Role of Thermal Spray Coatings on Wear, Erosion and Corrosion Behavior: A Review

Jimmy Mehta, Varinder Kumar Mittal and Pallav Gupta*

Department of Mechanical Engineering, A.S.E.T., Amity University, Uttar Pradesh, Noida-201313, India

Abstract

Wear, erosion and corrosion are the common problems been faced by every industry. Thermal spray coatings have emerged as one of the best technique to provide excellent resistance to wear and erosion. These spray techniques lead to superior bond strength, low porosity, resistance to erosion-corrosion, etc. Different compositions of CrC-NiCr, WC-Co, Al2O3-TiO2, etc. are extensively used in a wide variety of applications like gas turbines, boilers, shovel blades, aircrafts, etc. to improve the abrasive wear. Much literature is available for detonation gun, high velocity oxy-fuel and plasma spray as coating techniques. In recent years, efforts have been made to use alloy substrates and rare earth metals with different composition for developing new coatings. In this review paper, comprehensive and critical analysis has been made on available literature for different types of spray coatings and their applications.

Key Words: Thermal Spray Coatings (TSC), Detonation Gun, High Velocity Oxy-fuel, Wear, Erosion, Corrosion

1. Introduction

Tribology is derived from a Greek word “Tribos” means rubbing. It deals with friction, wear and lubrication in all contacting parts. Mechanical components have been used in variety of applications to serve under severe conditions of high load, high/low temperature and adverse chemical environment. However, wear is very common problems, which have been faced in almost all industries wherever mechanical/moving components are involved. As a result, these components are required to be replaced or repaired immediately else it would increase the cost and decrease the service life of the component, thus affecting the efficiency of operation. Surface coatings are widely used which can act as a barrier between the bare metal and the catastrophic environmental conditions thereby enhancing the service life of the component/assembly. Table 1 shows the difference between various types of coating methods. Among the commercially available thermal spray coating techniques, detonation spray and HVOF spray are the best choices to get hard, dense and wear resistant coatings [1]. Diverse functions of the protective coatings can be listed such as wear and corrosion resistance, thermal or electrical insulation, etc. that can be achieved through different available coating techniques and coating materials [2]. There are various thermal spray coating techniques available and selection of the best technique depends upon the functional requirements, adaptability to the coating material for the intended technique including level of adhesion (size, shape, and metallurgy of the substrate), availability and cost of the equipment [3]. Types of thermal spray techniques are: Plasma spray, Detonation Gun spray, Wire arc spraying, Flame spray, High velocity oxy-fuel coating (HVOF), Warm spraying and Cold spraying [4]. Figure 1 shows the basic steps of thermal spray process. The various types of coating which are being used include:

1. Metallic: NiCrAlY, Cr3C2-NiCr, Tribo-alloy etc.
2. Carbides: TiC, SiC, WC, Cr2C3 etc.
3. Oxides: Al2O3, Cr2O3, TiO2, ZrO2 etc.

*Corresponding author. E-mail: pgupta7@amity.edu
2. Thermal Spray Coating and Its Types

HVOF spraying is a comparatively new, cost effective and quickly growing thermal spray technique for depositing cerments, and metallic and ceramic protective overlay coatings onto engineering components to allow them to function under extreme conditions. Several HVOF sprayed coatings have been subjected to corrosion testing in seawater, including cerments and anti-corrosion alloys [5]. It is capable of producing coatings with high hardness, low oxidation, high abrasion resistance, low porosity and high erosion resistance [6]. These are homogeneous and dense, compared to the other types of thermal sprayed coatings; nevertheless, some residual oxides and porosity remain at splat boundaries [7].

Table 2 shows the relevance of HVOF spraying technique using diverse powders. From the above table it can be concluded that HVOF can be applied to variety of substrate material. High velocity of particles during the deposition of coating powders, results in desirable characteristics such as lower porosity and elevated hardness of the coating [8]. Liu found out it as the most promising technique for developing wear resistant coatings [9]. Table 3 shows the different substrate material subjected to D-Gun Technique. Therefore it can be concluded that D-Gun coating can be applied to various materials like alloys, metals etc. Different powders can be used for spray technique exhibits extremely high hardness, superb wear resistance with high temperature stability, that is an essential thing for all tribological and high temperature erosion applications [10].

Ductile metals like copper, aluminum etc. are most suitable for cold spraying, but coating of other metals like W, Ta, Ti, MCrAlY, WC-Co, etc. by cold spraying has been also reported [11]. Figure 2 shows the graph revealing the operation range for different TSC. It clearly reveals that D-Gun and HVOF are the best as they have high density and are easily applicable to all materials like ceramics, metals, alloys etc.

Table 1. Difference between various types of coating methods

<table>
<thead>
<tr>
<th>Characteristic</th>
<th>Thermal spray</th>
<th>CVD</th>
<th>PVD</th>
</tr>
</thead>
<tbody>
<tr>
<td>Operating cost</td>
<td>Low to moderate</td>
<td>Low to moderate</td>
<td>Moderate to high</td>
</tr>
<tr>
<td>Process environment</td>
<td>Atmospheric to soft vacuum</td>
<td>Atmospheric to medium vacuum</td>
<td>Hard vacuum</td>
</tr>
<tr>
<td>Coating geometry</td>
<td>Line of sight</td>
<td>Omni-directional</td>
<td>Line of sight</td>
</tr>
<tr>
<td>Coating thickness</td>
<td>Thick, 50 μm-cm</td>
<td>Thin to thick, 0.1 μm-mm</td>
<td>Very thin to moderate</td>
</tr>
<tr>
<td>Substrate temperature</td>
<td>Low to moderate</td>
<td>Moderate to high</td>
<td>Low</td>
</tr>
<tr>
<td>Adherence</td>
<td>Good mechanical bond</td>
<td>Good chemical bond to excellent diffusion bond</td>
<td>Moderate mechanical bond to good chemical bond</td>
</tr>
<tr>
<td>Surface finish</td>
<td>Coarse to smooth</td>
<td>Smooth to glossy</td>
<td>Smooth to high gloss</td>
</tr>
<tr>
<td>Coating materials</td>
<td>Polymers, metals/powder/wire, ceramics</td>
<td>Metals, ceramics polymers</td>
<td>Metals, ceramics, polymers</td>
</tr>
</tbody>
</table>

Table 2. HVOF spraying on different substrate material

<table>
<thead>
<tr>
<th>Substrate</th>
<th>Coating powder</th>
<th>Advantage</th>
<th>Application</th>
</tr>
</thead>
<tbody>
<tr>
<td>AISI E4340 alloy steel</td>
<td>Cr2C2NiCr</td>
<td>High deposition efficiency</td>
<td>Pressure vessels and gears</td>
</tr>
<tr>
<td>Carbon steel alloy</td>
<td>Cr2C2-(Ni-20Cr)</td>
<td>High density, low porosity, excellent adhesive strength</td>
<td>High temperature application</td>
</tr>
<tr>
<td>310S steel</td>
<td>Cr2C2-25%Ni-Cr</td>
<td>Stable and superior wear resistance</td>
<td>Electric furnace, fossil fuel fired boiler</td>
</tr>
<tr>
<td>Superalloys 2014 i</td>
<td>NiCrAlY</td>
<td>Adherent, non-porous</td>
<td>Gas turbine</td>
</tr>
<tr>
<td>AISi substrate</td>
<td>Tungsten chromium carbide, composite NiCrSiB coating</td>
<td>High hardness and smooth surface finish</td>
<td>Industry fan blades</td>
</tr>
</tbody>
</table>

Figure 1. Basic steps of thermal spray process.
3. Effect of Thermal Spray coating on Wear

Wear is the process of removal of material from one or both of two solid surfaces in solid-state contact, when two solid surfaces are in sliding or rolling motion or both. Rate of material removal is generally slow, but steady and continuous.

Badoni and Joshi [13] studied the abrasive wear characteristics of high speed steel (HSS) coated by WC-Co and NiCr, deposited using detonation gun technique. Investigation was carried at different load and velocity for different compositions. It was revealed from the above investigation that WC-Co coated steel showed minimum wear rate at optimized condition. But wear rate is not directly proportional to load. It has also been mentioned that uncoated AISI 309 SS suffers significant wear scars along with peeling off its contact surfaces in the form of microchips under a normal load of about 70N with a sliding velocity of 1 m/s after a total sliding distance of 4080 meters [14]. Yadav and Mishra [15] studied slurry erosive wear on D-Gun sprayed coatings of SAE 431. It was examined that fretting damage of the coatings was very minute.

4. Effect of Thermal Spray Coating on Erosion

Erosion is the action of surface processes (such as water flow or wind) that remove soil, rock, or dissolved material from one location on the earth’s crust, then transport it away to another location.

Murthy et al. [17] investigated the effect of grinding on the erosion behavior of a WC-Co-Cr coating deposited by both HVOF and D-gun spray process. He also compared these techniques and found that the surface grinding improved the erosion resistance. Singh and Bhandari [18] observed the slurry erosion behavior of D-gun Stellite-6 coated and uncoated 13Cr4Ni steels at two different angles (30° and 90°) under a slurry concentration of 5000 ppm. Thakur and Arora [19] studied the slurry and dry erosion behavior of HVOF sprayed WC-CoCr cermet coatings. For experimental work they used air-jet erosion test rig at an impact angle of 60 m/s. Dhawan et al. [20] investigated slurry erosion performance of stainless steel (Grade-316), having an application in hydroturbine power plants. HVOF sprayed WC-Co/ NiCrFeSiB coatings on GrA1 boiler tube steel exhibit ductile and brittle mode of erosion under angular silica sand erodent of size 125–180 μm impacted at 40 m/s.

5. Effect of Thermal Spray Coating on Corrosion

Corrosion is a natural process, which converts a re-
defined metal to a more stable form, such as its oxide, hydroxide or sulfide. It is the gradual destruction of materials (usually metals) by chemical and/or electrochemical reaction with their environment.

Mishra et al. [7] observed the hot corrosion behavior of D-gun sprayed Al₂O₃-40%TiO₂ coating on Superni 718 and AE 435 super alloy in aggressive environment of Na₂SO₄ + 82%Fe₂(SO₄)₃ at 900 °C. It was concluded that both the coatings deposited on Ni-based super alloy imparted better hot corrosion resistance than the uncoated one. Mishra et al. [21] evaluated the hot corrosion performance of Stellite-6 and Stellite-21 coated as well as uncoated SAE 431 steel in aggressive environment of Na₂SO₄·82%Fe₂(SO₄)₃ under cyclic conditions at an elevated temperature of 900 °C for total duration of 50 cycles. Singh et al. [22] evaluated the corrosion resistance of plasma sprayed hydroxyapatite (HA) and HA silicon oxide (SiO₂) coated AISI 304 substrates. Results indicate that hydroxyapatite exhibits higher biocompatibility with human body fluid. Bhatia et al. [23] aimed to investigate the usefulness of HVOF sprayed 75% Cr₃C₂-25% (Ni-20Cr) coating to control hot corrosion of T-91 boiler tube steel at different operating temperatures viz 550, 700, and 850 °C. He used the thermogravimetry technique to study high temperature hot corrosion behavior. Bare super-alloys show spalling and peel of scale. AE 435 super-alloy performed better than Superni 718 and value of a para-bolic rate constant was found out to be 6.7245 mg²/cm⁴ and 39.443 mg²/cm⁴ respectively [24]. Corrosion resistance of the AISI 304 was found more after the deposition of the HA-SiO₂ coatings as compared to that of HA coating [25]. Coated specimens of T91 have shown minimum weight gain at all the operating temperatures when compared with uncoated samples [26]. Main aim of this experiment was to investigate the usefulness of cold sprayed. Ni-50Cr coatings to control hot corrosion of T22 and SA 516 boiler steels at 900 °C for 50 cycles that resulted in Ni-50Cr coated steels showing lesser weight gains and the oxide scales which remained intact till the end of the experiment [27].


Kamal et al. [28] studied the mechanical and micro structural properties of AISI E4340 alloy steel when Cr₃C₂-25NiCr coatings were applied through HVOF which resulted in production of better coatings than other types of thermal spray processes. Singh et al. [29] studied the oxidation resistance of alloy coating failure caused by the stresses generated in protective oxide scales and found out that scale cracking and spalling are the key factor to influence the lifetime of coatings. Chatha et al. found out that carbide-based coatings provide excellent erosion protection, but disagree on the optimum amount of carbide for maximum erosion resistance [30]. Grewal et al. [31] proposed that D-Gun Spray can be used for developing protective coatings of almost any material like oxides, carbides, metals, hard alloys and composite material, onto mild steel and other EN series. Kamal et al. [32] investigated the microstructure and mechanical properties of detonation gun sprayed NiCrAIY + CeO₂ alloy coatings deposited on super alloys. Den drict structure formation is depicted by the coating and the microstructural refinement in the coating was due to process on T-22 boiler steel (ASTM-SA213-T-22) and studied the cyclic oxidation in air which were conducted at 900 °C temperature in the laboratory using silicon car-bide furnace. Chawla et al. [33] deposited thin films of nanostructured TiAlN and AlCrN by physical vapor deposition Shukla et al. [34] tested the oxidation behavior of HVOF sprayed Cr₃C₂-NiCr coatings and the bare substrate, subjected to high temperature (900 °C) in air for 500 hours. Results show that there is better adherence to 310S. Singh et al. [35] revealed various significant factors influencing wear rate of coatings like impact velocity, slurry concentration and impact angle. After a fixed interval of time, weight loss of sample was found to increase. Oksa et al. [36] reviewed HVOF thermal spray technique, spraying process optimization, and characterization of coatings, which showed that differences from the starting powder to the final coating formation, affected the coating microstructure and performance. Chatha et al. [9] observed the behavior of Cr₃C₂-based coatings for industrial applications. NiCr offers corrosion resistance. Mahesh et al. [37] HVOF sprayed Ni-5Al coatings on Ni and Fe-based super alloy substrates were characterized to assess the micro structural features and strength in the as deposited condition for their applications in high-temperature corrosive environment of gas turbine. Wu et al. studied the high temperature properties of thermal barrier coatings (NiCrAIY/YPSZ and NiCrAIY/ NiAl/YPSZ) obtained by D-Gun spraying. The results
indicated that the D-Gun sprayed TBCs included a uniform ceramic coat containing a few micro cracks and a bond coat with a rough surface. Sova et al. [38] studied the development of multi-material coatings by cold spray and gas detonation spraying. Cold spraying (CS) and computer-controlled detonation spraying (CCDS) techniques were used to fulfill the main objective by the development of multi-functional multi material protective coatings.

7. Discussions

Thermal spraying processes are studied which is the most suitable and effective surface engineering technology. It is widely used to apply wear, erosion and corrosion resistance/protective coatings for various kinds of industrial applications. It was observed that the coatings offer excellent corrosion and oxidation resistance, high melting point, high hardness, strength and wear resistance at high temperature [39]. The lamellar structure and the presence of cracks and impurities could reduce the thermal conductivity of the ceramic coat. A dense coating with less porosity and inclusions were the result of HVOF process. Average bond strength and micro hardness of the coatings was found to be 58 MPa and 697–920 HV respectively. The hardness of coatings on three different super alloy substrates was measured and it was in the range of 210–272 HV. Average bond strength and surface roughness of the as sprayed coatings were found out to be 42.62 MPa and 9.22–9.45 μm respectively [40].

As far as Cold Spray was concerned, the separate injection of each powder into different zones of the carrier gas stream was applied. Cu-Al, Cu-SiC, Al-Al₂O₃, Cu-Al₂SiO₃, Al-SiC, Al-Ti and Ti-SiC coatings were sprayed successfully on the base material.

Methods and tools for controlling the spray process were presented and their use in optimizing the coating process [41]. In order to improve the adherence and oxidation resistance of coatings, rare earth elements (La, Zr, Ce, Y, etc.) were added in the coating powder composition. Addition of rare earth metals lead to the conclusion that the scale nucleates at reactive element oxide particles on the surface.

Figure 4 shows comparison of different coating powders deposited by D-Gun and HVOF with that of uncoated substrate material. As the load increases wear rate increases in case of NiCr deposited by HVOF. This could be due to improper spread of coating powder on surface. D-Gun showed the best result in all working loads. HVOF shows better wear resistance under impact wear and shows less porosity [12]. Powders like Cr₃C₂-NiCr, WC-Co, etc. have also shown good results. Kumar et al. [42] observed the microhardness and porosity level, which increased up to 0.93% while using HVOF spray coating. Hard facing has also proved as a better option in case of tiller blades, which are used in cultivation, and requires replacement after short period of time for effective and efficient working [43]. Coatings like chromium, tungsten carbides etc. exhibit high hardness depending only on how the coating layer has been deposited i.e. (nano-metric or micro-metric) on the substrate material [43,44].

D-Gun, HVOF, Plasma Spray etc. are the techniques, which are frequently being used and are easily available not only in India but also all over the world as much of the literature studied is out of India. Boron steel (a medium carbon steel) having high hardness can also be used as base material with and without coating. Uptil now it has only been used with hardening processes and no work with coating has been tried or done. Boron steel has
applications in harvesting instruments, spades, washers etc. Hence, this material can be used for testing and experimental work. A few literature reports are also available on boron steel.

Shakoor [45] compared the properties of Ni-B and Ni-B-ZrO2 coatings in their as deposited state to elucidate the effect of ZrO2 addition on structural, surface, thermal and electrochemical properties of binary Ni-B coatings. It is noticed that Ni-B coatings are amorphous in their as deposited state while addition of ZrO2 significantly improves the crystallinity.

8. Concluding Remarks

The present paper is a review on the role of TSC on wear, erosion and corrosion behavior. Various types of TSC along with industrial applications of boron steel has also been discussed. Following are the important concluding remarks of the paper: Coatings play an important and vital role in protecting/layering the substrate materials and alloys from wear, erosion and corrosion [1]. A lot of work has can be done in this field to study the mechanical and micro-structural properties with reference to the applied coatings. Optimization techniques like Taguchi Method, ANNOVA, etc. can also be used to analyze the results. D-Gun spray process and HVOF processes have proved to be quite effective and are easily available and not so costly. Nano-structured powder material and rare earth materials have also applications in this particular area but still a lot of efforts and different combinations of coatings has been explored.

References


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