance of the HVOF sprayed coating can not be improved by post treatments; however, shrouding of the in-flight particle with inert gas seemed to reduce the amount of oxide in coating. Lee et al. (2000) while studying the corrosion properties of HVOF sprayed Ni-Cr-W-Mo-B coating, observed that annealing of the coatings in a vacuum furnace of 10^{-7} MPa at 550, 750 and 950°C for 2 h after HVOF spraying improves the corrosion resistance due to increased microstructural and chemical homogeneity, such as the reduction of porosity, densification and reduction of the eutectic phase. Uusitalo et al. (2002) also supported the results of Lee et al. (2000) and reported that laser remelting of HVOF sprayed Ni-50Cr, Ni-57Cr, Fe_3Al, Ni-21Cr-9Mo coatings did not suffer from any corrosion damage, whereas as-sprayed coating was penetrated by corrosive species. Laser remelting efficiently removed the interconnected network of voids and oxides at splat boundaries of the HVOF coating.

Guilemany et al. (2001) have studied the influence of thermal treatments on the electrochemical corrosion resistance of HVOF Cr_3C_2-NiCr coatings. Firstly, a few layers of coatings were sprayed followed by thermal treatment with a gun and finally the remaining layers were sprayed. Results reveal that the thermal treatment with the gun during the spraying process increases the protection that the coatings offer against the pass of electrolytes to reach the substrate. Further, a long time spent between spraying, thermal treatment and spraying the rest of the coating layers again results in a poor corrosion resistance in comparison with the faster process.

Guilemany et al. (2002) have further reported that the sliding wear resistance of the

Cr_3C_2–NiCr coating can be improved by an adequate heat treatment (1 h at 1033 K) in an inert atmosphere. The formation of oxides, when heat treatment is carried out in an oxidizing atmosphere, increases the hardness values. But these oxides have prejudicial effect on the wear properties of the coatings when compared with coatings after similar heat treatments in an inert atmosphere. Small and well distributed Cr_3C_2 produced by heat treatment at 1033 K (inert atmosphere) greatly enhances the wear resistance of the coating (Guilemany et al., 2002).

7. Repair, Maintenance and Other Applications

The HVOF thermal sprayed process could be successfully used for forming the freestanding solid and industrially relevant components with various thicknesses. This outcome is promising for numerous applications of the HVOF process, in terms of manufacturing. The HVOF thermal spraying process has also been successfully used to repair stainless steel and D2 tool steel substrate with different depth of damage to a built-up thickness of up to 5.5 mm. Sprayed material had good adherence to the substrate under various types of aggressive machining processes (Tan et al., 1999; Stokes & Looney, 2001).

Traditionally, HVOF spraying techniques are predominantly being used as wear, corrosion and oxidation resistant barriers, resulting in increased lifetimes as compared with the uncoated substrate components (Sampath & McCune, 2000). However, as the technology has advanced, through new deposition techniques and improved tool design, the range of materials that can be effectively deposited by this process has increased to include low melting point ceramics such as alumina and materials for biomedical applications such as bioceramic coatings for dental implants (Haman et al., 1995). Now, HVOF coatings are increasingly used in many areas such as petrochemical and offshore industries, automotive components and general engineering applications including printing, textiles and mining (Sturgeon et al., 1994). HVOF technique can be used to spray-form thermocouples, humidity sensors, strain gages, and sensor arrays (Fasching et al., 1995).

Dent et al. (2001a) successfully deposited $BaTiO_3$ by HVOF for use as prototype dielectric layers for applications as meso-scale conformal circuits. Dielectric constants of up to 115 have been achieved in 150 µm thick layers of the HVOF deposited material.

8. Concluding Remarks

1. During the HVOF spraying process, hypersonic gas velocities of about 1800 ms^{-1} and a combustion temperature of about 3000^0 C are generated. These rapidly expanding gases accelerate the powder particles to velocities up to 800 ms^{-1}, which allow development of dense coatings with very low porosity usually below 1%, considerably less than plasma sprayed coatings (2-3%).
2. Coatings produced by the HVOF process have increased thickness capability, high hardness values and less effect on the environment (reduced decarbonization, oxidation and loss of key elements by vaporization) during the spray process.
3. HVOF-sprayed MCrAlY coatings are also replacing some low-pressure plasma-sprayed coatings for high temperature oxidation/hot corrosion and TBC bond-coat applications for repair and restoration of existing components.
4. A good amount of work has been done to evaluate the performance of HVOF sprayed coatings for their corrosion-erosion and wear protection properties. However, formation of oxides during HVOF spraying may affect the performance of the coatings in corrosive environments. High temperature oxidation and hot corrosion behaviour of HVOF coatings need to be investigated in detail to explore the possibility of applying these coatings in high temperature aggressive environments.
5. Contradictory results are published on the post treatments of the HVOF sprayed coatings and more detailed study is required to evaluate the effects of post heat treatment of the coatings on their physical, mechanical and chemical characteristics.

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