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A REVIEW ON HVOF SPRAYED COATINGS OF NiCrAl

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ABSTRACT

High velocity oxy-fuel (HVOF) process is a thermal spraying process which can be used to produce quality coatings. The high speed involved in this process is quite effective in some ways as in providing less porous coatings, coatings with high hardness etc. the higher kinetic energy generated as a result of this high speed should produce dense coatings. The Thermal Barrier Coating on the surface of any material decreases the thermal conductivity which in turn reduces the exposed temperature of the substrate and finally results in reducing the thermal stress in various components. In this review paper focus has been drawn towards various performance characteristics, such as oxidation behaviour, corrosion resistance, thickness, porosity etc. of HVOF sprayed NiCrAl coatings on Ni and Fe based Superalloys. The process, process parameters and superalloys reviewed were the same whereas NiCrAl coatings were reviewed with different combinations.

KEYWORDS: Thermal Barrier Coating, Hot corrosion, Oxidation, High Velocity Oxygen Fuel process

INTRODUCTION

In various applications, as in thermal power plants etc. mechanical components operate under severe conditions, such as high load, high speed, extreme temperature and other hostile chemical environments. But the hot section components are designed only to provide the structural and mechanical reliability in actual conditions, not the high temperature protection. Therefore, it is necessary to apply the required surface modification of these components in order to protect them against various types of degradation[1]. Thermal Barrier Coatings (TBC) are applied to the material to enhance its ability to sustain elevated temperatures. In general TBC provide a barrier to the increased flow of heat by insulating components such as gas turbine, engine parts etc. which are operating at elevated temperatures. TBCs can be described as complex thick films of a refractory material which protect the metal part from the extreme temperatures. Due to the coatings, metallic materials can be used above their melting points. Temperature drop across coatings can be determined by thermal conductivity of the coatings [2]. According to {(Maloney, M. J., Thermal Barrier Coatings Systems and Materials, US Patent 6 117 560, (2000)} it has been estimated that a

50% reduction in thermal conductivity will reduce the alloy temperature by about 55°C.

There are some prerequisites to the selection of TBC materials such as low thermal conductivity, high melting point, large temperature gradient when exposed to heat flow, good adherence to the metallic substrate, chemical inertness, low sintering rate of the ceramic matrix, no phase transformation during thermal cycling i.e. the material must not undergo phase transformations on cycling between room temperature and high temperatures. Because such phase transformations usually result in volume changes, which detract from its ability to withstand repeated thermal cycling.

Generally MCrAlY (where M is either Ni or Co or a combination of both) are widely used due to their excellent high temperature performances. These coatings are used as protective coatings, at high temperatures, in hot corrosive or oxidising environments. These coatings can be deposited by thermal spray processes such as vacuum plasma spray[2], high velocity oxygen- fuel(HVOF)[3] and by physical vapour deposition such as electron beam vapour deposition (EBPVD) [4], sputtering [5]. Above mentioned processes should produce coatings with sufficient bonding strength to substrate. The

bright side of the MCrAlY systems is the high temperature oxidation characteristics which also allow these alloys to be used as stand-alone coatings. The ability of NiCrAlY to produce a thermally grown oxide (TGO) is the reason of its high temperature oxidation resistance.

High velocity oxy-fuel (HVOF) thermal spray process is an economical and simple method to develop the quality coatings with excellent corrosion and wear protection [6]. Flexibility and cost effectiveness of HVOF is the reason that this process has been widely adopted in many industries [7] such as aerospace, automotive and other industries [8]. Therefore, HVOF has been reviewed in present study as a means to deposit the coatings[9].

HIGH VELOCITY OXYGEN-FUEL (HVOF) PROCESS

Principle

The High Velocity Oxygen Fuel (HVOF) process comes under the category of flame spray process. The main distinctions between conventional flame spray and HVOF are-

- In HVOF, confined combustion is used to heat the powdered coating material and an extended nozzle is used to accelerate the powdered coating material.
- Typically HVOF devices perform their operations at hypersonic gas velocities, greater than MACH 5 [10]. As a result of these extreme velocities, kinetic energy is produced which help in developing very dense and well adhered coatings in the as-sprayed condition.

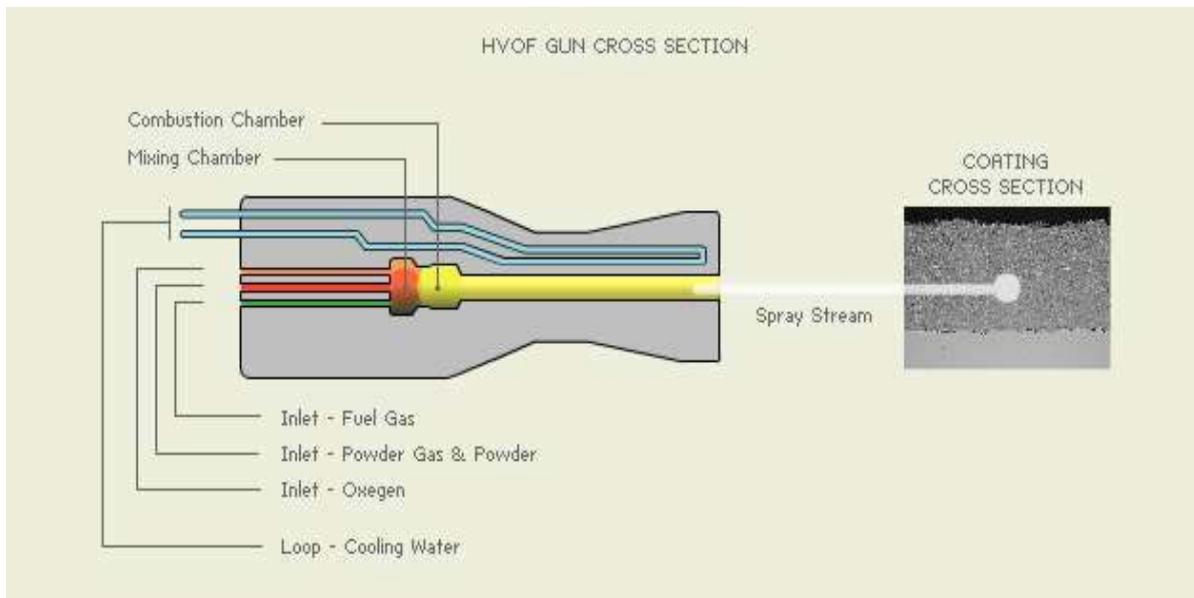


Fig.1 HVOF gun cross-section[10].

Equipment

The HVOF gun has three different inlets for three different inputs i.e. fuel gas, oxygen, and ceramic powder. After entering through inlets these three components are then mixed in the mixing chamber and after mixing are subjected to combustion in the combustion chamber. After combustion this final product flows through a nozzle and is directed towards the substrate to form the coating.

Process

In HVOF, oxygen and a suitable fuel (hydrogen, acetylene, propylene or propane) is fed into the spraying gun along with ceramic powder, through different inlets, where it undergoes combustion process to produce a high pressure flame. The powder melts due to this combustion process, and is then passed through a nozzle to increase the velocity. Dense and strong coatings can be achieved through this process.

**HVOF SPRAYED NiCrAl COATING:
A. MECHANICAL PROPERTIES**

According to R.A. Mahesh et al. Chemical composition of the super alloys used in the study were-

Alloy	Fe	Ni	Cr	Ti	Al	Mo	Mn	Si	Co	W	P	C	S
Superni 76	19.69	Bal	21.49	-	-	9.05	0.29	0.39	1.61	0.6	0.005	0.086	0.002
Superni 750	7.32	Bal	15.28	2.37	0.59	-	0.06	0.07	0.05	-	0.85	0.07	0.004
Superfer 800	Bal	30.8	19.5	0.44	0.34	-	1.0	0.6	-	-	-	0.10	0.006

Table 1. Composition of Super Alloys[1].

The spray parameters used were-

- Oxygen flow rate — 0.0042 m³/s,
- Fuel (LPG) Flow Rate — 0.0010 m³/s,
- Air Flow Rate — 0.010 m³/s,
- Spray Distance — 200 mm,
- Fuel Pressure — 0.59 N/mm²,
- Oxygen Pressure — 0.78 N/mm²,
- Air Pressure — 0.59 N/mm².

Nominal composition of NiCrAl (MEC-1047) coating powder was:
Ni-17.92Cr-6.66Al-0.29Fe-0.66Mn-0.054C-0.90Si (wt%).

Microhardness

According to R.A. Mahesh et al. hardness profiles are found to be a function of distance from the coating substrate interface along the cross-section of the coatings. Variation in the hardness of the coatings depends upon distance from the coating substrate interface. While the minimum hardness values, at the maximum distance from the interface, were almost the same. The maximum hardness values of the coating decreased from alloy 1 to alloy 3 at the interface. The maximum hardness value of the substrate was almost in the range of minimum hardness value of coatings.

Presence of porosity, oxide inclusions, melted, unmelted particles in the coating might be the reason for variation in the microhardness value of the coating along the cross-section. There are some other literatures resembling such variations in microhardness values measured for the thermal sprayed coatings [11-14]. The higher hardness value at the coating substrate interface may be partially attributed by the work-hardening effect due to the sandblasting of the substrate prior to the coating process [15] and one more reason might be the high-speed impact of coating particles [16-18].

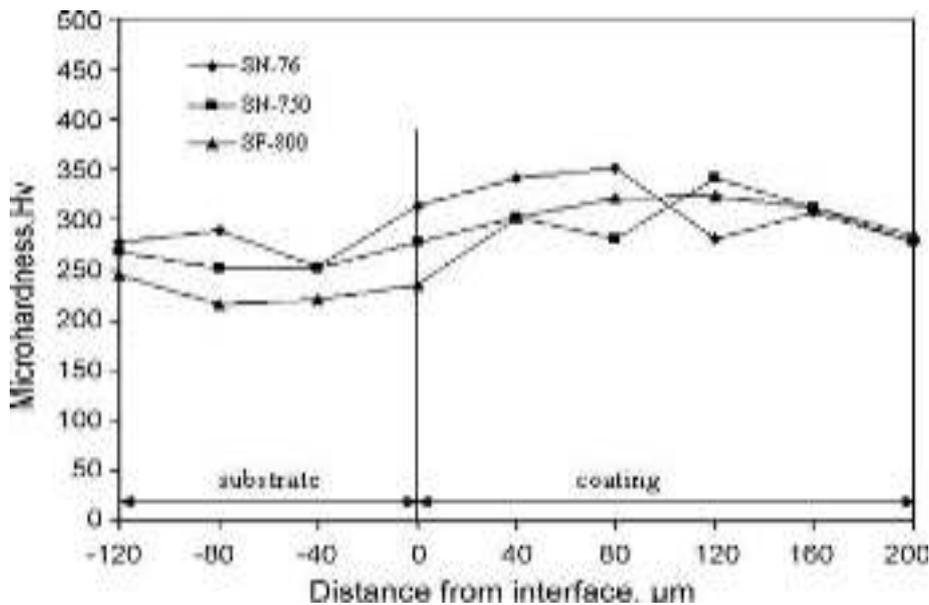


Fig.2 Microhardness profiles for HVOF sprayed NiCrAl coatings on the different superalloys[1].

Thickness and Porosity

According to R.A. Mahesh et al. Different points of the coating thickness were measured along the cross-section for the three Superalloys. So the average coating thickness of 175 μm for Superni 76, 139 μm for Superni 750 and 97 μm for Superfer 800 were found. Due to shortage of time, high velocity particles penetrating on substrate didn't get much time to cool, which resulted in increased bond strength and lower porosity. Dense coat generated on substrate provides a better corrosion resistance than the porous coatings, as porosities can harm the persistent corrosion resistance of the coating [19,20]. In this study, the porosity of the NiCrAl coatings was less than 1.70%[1].

B. MICROSTRUCTURAL PROPERTIES

The results shows Nickel-chromium were present in higher amount at the centre region of splat, whereas aluminium was present at the boundaries where nickel and chromium were absent[1]. Diffused

oxygen was also present into the coating, at the splat boundaries. In the coating, diffused iron from the substrate was present at the intersplat regions. Chromium co-existed with aluminium at the splat boundaries. An in-flight oxidation of aluminium might have occurred during the coating process which creates a thick band of aluminium at the coating-substrate interface. And a small amount of manganese and silicon diffused from the substrate migrates into the coating. The dark area generated near the coating-substrate interface indicates the presence of aluminium oxide, which amplifies the oxidation of aluminium during coating process. Presence of thin band of iron on the surface indicates the diffusion of the substrate elements during coating process.

C. OXIDATION BEHAVIOUR

NiCrAlY powder of chemical composition:

Ni-22.1Cr-10.4Al-1.01Y (wt%).

An additive CeO₂ (0.4 wt%) with 99.99% purity was added in to NiCrAlY powder.

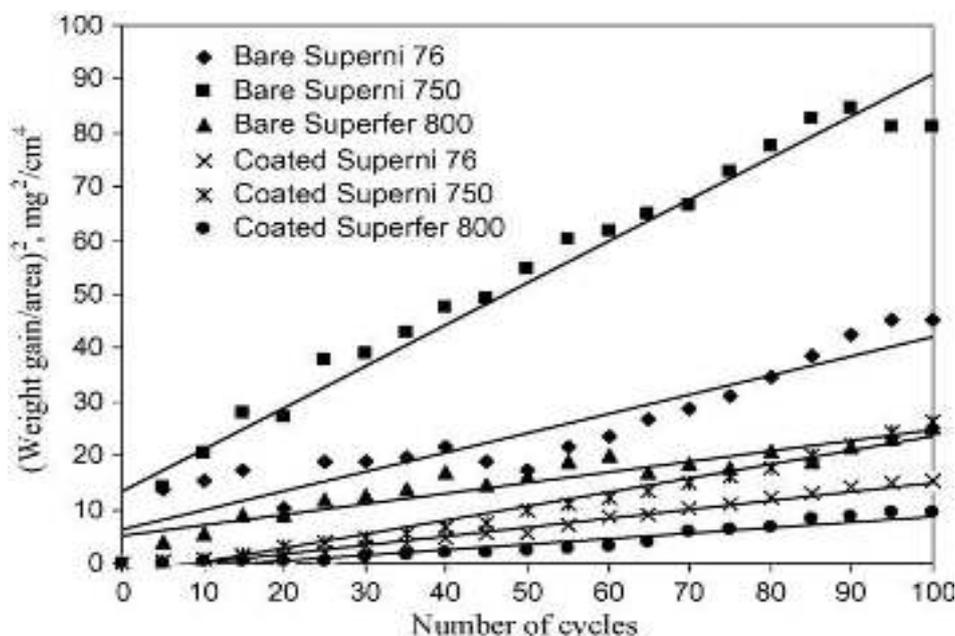


Fig.3 (Mass gain/area)² versus number of cycles for bare and NiCrAlY-0.4 wt.% CeO₂ coated superalloys oxidised in air at 900°C for 100 cycles[21].

The weight gain per unit area vs. number of cycles plotted for the non-coated and coated alloys is shown in above figure. The weight gain is high in non coated alloys than in coated super alloys and gradually equalises. The weight gain (mg/cm²) was higher in case of non coated Superni 750 than in non coated Superfer 800 in the given environment. When the coating of NiCrAlY-0.4 wt% CeO₂ was applied to the Superalloys, the weight gain was again found higher in case of coated Superni 750 than in case of coated Superfer 800. The Kp values are lower for all coated Superalloys as compared to that of non coated

Superalloys which indicates better resistance to oxidation at 900°C.

After oxidation of coated Superni 750, oxides of nickel, chromium and aluminium were found, while minor amount of iron was diffused from the substrate into the coating. In case of coated Superfer 800 and Superni 76, the surface mainly consists of oxides of nickel, chromium and aluminium. The surface formed after the coating was uniform and free from cracks. The presence of NIO was also evident [22-24]. The initial rate of oxidation was high in case of non coated Superalloys, but when the oxides are formed it levels off.

In the early stages, a rapid weight gain was found but as the process continues, it slows down with the formation of oxides at the pores and splat boundaries. The similar results were observed by

Zhang et al. [25], which conclude that partially oxidised coatings acts as a diffusion barrier to the oxidising species.

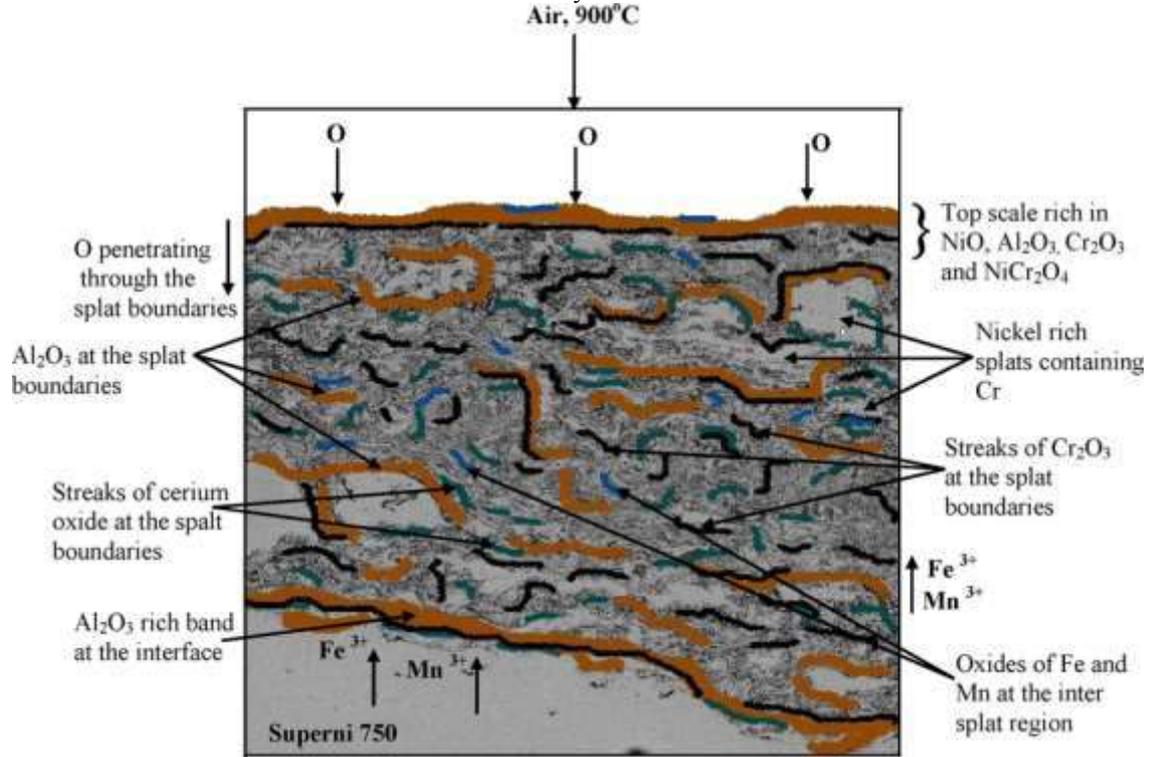


Fig.4 Probable oxidation mechanism for the NiCrAlY-0.4 wt% CeO2 coated Superni 750 exposed to air at 900°C for 100 cycles[21].

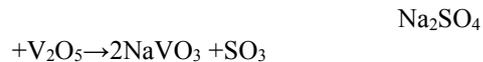
D. HOT CORROSION BEHAVIOUR AT 900°C

The chemical composition of the powder used:

Ni-17.92 Cr-6.66 Al-0.66 Mn-0.054 C-0.90 Si-0.29Cr (wt%).

The weight gain/unit area for non-coated and NiCrAl-coated Superalloys exposed to the Na2SO4-60%V2O5 salt environment at 900 °C for 100 cycles are shown in Fig.5. The maximum weight gain was for the Ni-based uncoated superalloy Superni 750, whereas for uncoated Superfer 800 it was minimum among all the superalloys. But for the last 20 cycles the weight decreases in case of SN 750. While in case of NiCrAl-coated Superalloys, Superni 76 has shown maximum weight gain whereas the weight gain of Superni 750 was minimum, three times less than that of Superni 76.

In the early stages of hot corrosion study, the weight gain for coated Superalloys is relatively high but increases gradually afterwards, whereas for uncoated Superalloys it increases continuously. The similar have been observed by Tiwari et al. [26] for the uncoated Superalloy substrates. According to Hwang et al.[27], the reactions of sodium sulphate and vanadium oxides shown as-



Sodium vanadates can significantly increase the rate of oxidation of nickel base Superalloys and they are highly corrosive. They are also volatile and rapidly vaporise from the surface. That is why there is an increase in the mass gain of uncoated Superalloys during the early stages of hot corrosion. The rapid formation of oxides at the splat boundaries might be the reason for high initial oxidation rate of coated Superalloys.

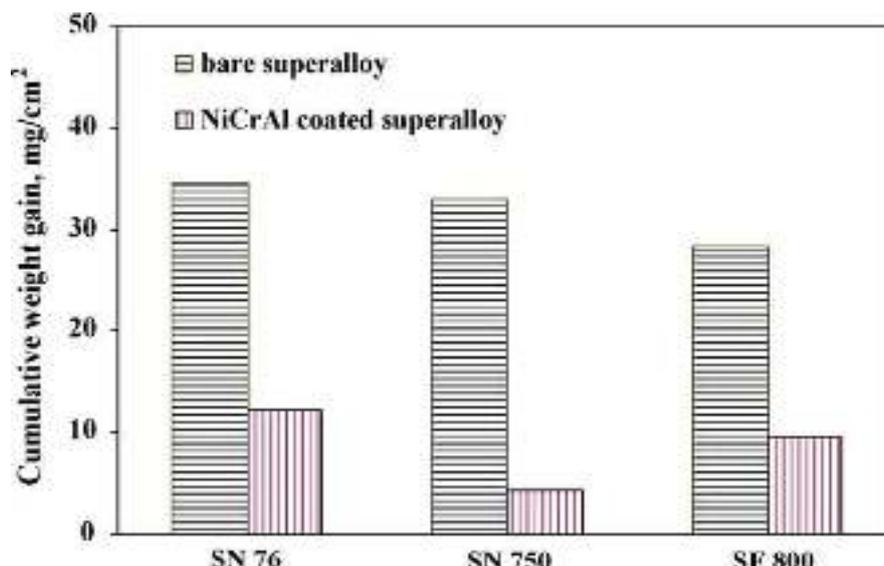


Fig.5 Bar chart showing cumulative weight gain per unit area for bare and NiCrAl coated Superalloys subjected to molten salt environment at 900°C for 100 cycles[9].

CONCLUSION

Various characteristics of three Ni and Fe based superalloys were reviewed using the same coating process (HVOF) and process parameters but the composition and the environment of NiCrAl bond coat were subjected to change[1,9,21]. Microstructural properties and mechanical aspects were reviewed with NiCrAl bond coat[1], high temperature oxidation behaviour was reviewed with NiCrAlY-0.4 wt% CeO₂ coating[21], and corrosion resistance was reviewed in Na₂SO₄-60% V₂O₅ salt environment at 900°C for 100 cycles[9].

1. Microstructural and mechanical properties with NiCrAl bond coat showed less porous structure with high hardness values at the coating- substrate interface which decreased from alloy 1 to alloy 3 while the minimum hardness values were almost the same for all the alloys at the farthest place from interface. Nickel and chromium both were found in centre region whereas aluminium along the splat boundaries. Aluminium oxide was present at the interface. Iron, manganese and silicon were also present in traceable amount which might have migrated from the substrate into the coating during HVOF spraying process.
2. Oxidation behaviour with NiCrAlY-0.4 wt% CeO₂ coating showed that the weight gain of non-coated superalloys was higher compared to that of the coated superalloys. The sequence of weight gain was similar for both coated and non coated alloys. Higher weight gain was for superni 750 whereas least weight gain was for superfer 800. Oxides of chromium, aluminium and nickel along with spinel of nickel and chromium were present. Whereas oxides of iron,

manganese and titanium were also present in smaller amounts. These oxides might have formed by the diffusion of elements from the substrate to the top scale.

3. Corrosion resistance with Na₂SO₄-60% V₂O₅ salt environment for 100 cycles showed differing sequence for coated and non-coated superalloys. The maximum weight gain was for non-coated Superni 750, whereas for non-coated Superfer 800 it was minimum. While in case of NiCrAl-coated Superalloys, Superni 76 has shown maximum weight gain whereas the weight gain of Superni 750 was minimum. Cr₂O₃ and Al₂O₃ were formed alongside splat boundaries while nickel remains unoxidised even after 100 cycles at 900°C.

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