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An Investigation on High Temperature Erosion Behaviour of Plasma Sprayed CoCrAlY/Al_2O_3/YSZ on Fe and Ni Based Alloys

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ABSTRACT

Parts of aircraft and gas turbines used for power production are subjected to severe erosion damage since aircrafts frequently operate in sandy environment. Low cost fuel such as poor quality coal is used in gas turbines which produce suspended hard particle in the exhaust. In the past, researchers have worked on minimising the erosion by using certain coatings. Development of new coatings is necessary in order to explore further in improving resistance against erosion process under high operating temperature of gas turbine, aero engines and other components. In the present work, the investigation of elevated temperature erosion behaviour of CoCrAlY/Al_2O_3/YSZ coatings synthesised by plasma spraying on two different base metals, namely, Hastelloy X (Superni 76) and AISI 321 (MDN 321) was carried out. The coated samples were subjected to erosion test at 600ºC with the impact angles of 30º and 90º under steady state condition. Alumina powder was used as erodent material of uneven angular shape of 50 μm particle size. The morphology and phase formed on eroded surface are characterised using SEM and X-ray diffraction to determine the erosion mechanism. The rate of erosion is determined by weight loss method and the CoCrAlY/Al_2O_3/YSZ coating showed up to about 25% lower erosion rate than the substrate alloy. It was observed that the erosion resistance of CoCrAlY/Al_2O_3/YSZ coating on both MDN 321 and Superni 76 gave almost similar erosion resistance which shows that the erosion behaviour of coating is not influenced by substrate unless spray parameter and substrate roughness is changed.

Keywords: Ceramics, erosion mechanism, high temperature erosion, plasma spray, substrate

INTRODUCTION

Solid Particle erosion is a major material degradation process in many industries like power production, chemical plant, mining machineries and also aircraft engines. Gas turbines are the power source for these industries and engines, which operate in harsh environment. This imposes continuous

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development of new materials. Aircraft engine parts (compressor, turbine and propeller blades) are exposed to severe erosion media (Sundararajan & Roy, 1997). Thermal spray coatings can provide greater resistance to surface degradation process, which enhances the lifecycle of component by maintaining the mechanical strength of the base metal.

There are many thermal spray processes available; among that plasma spraying is a well-established and versatile technique for producing metals and ceramics coatings. It is recorded as a promising technology by providing reliable and cost-effective solution for many industrial problems (Sidhu & Prakash, 2006). In plasma spraying, the coating material in the form of powder is introduced into a high temperature plasma jet and the particle gets melted and accelerated towards the substrate. Upon impact, the molten particle is flattened and quenched on the substrate asperities. This results in a layered microstructure, which may contain typical defects such as pores, splat boundaries and micro cracks. Plasma spraying provides coatings with thickness from tens of micrometres to hundreds of micrometres deposited with high deposition rate, which also gives good quality and good adherent coating.

The plasma sprayed MCrAlY (where M is nickel, cobalt, or a combination of Ni and Co) coatings on Ni-based super alloys and other high strength alloys have been found to enhance the hot corrosion and oxidation resistance, which leads to the formation of oxides, and spinals of nickel, aluminium, chromium and cobalt (Seo et al., 2008). Yttrium and aluminium are the two elements in MCrAlY combination, which oxidise during thermal spraying because of their high affinity to the oxygen. Thus, there are more chances of fine dispersed Al and Y rich oxides in the as-sprayed coatings (Brandl et al., 1998). CoCrAlY bond coat performs excellent hot corrosion and oxidation resistance with high levels of Al and Cr, especially in marine operating condition, although there is a lag in remarkable erosion and wear resistance (Li et al., 1998). Various hard phases used for Ni based coatings as reinforcing additives are WC, Al_2O_3, Cr_3C_2, Cr_2O_3, TiC, SiC, TiN, CeO_2, TiO_2, etc. There are, however, only few reinforcing like MoS_2, Ce, Si, Y_2O_3 etc (Ogawa et al., 2006; Ramesh, et al., 2010; Kim & Korsunsky, 2010) on Co based coating. Ramesh et al. (2010) studied the solid particle erosion resistance of WC–Co/NiCrFeSiB coating deposited using HVOF spraying process and observed that the HVOF spraying led to a high retention of WC in the coating matrix. The average value of microhardness was reported as 1223 $HV_{0.3}$ and the main erosion mechanism of the coating was attributed to brittle mode. It was reported that plasma sprayed NiCrSiB/Al_2O_3 coating on AISI 304 substrate material showed a better performance in 30º impact angles, but coating could protect the substrate at both 30º and 90º of impact angles. The coating shows improved hardness value from 160-673 HV at 200 g load. The presence of groves, lips, splat removal and detachment of Al_2O_3 hard particles combined to form both ductile and brittle mode of erosion (Praveen, 2015).

In the present study, Al_2O_3 powder is mixed with a CoCrAlY powder and atmospheric plasma spraying was used to deposit the composite coating on Ni and Fe based alloys. Al_2O_3 was selected due to its high hardness, low cost, better thermal stability, better wettability and thermal expansion coefficient similar to Ni alloy (Praveen, 2015). The erosion behaviour of coatings was studied at 30º and 90º of impingement angles and the eroded surfaces were analysed with SEM images to identify the erosion mechanism.

MATERIALS AND METHODS

Substrate material and coating characterisation

Austenitic stainless steel (MDN 321) and Nickel based super alloy (Superni 76), which are used as material for aircraft engine parts, furnaces and many high temperature application, have been used as substrate in the present study. The specimens MDN 321 and Superni 76 are cut into the dimensions of 25x25x4 (mm) and 25x25x3 (mm) respectively from cold rolled plate for erosion studies. Samples were cleaned in acetone and grit blasted using alumina powder of 150µm before the atmospheric plasma spray process for better adhesion between coating and substrate. CoCrAlY/28%Al_2O_3/2%YSZ composite powder of particle sizes -15 to +45µm was deposited using the plasma spray process.

YSZ is a rare earth element which is used mainly for wear and erosion application due to its high hardness. Addition of rare-earth elements (CeO_2, La_2O_3, and Y_2O_3) provides increases in wear, corrosion, oxidation resistance and also improves the hardness, toughness, bond strength, and thermal shock resistance of various coating materials (Sharma, 2012). The plasma spray process was carried out using METCO USA 3MB equipment (Spraymet Surface Technologies Private Limited, Bangalore, India). The spray parameter adapted during deposition is listed in Table 1.

The coated samples were sectioned and polished to determine coating thickness, porosity and morphology using optical microscope supported with image analyser software and SEM. Hardness was carried out using Mitutoyo hardness tester. X-ray diffraction was done to analyse different phases in powder coating.

Table 1
Plasma spray parameters

Argon flow rate	40 l/m
Hydrogen flow rate	5-7 l/m
Current	490 A
Voltage	60-70 V
Powder feed rate	60 g/m
Stand of distance	100-120 mm

Erosion Studies

Erosion tests were carried out as per ASTM G76-13 standard using solid particle Air Jet Erosion Tester TR-471-800 (Ducom Instruments Private Limited, Bangalore, India), which can operate at the maximum temperature of 800ºC. The erosion studies were performed both on the substrate and coating at 600ºC for comparison. The testing conditions of erosion in the present study are listed in Table 2.

Before testing, the samples were cleaned with acetone, followed by drying and later weighed using electronic weighing balance with least count 0.1 mg. The samples were then fixed to the holder with two different angles of 30º and 90º and allowed it to erode for 5 cycles having each cycle of 10 minutes. Then, the eroded samples were cleaned with high pressure air to remove erodent particle and weighed to determine the weight loss.

Table 2
Erosion Test Conditions

Erodent material	Alumina
Erodent average size	50 µm
Particle velocity	35 m/s
Erodent feed rate	2 g/min
Impact angle	30º and 90º
Temperature	600ºC
Cycle test time	10 min
Nozzle diameter	1.5 mm
Standoff distance	10 mm

RESULTS AND DISCUSSION

Microstructure and Properties of Coating

Cross section of the coated sample observed in SEM is shown in Figure 1 and the scale bar in the SEM image shows the appropriate coating thickness ranging from 150 µm to 200 µm. Elliptical splats formed due to the impacts of fully melted and partially melted particles could be seen. Marked small round partially melted particles could also be seen in back scattered image in Figure 1(a). The grey region was found to be Al_2O_3 and white region corresponded to Co rich phases, and pores could also be seen with spotted black colour. Pores present between the boundaries of splats can be observed in secondary electron image as shown in Figure 1(b). Surface morphology of coating, distribution of splats and the splat formed during the molten particle impact are shown in the magnified SEM image in Figure 1 (c, d) and d respectively.

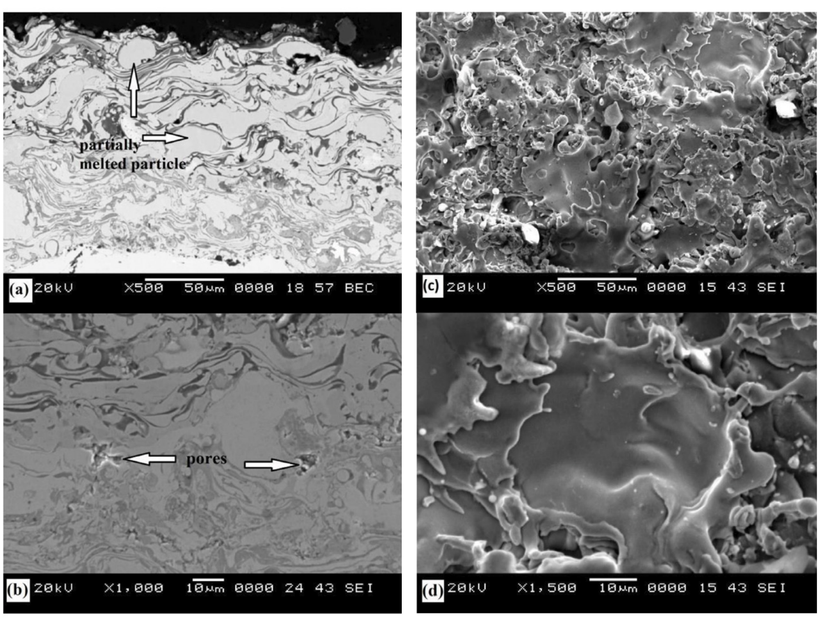


Figure 1. The SEM images of cross section (a, b) and surface (c, d) of as-coated sample.

The X-ray diffraction pattern of powder and plasma sprayed CoCrAlY/Al_2O_3/YSZ shown in Figure 2 shows some similar peaks of Cr, α-Co and Al_3Co. Cr and Al_2O_3 are the major phases in the powder with α-Co and Al_3Co as minor phases having low intensity peaks. Cr oxide has been observed in the coated sample, which was formed due to the occurrence of oxidation during in-flight time, and plasma spray process has higher in-flight time compared to other thermal spray process (Wang et al., 2015). The slight amorphosisation may occur during the process leading to change in X-ray diffraction pattern peak height and width, which can be observed in the X-ray diffraction pattern.

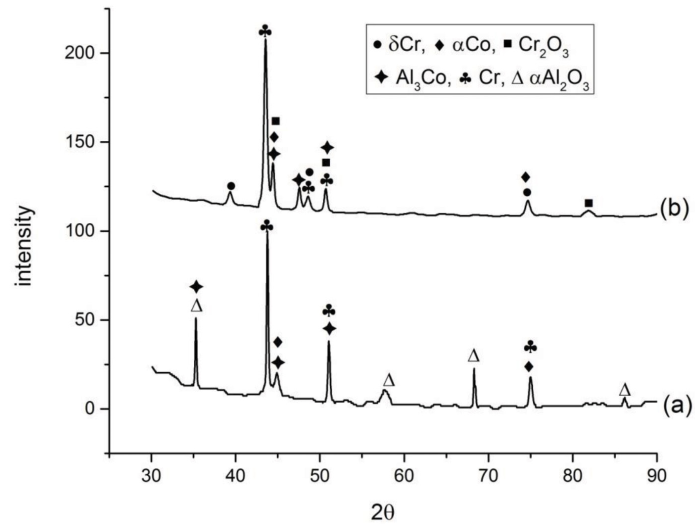


Figure 2. The X-ray diffraction pattern of (a) CoCrAlY/Al2O3/YSZ powder; (b) As coated

The variation of the microhardness values of the substrate and coating is shown in Figure 3. Both MDN 321 and Superni 76 substrates obtained the hardness value of 185 HV and 280 HV respectively. The CoCrAlY/Al_2O_3/YSZ coating shows the hardness value of 285 HV.

The increase in the hardness of substrate can be observed near the interface because of work hardening effect during the sand blasting prior to plasma spray process. The variation of the microhardness values of coating across the cross section is due to heterogeneous nature and distribution of Al_2O_3 in CoCrAlY matrix. Similarly, Praveen et al. (2015) reported that the heterogeneous nature of Plasma Sprayed Al_2O_3 with Ni based powder coating with the microhardness value of 673 HV with the load of 300 g.

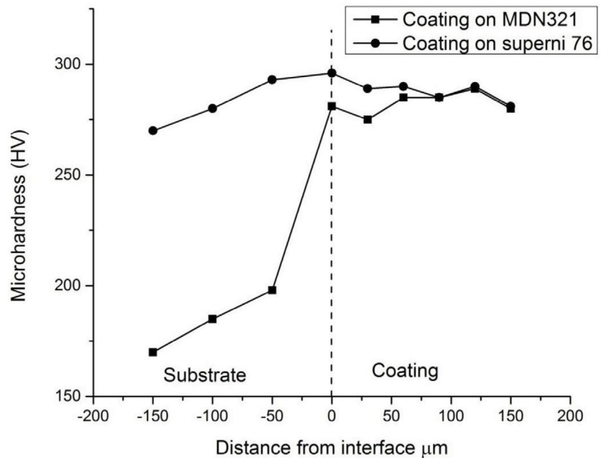


Figure 3. Microhardness variation along the cross section of coating and substrates.

The influence of impact angle on solid particle erosion

The volumetric erosion rate of coating on two substrates with different impact angles of 90º and 30º is represented in a bar chart in Figure 4. At both 90º and 30º of impact angles, the coated samples showed better erosion resistance performance on both Ni and Fe based alloy substrates. By quantifying the volumetric erosion rate, it is clear that coating shows better performance at 90º compared to 30º impact angles. In general, brittle coating material undergoes rapid erosion at higher angle than at smaller angle of impact and ductile coating material shows rapid erosion at lower angle than higher angle of impact (Tu et al., 1997). From the above reference, it can be reported that CoCrAlY/Al_2O_3/YSZ coating follows ductile erosion mechanism. Coating shows less erosion volume loss compared to plasma sprayed NiCrSiB/Al_2O_3 (Dallaire et al., 2001; Ramesh et al., 2010) which has same harphase Al_2O_3. Figure 5 (a, b) shows the cumulative erosion loss in each cycle of 10 minutes; it was observed that steady state erosion took place in last 3 cycles as compared to the first 2 cycles. At 90º of impact angle, the coating on both substrates follows the same sequence, which has less erosion in the initial cycle and reaches steady state during the last 3 cycles. However, the reverse pattern of erosion, followed 30º of impact angle which has higher value of erosion at initial cycle and attained steady state during the last cycles.

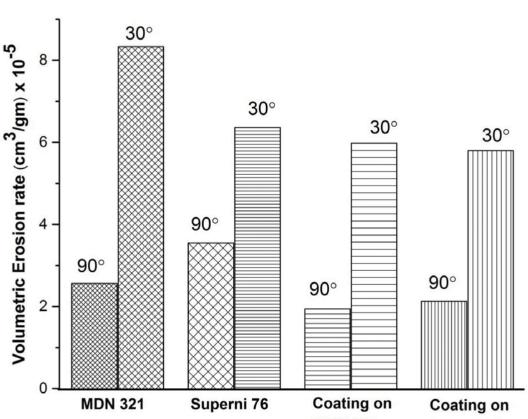
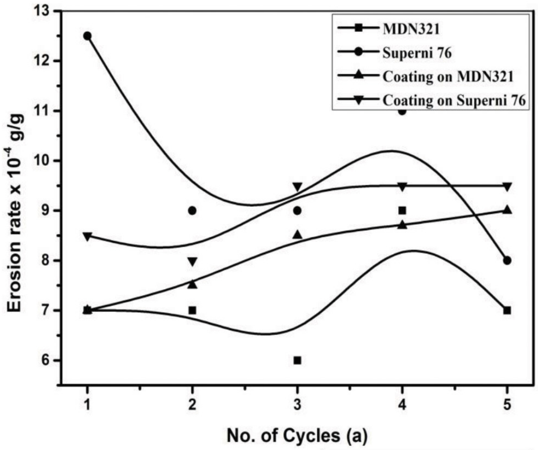
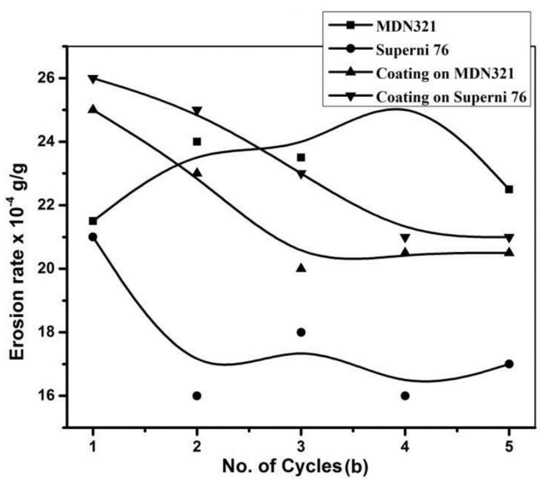


Figure 4. Bar chart illustrating volumetric erosion rate at 90º and 30º of impact angles.



(a)



(b)

Figure 5. The cumulative variation of the erosion rate with the cumulative weight of the erodent for uncoated and CoCrAlY/Al2O3/YSZ at 90° (a) and 30°; (b) of impact angles.

Erosion Mechanism

Plasma sprayed CoCrAlY/Al_2O_3/YSZ coating on both MDN 321 and Superni 76 substrates follows a similar erosion mechanism in both 90º and 30º of impact angle. The surface morphology of CoCrAlY/Al_2O_3/YSZ coating at 90º impact angle is shown in Figure 6, which reveals the presence of impact craters, indentation, raised lips and micro cuttings. The indentation on the surface followed by raised lips (Figure 6(a) and (b)), which in turn are plastically deformed from the surface, due to high strain produced by the repeated impacts of erodent particle. Erodent particles, which stick on the surface of coating, can be seen in Figure 6(a). In the feather region, the removal of splats, which forms slightly bigger craters, can be seen. The marked region in 6(b) and 6(d) shows the initial stage of splat removal which loosens the splat boundary by the repeated impact attributed to ductile erosion.

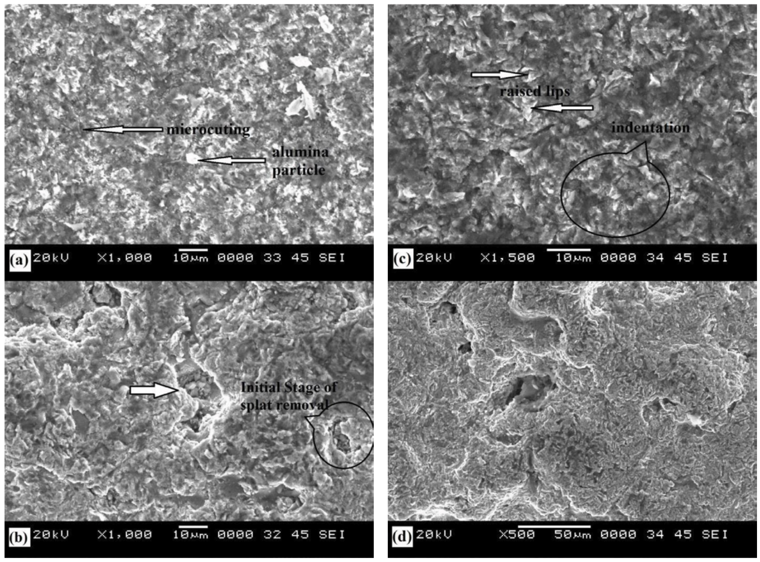


Figure 6. The surface morphology of coating on MDN 321 (a, b) and Superni 76 (c, d) showing erosion on both centre and feather region with impact angle of 90º.

The surface morphology of coating eroded at 30º of impact angle is shown in Figure 7. The presence of grooves and lips represents the material by cutting and ploughing mechanism (Figure 7(c) and 7(d)). Larger groves are formed on the softer Co-rich region and these grooves are formed by microcutting mechanism. The higher tangential force acts on the hard phases during lower impact angle results in bigger craters, indicating the material removal by chipping mechanism. The number of lips (Figures 7(a) and 7(c)) was observed on the surface, which shows erosion is done by ploughing mechanism.

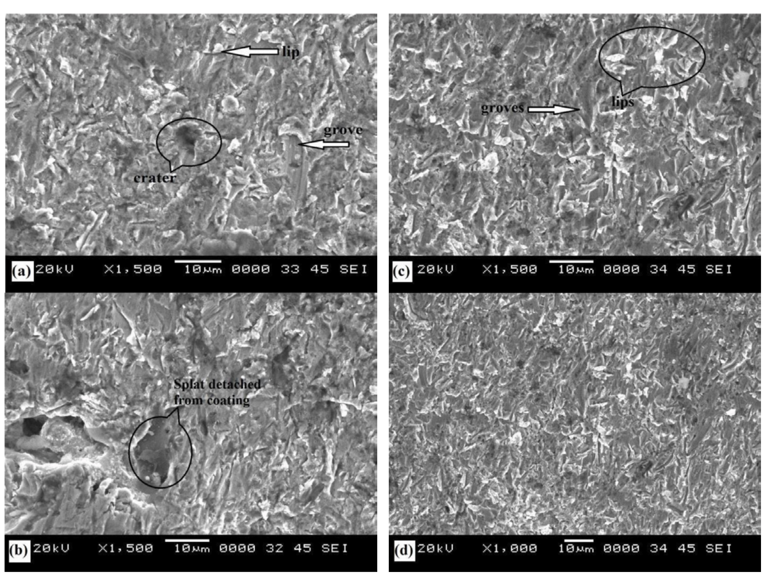


Figure 7. The surface morphology of coating on MDN 321 (a, b) and Superni 76 (c, d) showing erosion on both centre and feather region with impact angle of 30º.

CONCLUSION

The plasma spraying technique was used to successfully deposit CoCrAlY/Al_2O_3/YSZ coating on Fe and Ni based substrate materials. Coating with the porosity less than 1.5% and average hardness of 287 HV at 200 g load has been achieved. The results of solid particle erosion at 600ºC indicated that the plasma sprayed CoCrAlY/Al_2O_3/YSZ coating has ability to protect both Fe and Ni based substrate at both 30º and 90º of impact angles. The erosion performance is almost similar for coating on both Ni and Fe based since coating properties are the same, unless coating parameter, substrate temperature and roughness are changed. Coating shows better erosion resistance in 90º compared 30º of impact angles. The presence of indentation with raised lips, groves, craters without cracks and erosion loss is more in lower impact angle than higher impact angle, which concludes that the material removal is by ductile erosion mechanism.

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