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High Temperature Oxidation and Wear Resistant Bi-Layer Coating for Turbocharger Housing

Hitesh Vasudev, Lalit Thakur and Amit Bansal

Abstract

An upsurge in the demand of higher power generation has been observed in the last few decades. Consequently, the mechanical components of power generation are forced to operate in the extreme working conditions for longer duration, which results in the accelerated wear and corrosion of the material. Conventional material such as grey cast iron (GCI) is a preferred material of components used for power generation at high temperature. Grey cast iron exhibits poor wear and corrosion resistance at high temperature. On the other hand, an advanced material such as Alloy-718 is capable to withstand the high-temperature wear and oxidation for prolonged duration of time. In the current research, high temperature corrosion and erosive wear performance of grey cast iron (GCI) components has been enhanced by depositing a bi-layer Alloy-718/NiCrAlY coating by using high velocity oxy-fuel (HVOF) thermal spray process. Furthermore, the high temperature corrosion and erosion behaviour of GCI substrate and the deposited coating has been discussed. The various characterization techniques such as scanning electron microscopy (SEM) X-ray diffraction, and Vickers micro-hardness testing were conducted for the GCI substrate and Alloy-718 coating, respectively. The Alloy-718 coating showed the increased resistance against high-temperature erosion and oxidation, which can be attributed to its good bonding with the substrate, high hardness and formation of protective phases at high-temperature.

Keywords: high-temperature, turbocharger, Alloy-718/NiCrAlY, HVOF, grey cast iron

1. Introduction

The present scenario of the automotive engineering is concerned with the higher power generation. There is a huge requirement of the materials which can sustain the high temperature in order to increase the power generation of the systems. These materials require high thermo-mechanical properties to withstand the hostile conditions like oxidation and erosion at elevated temperatures up to 900°C. The surface of the components deteriorates rapidly at such aggressive conditions. Grey cast iron (GCI) is one of the most commonly used materials in the turbocharger housing and its integral parts such as housing of bearing. The GCI components must work satisfactorily for prolonged duration of time under such aggressive working condition [1–4]. However, the GCI alone cannot provide enough oxidation and erosion

resistance at high temperature. Thus, there is a need to modify the surface properties of the GCI component which enables it to work under high temperature oxidation and erosion environment. There are number of methods to modify the surface properties of materials such as by changing the surface chemistry of the materials with the help of surface modification techniques such as carburizing, nitriding and cyaniding, etc. The various methods of surface engineering applied for surface modification are given in **Table 1**. The methods employing the deposition of a layer of superior material is commonly employed in surface engineering. This can be

S. no.	Surface treatment/coating type	Primary property benefits
1	Changing the surface metallurgy	
	Localized surface hardening (flame, induction, laser, and electron-beam hardening)	Improved wear resistance through the development of a hard martensitic surface
	Laser melting	Improved wear resistance through grain refinement and the formation of fine dispersions of precipitates
	Shot peening	Improved fatigue strength due to compressive stresses induced on the exposed surface, also relieves tensile stresses that contribute to stress-corrosion cracking
2	Changing the surface chemistry	
	Carburizing	Used primarily for steels for increased resistance to wear, bending fatigue, and rolling-contact fatigue
	Nitriding	Used primarily for steels for improved wear resistance, increased fatigue resistance, and improved corrosion resistance (except stainless steels)
	Carbonitriding	Used primarily for steels for improved wear resistance
	Boronizing (boriding)	Improved wear resistance, oxidative wear, and surface fatigue
	Ion implantation	Improved friction and wear resistance for a variety of substrates
	Laser alloying	Improved wear resistance
3	Adding a surface layer or coating/cladding	
	Physical vapour deposition (PVD)	Improved wear (e.g. tools and dies) and corrosion resistance, improved optical and electronic properties
	Chemical vapour deposition (CVD)	Improved wear (e.g. tools and dies), erosion, and corrosion resistance; also used for epitaxial growth of semiconductors
	Thermal spraying	Primarily used for improved wear resistance (many coating systems including Ni-based alloys, ceramics and cermets), but also used for improved corrosion resistance (aluminum, zinc, and their alloys) and oxidation resistance (e.g. MCrAlY), thermal barrier protection (partially stabilized zirconia), electrically conductive coatings (e.g. copper and silver), and dimensional restoration
	Electroless plating	Improved corrosion resistance (nickel-phosphorus) and wear resistance (nickel-phosphorus and nickel-boron)
	Weld overlays	Improved wear resistance (hardfacing alloys) and corrosion resistance (stainless steel or nickel-base overlays) and dimensional restoration (buildup alloys)
	Laser cladding	Improved wear and corrosion resistance

Table 1.
Surface engineering options and property enhancement.

done by number of methods such as weld overlaying, cladding and thermal spraying, etc. Nowadays, the thermal spraying methods are used in various industries due to their specific advantages such as ease of operation, enhanced surface properties, less detrimental effects to the substrate and to produce the coatings on any intricate shaped components [5–7]. This process is utilized in the deposition of almost all class of engineering materials like polymers, ceramic, metal, and composite [8, 9].

There are various techniques of thermal spraying but the high velocity oxy-fuel (HVOF) process is gaining popularity due to its specific characteristics such as corrosion and wear resistant coating, high velocity up to 1000 m/s, lower porosity content and dimensional restoration. This high velocity in this technique causes feedstock powder to deform plastically on the surface of the substrate [10]. Moreover, this technique has taken up by numerous industries due to its mobility, economical processing and ease of operation with safety along with excellent quality of the coating. High velocity oxy-fuel (HVOF) process provides the coatings with high hardness, very low oxidation, good abrasion resistance, lower porosity levels and high erosion resistance as compared to the other thermal spray coating techniques [11]. The characteristics of high velocity makes it enable to deposit coatings with improved bonding with the substrate that results in higher hardness, less porosity and high density. The various attributes of different thermal spray methods involves the type of heat source used, which is responsible for the temperature of the process, the velocity of powder particles and the rate at which powder is being feed for the deposition purpose. The comparison of various characteristics of thermal spray coating processes is given in **Table 2**.

Oxidation is related to the formation of some undesired phases like porous and non-coherent oxides on the surface of the material, which is responsible for the failure of the component. The oxidation generally starts from the surface due to diffusion of oxygen and further propagates to the sub-surface of the material in an aggressive thermal cycling condition. This problem is observed in turbocharger housing and bearing housing. These components also suffer from an erosive wear along with the oxidation. In the erosion of components, the hot air strikes on the surface of the components in cyclic and repetitive manner, and this air contains some unwanted dust particles. The intensity of these particles and hostile environment are two major reasons responsible for the degradation of the surface with erosion at elevated temperature above 500°C [12]. The oxidation of component is not only a single problem to solved by using Ni-based coatings, the erosion is also present due to the erodent particles impacting on materials surface at high velocities; thus there is a requirement of feasible solution which can help to minimise both the problems of oxidation and erosion at a same time.

Coating process	Source of heat	Feedstock material	Feedstock powder temp (°C)	Velocity of powder (m/s)	Deposition rates (kg/h)
Flame spray	Oxy-acetylene	Powder or wire	3100	40	2–5
Plasma spray	Plasma arc	Powder	10,000	200–400	3–8
LPPS	Plasma arc	Powder	11,000	200–400	3–8
Detonation spray	O ₂ -acetylene-N ₂ + gas detonation	Powder	4700	800	0.6
HVOF	Oxy-fuel combustion	Powder	3000	800	2–4

Table 2.
Attributes for different thermal spray processes.

Nowadays, the Ni-Cr coatings are used as a most preferred candidate for the oxidation resistance of components operated at high temperature range up to 650°C. However, these coatings suffered a problem of diffusion of Fe element from the substrate to the coating, when applied on the ferrous materials against oxidation at high temperature. The Ni-50Cr coatings were also used to minimize this problem by using HVOF process [13]. The composite coatings then came into use and were utilized to provide resistance against erosion and corrosion at high temperature. The Cr₃C₂-NiCr, NiAl-40Al₂O₃, and Cr₃C₂/TiC-NiCrMo composite coatings were deposited on low carbon steel to check its performance against erosion-corrosion at 400°C. The inter-metallic present in NiAl-40Al₂O₃ was responsible for the maximum resistance to the erosion-corrosion [14].

In the recent time, the superalloy materials are extensively used for high temperature applications. Their versatile use in these applications is due to fact that they can maintain their high strength, low temperature ductility and excellent thermal stability. Superalloys are mainly precipitation hardened or solid solution hardened nickel, iron, and cobalt based heat resistant alloys, which exhibit various properties such as good mechanical strength, wear resistance and high temperature stability. These superalloys are further classified into cast, wrought and powder metallurgy alloys. A general classification of superalloys is shown in **Figure 1**. More than 50% of the primary materials used in the hot portions of the gas turbine engines such as blades, vanes and combustion chamber are superalloys. Typical applications of superalloys include gas turbines and jet engines [15]. The versatile use of superalloys in such applications is due to fact that the thermodynamic efficiency of turbine engines is increased with increased turbine inlet temperature. These motivated the designers for increasing the maximum operating temperature using the superalloys. The Ni-based superalloys are most commonly used in high temperature applications, followed by the cobalt-based alloys and then the iron-nickel alloys. The Ni-based alloys are preferred for high temperature applications because of their excellent oxidation resistance at high temperature. The Ni-based superalloys are most stable materials at high temperature due to their face-centered cubic (FCC) crystal structure. FCC crystal structure is required at high temperature because

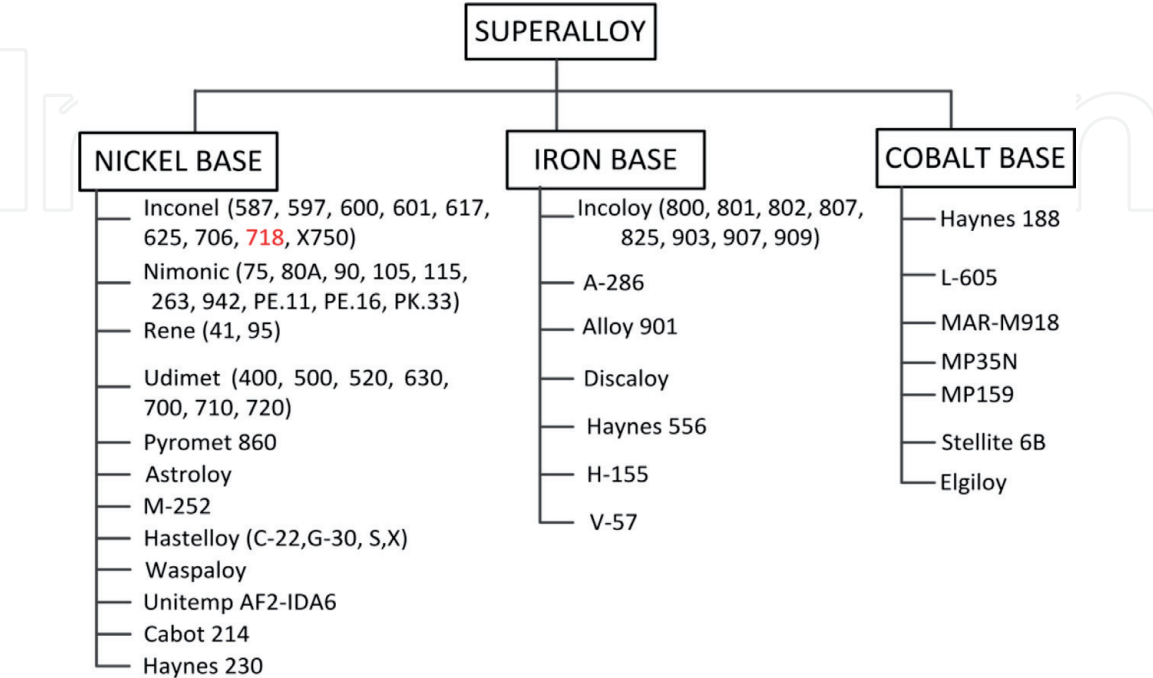


Figure 1.
Classification of superalloys [25].

of its close packed structure. Consequently, the creep, which is more prominent at high temperature, is less in FCC crystal structure. Thus, in the current research work, a nickel based superalloy Alloy-718 was selected as a feedstock powder for increasing performance of GCI at high temperature application. Alloy-718 is well known for its thermo-mechanical strength at elevated temperatures [16]. The NiCrAlY was also deposited before the coating of Alloy-718 as a bond coat material. The NiCrAlY also provides a rough surface for Alloy-718 top coat and also restricts the diffusion of elements from substrate to coating and vice-versa [17]. Hence, a bi-layer of Alloy-718/NiCrAlY was deposited on the GCI substrate by using thermal coating technique known as high velocity oxy-fuel (HVOF) spray process. The deposited bi-layer coating was investigated for its performance against high temperature erosion and oxidation. The oxidation test was conducted for 50 cycles at 900°C in a tube furnace, whereas the erosion test was conducted by using high temperature air-jet erosion testing rig at 800°C. The microstructure and mechanical characterization were performed to analyse the properties and performance of deposited bi-layer coating. The mechanical characterization mainly included the micro-hardness testing and erosion test, whereas, the microstructural analysis covers the porosity analysis, inter-splat bonding and morphology of the sprayed coating.

2. Experimentation

2.1 Materials and coating deposition

In the present work, the grey cast iron (GCI) was selected as a substrate material due to its extensive use in the manufacturing of turbocharger housing, turbocharger core and bearing housing in the turbocharger. The Alloy-718 feedstock powder was used as a coating material and NiCrAlY was selected as a bond coat between the top coat (Alloy-718) and the GCI substrate material. Therefore, bi-layer coatings consisting of Alloy-718/NiCrAlY were deposited on a grey cast iron substrate using the HVOF process. The GCI was cast into a flat plate and further machined into coupons as per the sizes required for characterization and testing purpose. The chemical composition of the GCI, and feedstock powder was checked by using optical spectrometer (Make: Metal Vision, Model: 1008i). The chemical composition of GCI in wt% was found to be 3–3.5 wt% C, 2.7 wt% max Si, 1 wt% max P, 1 wt% max Mn, 0.15 wt% S, balance Fe. The chemical composition of Alloy-718 in the wt% comprises of Ni—55.0, Cr—21.0, Fe—19.0, Nb—5.1, Mo—3.2, Al—0.5, Ti—1.2 and C—0.08. Ni, Cr and Fe are the major elements of Alloy-718 powder, whereas, Nb, Mo and Al are some other important elements of Alloy-718.

The coating powders (Alloy-718, and NiCrAlY) were purchased from MECPL, Jodhpur, India, and the deposition of the bi-layer coatings was also performed at MECPL, Jodhpur, India. The bi-layer coating was deposited with the help of a HVOF system Hipojet-2700 (manufactured by MECPL, Jodhpur, India). The various coating process parameters of the HVOF process include stand-off distance 235 mm, oxygen flow rate of 250 SLPM, oxygen pressure of 9 bar, powder feed rate of 40 g/min, LPG fuel gas flow rate of 39 SLPM and fuel gas pressure of 5 bar.

2.2 Material characterization

The characterization of as-sprayed, oxidized and eroded coatings was carried out on the surface and the cross-section by using scanning electron microscopy (SEM) equipped with energy dispersive spectroscopy (Model: Gemini ultra plus, Zeiss).

The various phases formed in the as-sprayed, oxidized and eroded coating were revealed by using X-ray diffraction (XRD) analysis with Cu-K α as source of radiation at 40 kV and 40 mA. The micro-hardness of the bi-layer coating was measured by using Vickers micro-hardness tester, where the 10 indents were taken across the cross-section of coated sample at a test load of 200 g with a dwell period of 10 s. Porosity of the coating was measured on the cross-section by using optical images taken from an optical microscope attached with an image analysis software (Dewinter Material Plus, Version 4.3).

2.3 Oxidation and erosion testing

The coated and bare GCI specimen were subjected to high-temperature oxidation at 900°C for 50 cycles of thermal cyclic operation. In the oxidation test, 1 cycle was comprised of 1 h. heating of sample followed by air cooling for 20 min. The six sided coated samples having dimensions of 25 × 15 × 5 mm³ were placed in an alumina crucible and fed inside the tube furnace for oxidation test. Thermo-gravimetric analysis was used to measure the weight loss (mg/cm²) of the coating and substrate during oxidation test.

The erosion test was also performed by using hot-air jet erosion test rig at a high temperature of 800°C as per the ASTM G76-02 standard. The erosion rate (g/g)) (ratio of wear loss of mass in grams to the erodent mass in grams) was calculated after measuring the change in the weight of the coating and substrate by using weighing balance (Model: ML-220, Make: Mettler Toledo). The impingement angles of 30 and 90° were considered in the present study to compare the erosion rates of the substrate and coating. The various process parameters of erosion test include erodent feed rate of 6 g/min, erodent velocity of 60 m/s, and exposure time of 10 min. The aluminum oxide having an average particle size of about 60 μ m was used as the erodent in the present study.

3. Results and discussion

3.1 Microstructural study

The SEM micrograph indicating the spherical morphology of the Alloy-718 powder along with its EDS is shown in **Figure 2a** and **b**, respectively. The XRD spectrum of the Alloy-718 powder is shown in **Figure 2c**. From SEM micrograph, the average powder particle size of Alloy-718 powder was observed to be around 45 μ m. The XRD spectrum of Alloy-718 powder indicates that Ni, Cr, and Fe are present as major elements in the form of a solid solution and EDS spectrum (**Figure 2b**) confirms the presence of these elements in the powder.

The SEM/EDS analysis of the NiCrAlY powder is shown in **Figure 3a** and **c** respectively. The SEM micrograph of NiCrAlY powder shows the average powder particle size of 45 μ m which is approximately same as that of Alloy-718 powder. The XRD pattern of NiCrAlY powder is depicted in **Figure 3b**; it shows the presence of Ni and Cr as major elements and further EDS confirms the presence of these elements in the powder. The XRD pattern of NiCrAlY shows the β -phase of NiAl, Cr, and Ni.

The as-sprayed Alloy-718 coating shows (**Figure 4**) the presence of some un-melted, melted, and semi-melted particles. The proper interference between melted and un-melted splats can be observed. The various powder particles seem to have flattened and spherical appearance. The powder particles were not completely melted due to moderate flame temperature of HVOF process as compared to the

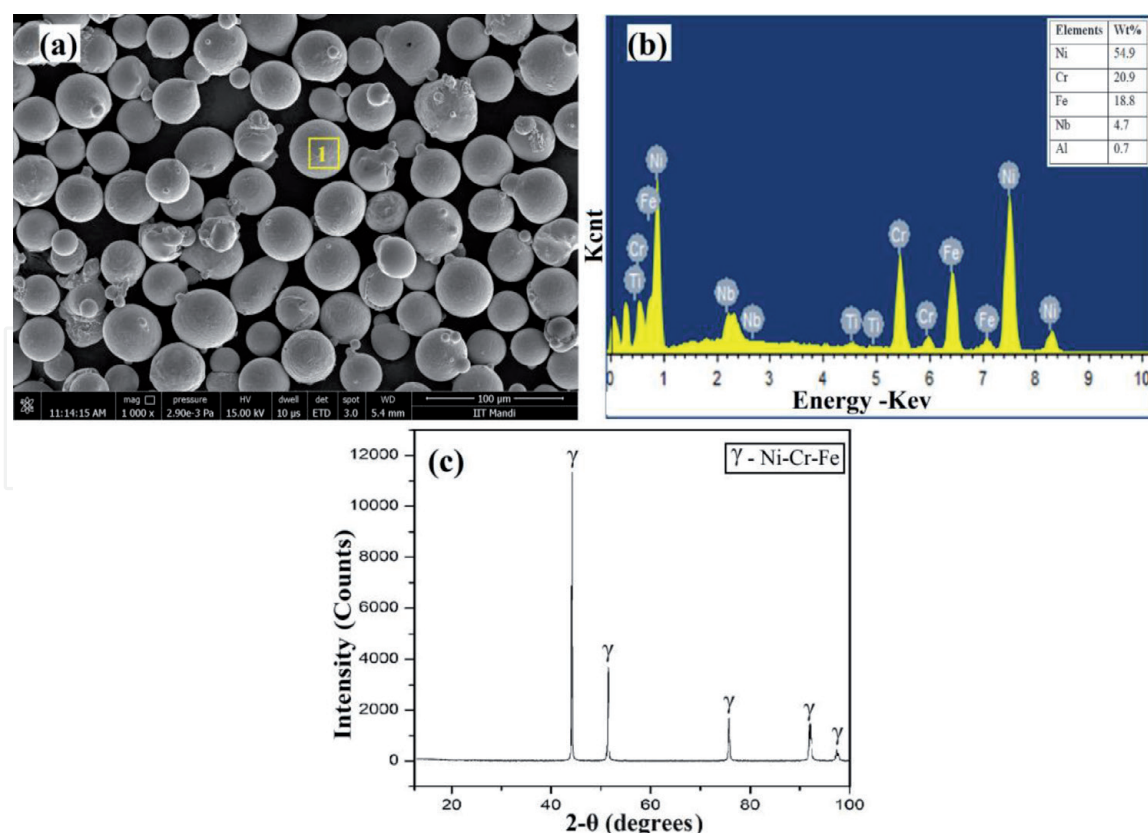


Figure 2.
(a) SEM micrograph of Alloy-718 powder, (b) EDS corresponding to point 1 and (c) XRD pattern of Alloy-718 powder.

plasma spray (PS) process. The temperature range in HVOF thermal spray process is around 2900°C, which is significantly low as compared to the temperature range in plasma spray process. The melted/semi-melted powder particles were splashed throughout the surface of coating without the absence of cracks. The EDS spectrum (**Figure 4b**) taken on the melted particle corresponding to point 3 confirms the presence of Ni, Fe, Cr, O, and Al elements. The XRD pattern (**Figure 4c**) of as-sprayed coating of Alloy-718 showed the solid solution of Ni-Cr-Fe as a major phase along with some oxides such as Al_2O_3 , Cr_2O_3 , and NiO . The oxides may be formed due to oxidation of in-flight powder particles during the deposition of coating [18].

The SEM micrograph and X-ray maps were acquired on the cross-section of bi-layer coating, as presented in **Figure 5**. From the SEM micrograph, it is clear that a NiCrAlY bond coat of about 50–60 μm thickness is introduced between substrate and top coat (Alloy-718). The coating shows well bonded interfaces with excellent mechanical anchorage. The splat formation of the deposited coating resulted in good inter-splat bonding. The X-ray maps show the intense presence of Fe in the substrate, whereas the bond coat region has a Ni and Cr in high density. The top coat (Alloy-718) region shows the presence of major elements Ni, Cr and Fe along with O. The presence of O in the Alloy-718 coatings in the X-ray mapping endorsed the formation of oxides such as Al_2O_3 , Cr_2O_3 , and NiO . The porosity across the cross section was measured, as described in the Section 2.3 was found to be in a range of 1–1.5%.

3.2 Micro-hardness study

The micro-hardness of the bi-layer coating on the cross-section was measured, as described in Section 2.2. The micro-hardness of HVOF sprayed coating was found to be higher than that of the GCI. There is an increase in the micro-hardness values for the GCI substrate at the interface of bond coat-substrate, which may be attributed to

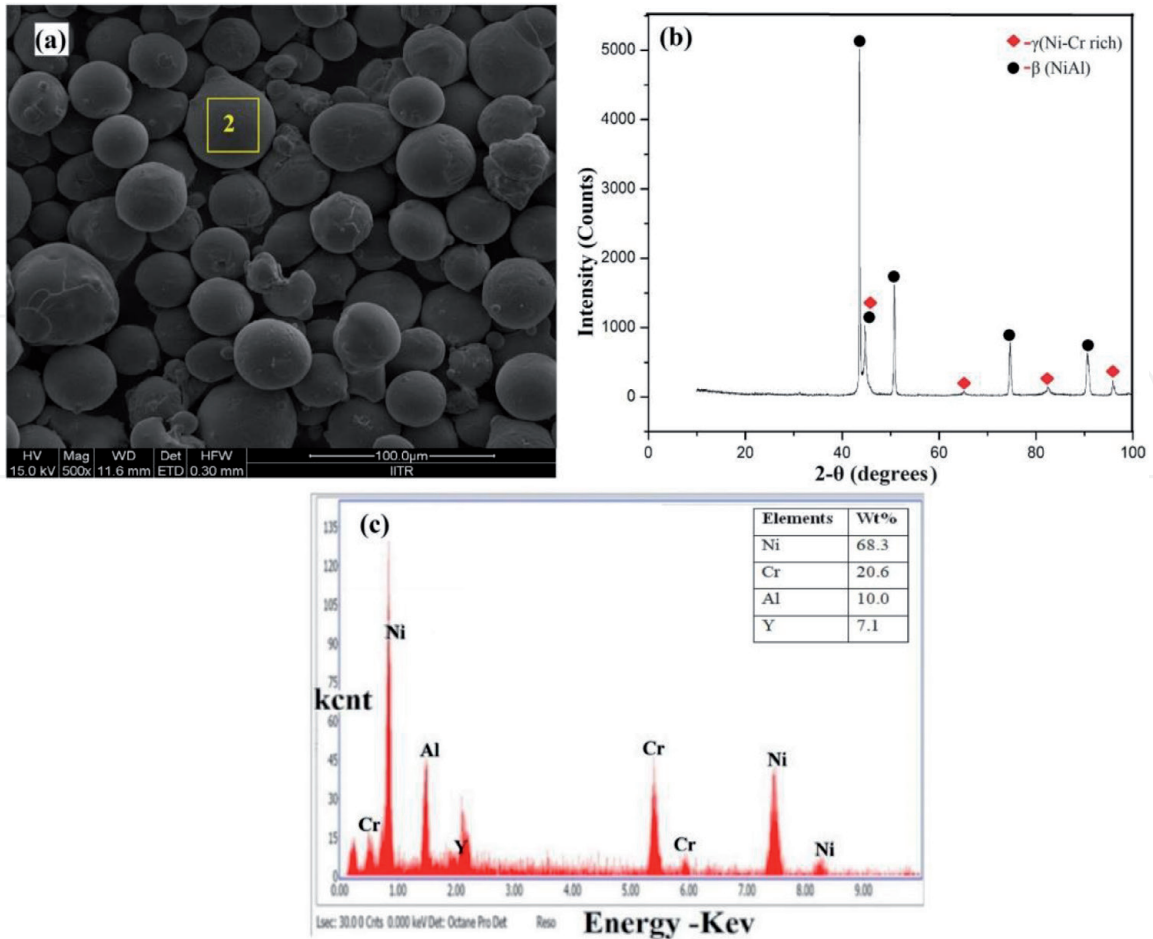


Figure 3.
(a) SEM micrograph of NiCrAlY powder, (b) XRD pattern of NiCrAlY powder and (c) EDS corresponding to point-2.

the grit blasting operation prior to the coating, which produces the strain hardening effect on the substrate before the deposition of coating process [13]. The hardening of the coated substrates in the present research work might also have occurred due to the impacts of high velocity powder particles during the HVOF deposition process. Similar kind of effect has also been reported by some researchers [11]. The micro-hardness values of the coatings are measured to be greater than the GCI substrates. High micro-hardness value is attributed due to the high kinetic energy of feedstock powder particles which ensures an excellent cohesion of powder particles; it results in denser coatings and with homogeneous microstructure and absence of unwanted oxides. Moreover, the effect of solid solution hardening is significant in case of Alloy-718 and it is intrinsically harder than GCI. The micro-hardness of the HVOF coating deposited in present work is in good agreement with the earlier research work [14]. The variation in micro-hardness value across the cross-section of coating and substrate was measured by taking 10 indents and their average hardness value was reported. The measured micro-hardness of the GCI substrate was found to be 230 ± 12 HV. The average micro-hardness of the bond coat was 350 ± 15 HV and for the Alloy-718 coating, it was 565 ± 18 HV. The higher hardness value is also attributed to the closely packed structure, and good inter-splat bonding due to high velocity of HVOF process [19].

3.3 Oxidation study

The oxidation behaviour of the coated specimen was investigated, as described in Section 2.3. In high temperature oxidation study, a change in weight gain

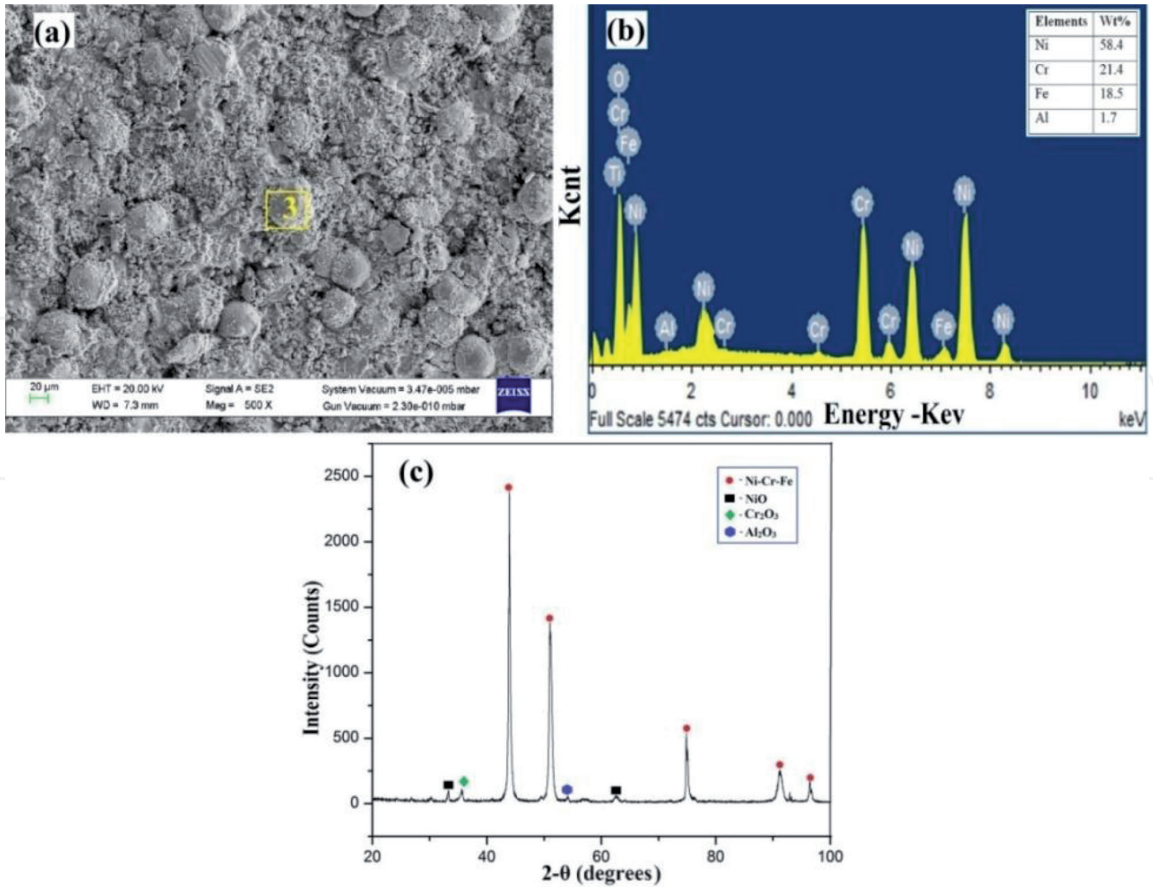


Figure 4. (a) Surface morphology of Alloy-718 coating, (b) EDS corresponding to point 3 and (c) XRD pattern of Alloy-718 coating.

(mg/cm²) of the uncoated and as-sprayed Alloy-718 coating specimens was recorded for 50 cycles. The GCI substrate and Alloy-718 coating showed the weight gain of 123.4 and 2.10 mg/cm², respectively. The weight gain in case of Alloy-718 coated cast iron has reduced to large extent, which shows the oxidation resistance at high temperature as compared with the bare GCI substrate. The calculations of parabolic rate constants (K_p) indicate the lesser oxidation rate of the Alloy-718 coating as compared to GCI substrate, as shown in **Table 3**. The calculations of the parabolic rate constants were obtained by using linear least square algorithm- ($\chi^2 = K_{pt}$), where “ x ” is the gain in weight/unit of surface area (mg/cm²), K_p is a parabolic rate constant and “ t ” is the number of thermal oxidation cycles to which specimens were exposed. The data of bare GCI substrate and Alloy-718 coated specimens confirms the parabolic oxidation law and the coating showed a superior resistance to oxidation. The value of parabolic rate constants showed the higher resistance of Alloy-718 coating as compared to bare GCI.

The SEM/EDS analysis and XRD of GCI substrate corresponding to 50 cycles of air oxidation at 900°C is shown in **Figure 6**. The SEM micrograph shows the oxidized layer of scale of around 280 µm. The EDS corresponding to point 1 shows the presence of Fe and O elements. The GCI is composed of ferrite matrix with graphite flakes. These flakes are the preferred sites for oxidation. During oxidation at high-temperature, the oxygen enters into the subsurface through the interconnected graphite flakes and form cracks inside the sub-surface. This phenomenon occurred rapidly after 570°C by means of diffusion according to Fe-O phase diagram [20]. The XRD pattern of oxidized GCI shows the formation of iron oxides such as FeO, Fe₂O₃, and Fe₃O₄. These oxides are well known for their non-coherent and porous nature which results in intense oxidation of GCI at high temperature [20].

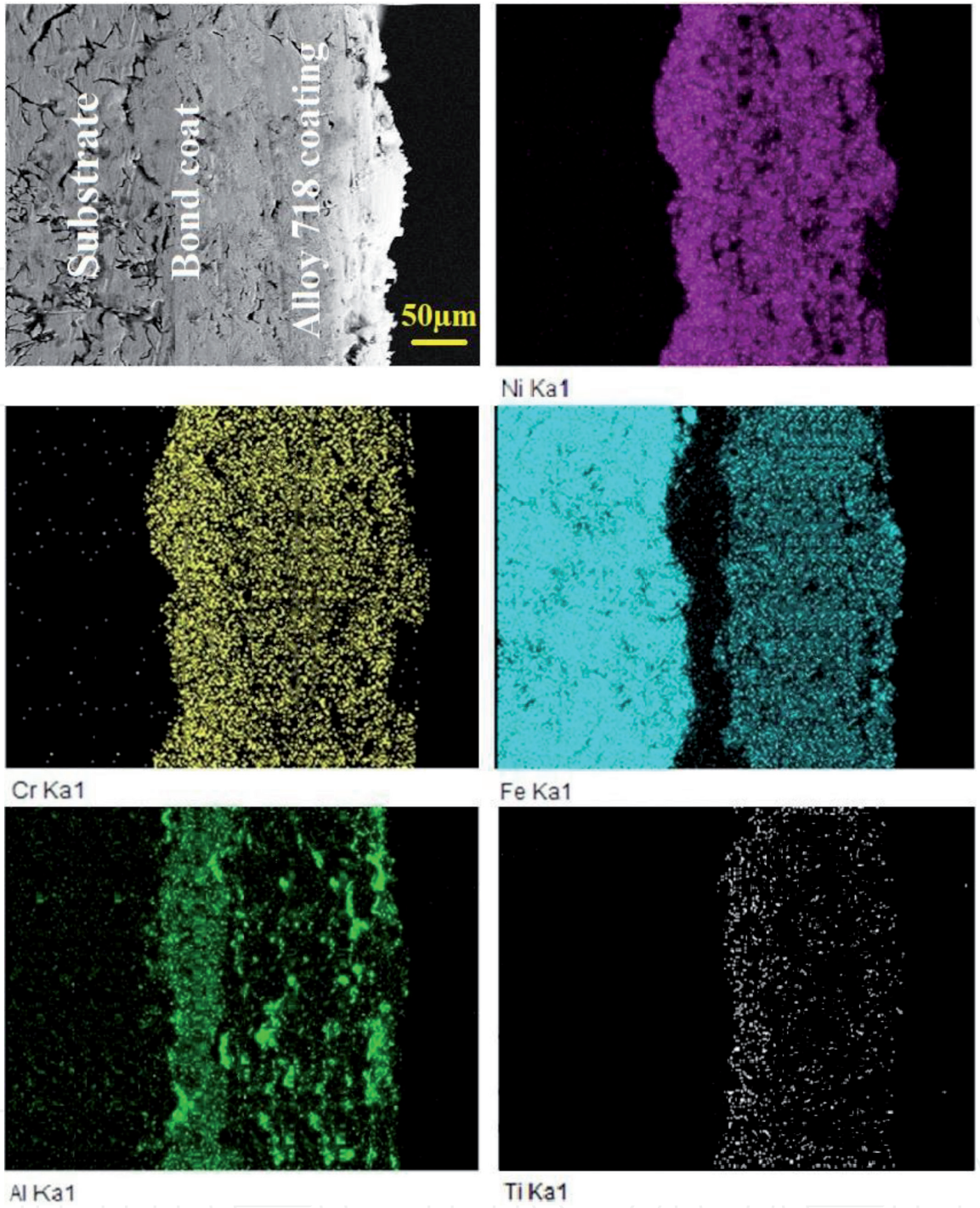


Figure 5.
SEM micrograph and X-ray maps of Alloy-718/NiCrAlY bi-layer coating [30].

Specimens	$K_p (10^{-3} \text{ mg}^2 \text{ cm}^{-4} \text{ s}^{-1})$
Bare GCI	84.05
IN718 coated cast iron	0.02

Table 3.
Parabolic rate constants for bare and Alloy-718 coated GCI.

The weight gain and parabolic rate constant values of substrate and Alloy-718 coatings after the oxidation test are presented in **Table 3**. The high weight gained by the GCI during oxidation test was attributed due to the formation of iron oxides. On the other hand, the bi-layer Alloy-718/NiCrAlY coating showed a decreased weight gain and parabolic rate constant.

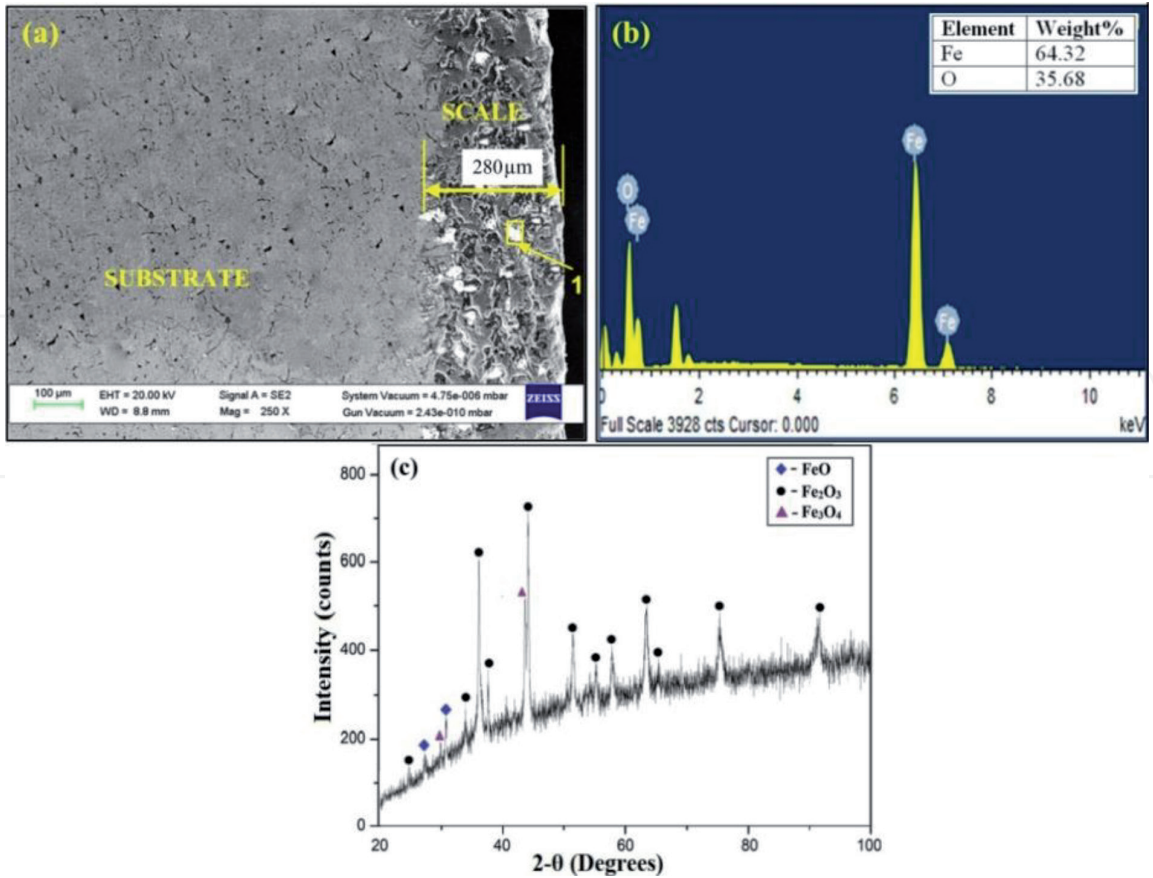


Figure 6.
(a) SEM micrograph, (b) EDS spectrum corresponding to location 1, and (c) XRD of GCI subjected to 50 cycles of air oxidation at 900°C.

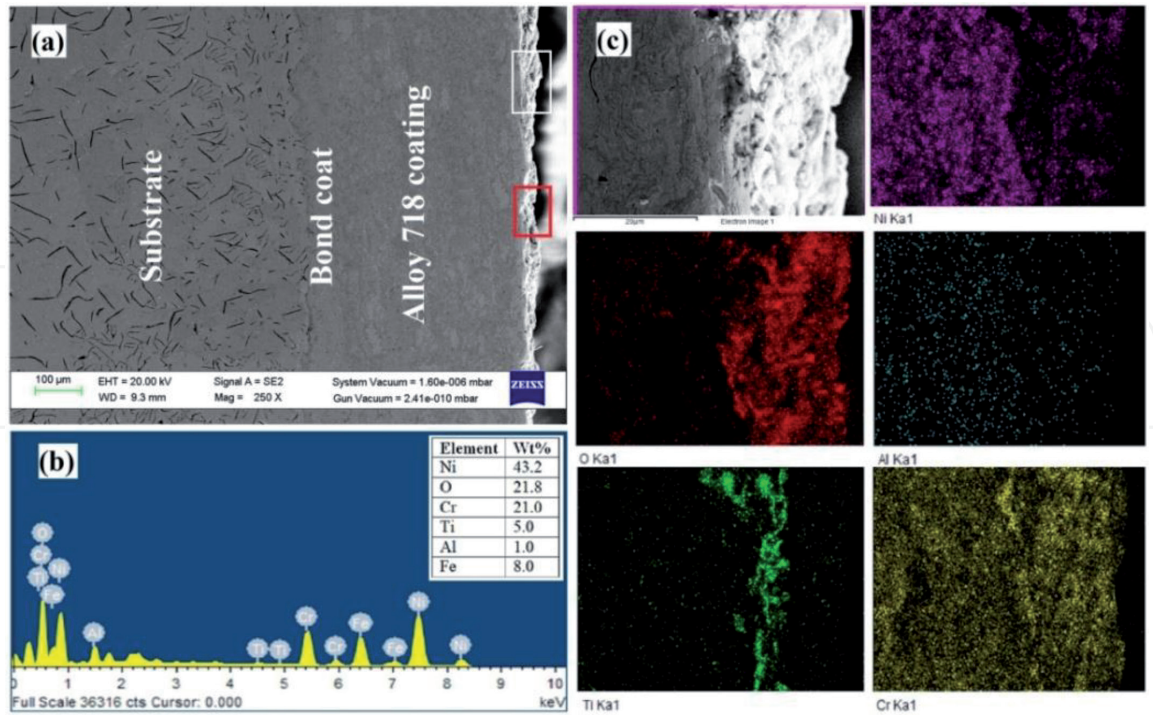


Figure 7.
(a) SEM micrograph along with EDS corresponds to white rectangle area as shown in (b), and (c) X-ray mapping of oxidized bi-layer Alloy-718/NiCrAlY coating at 900°C corresponds to red rectangle area [30].

The SEM micrograph along with EDS of the oxidized layer and X-ray mapping of oxidized bi-layer Alloy-718/NiCrAlY coating is shown in **Figure 7**. The SEM micrograph indicates the formation of oxide scale with at thickness of about 20 μm.

The decrease in thickness of the oxidized layer as compared to the thickness of scale formed in the GCI substrate indicated the high oxidation resistance of the deposited coating. The dense layer of scale is formed on the surface of the bilayer Alloy-718/NiCrAlY coating. The presence of the Cr and O can be observed in this layer which ensures the formation of Cr_2O_3 by selective oxidation. The Cr_2O_3 provides a thermal stability at high temperature and prevents the substrate from oxidation [21]. The TiO_2 was also formed at the interface of the scale and top coating. The oxide scale is rich in Cr and O confirmed by EDS mapping and further the presence of Cr_2O_3 is endorsed by XRD pattern of oxidized Alloy-718/NiCrAlY coating, as shown in **Figure 8**.

The XRD pattern (**Figure 8**) of oxidized bilayer coatings also shows the presence of protective phases such as NiCr_2O_4 and Al_2O_3 along with the Cr_2O_3 and TiO_2 . The presence of these protective phases is mainly responsible for the increased oxidation resistance of bilayer Alloy-718/NiCrAlY coating.

3.4 Erosion testing

There are two ways to analyse the wear erosion mechanism for material removal and these include the analysis of erosion mechanism on the basis of nature of material and secondly, on the basis of the impact angles of the erodent striking at the surface of the material. In first method, the ductile and brittle nature of the material is considered as material removal mechanism in the erosive wear. The repetitive plastic deformation causing the strain hardening and cutting are the two possible mechanisms which take place during the erosive wear, which leads to surface degradation. In case of ductile material, the micro-cutting followed by the separation of material from its surface is a responsible mechanism of material removal [22]. On contrary to that, brittle materials fail by fatigue process which is due to repetitive impacts of the erodent particles striking on the surface of the material. These particles transfers their energy to the surface in repetitive and continues manner so as to produce repetition and eventually results in fatigue failure. Therefore, the repetitions of impacts create cracks on the surface and debonding of the splats revealing the brittle nature of the coating. The impact angle is also another factor for defining the material removal mechanism and the erosion mechanism is directly affected by the impact angle of impingement of the erodent particles [23]. There is variability in the impact angles of the actual

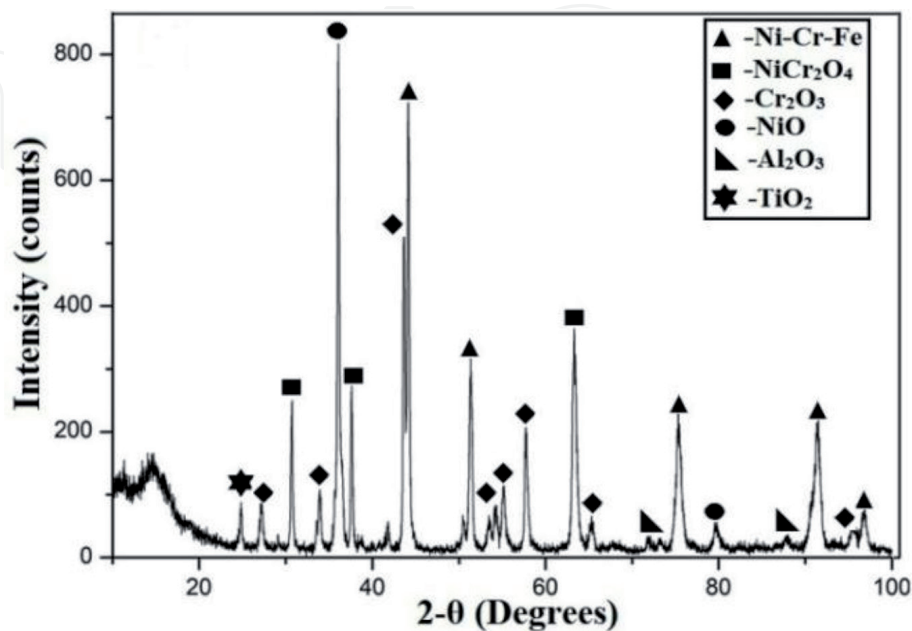


Figure 8.
XRD pattern of oxidized Alloy-718/NiCrAlY coating at 900°C [30].

applications like hydrodynamic turbine, boilers, heat exchangers, rocketry components and gas turbines at which the working fluid enters in the system and strikes the surface to cause material degradation at the working surface of the component. There are different angles from low to high and material removal mechanism varies according to variation in the impact angles. For low impact angles, cutting of material and chip formation leads to the material removal process. The ductile mechanism of erosion is analysed for higher erosion rates at lower angles of 20 and 30°. The angle is at or close to 90° for erosion failure includes lips formation mainly for the material which deforms at higher rate and the removal of material takes place in the form of platelets on repetitive striking of impacted erodent particles. However, the materials with minimum erosive wear resistance at 90° fall under the category of brittle mode [24].

The high-temperature erosion test was conducted at 800°C for two impact angles viz. 30 and 90°, respectively. The erosion rates of GCI and Alloy-718/NiCrAlY coating were measured, which showed the significant increase (around three times) in erosion resistance by using coating as compared to GCI. The erosion resistance of coating has improved in both impact angles condition. This increased erosion resistance is attributed to the solid solution hardening effect in Alloy-718 coating [25]. The presence of Cr₂O₃ and Al₂O₃ on the surface also contributed to the erosion resistance due to their hardness and thermal stability of these oxides [3, 26].

The SEM micrographs were used to analyse the eroded surface of the GCI and Alloy-718/NiCrAlY coating, as shown in **Figure 9**. The SEM micrographs of GCI showed the cracks on the surface when impacted at 90° and this can attributed to the repetitive impacts of erodent particles at normal angle. The repetitive impacts has led to the surface cracking and eventually the material is pulled out from the surface, as shown in eroded surface of GCI at 90°. Hence, brittle fracture mechanism is responsible for the surface degradation of GCI material during the erosion

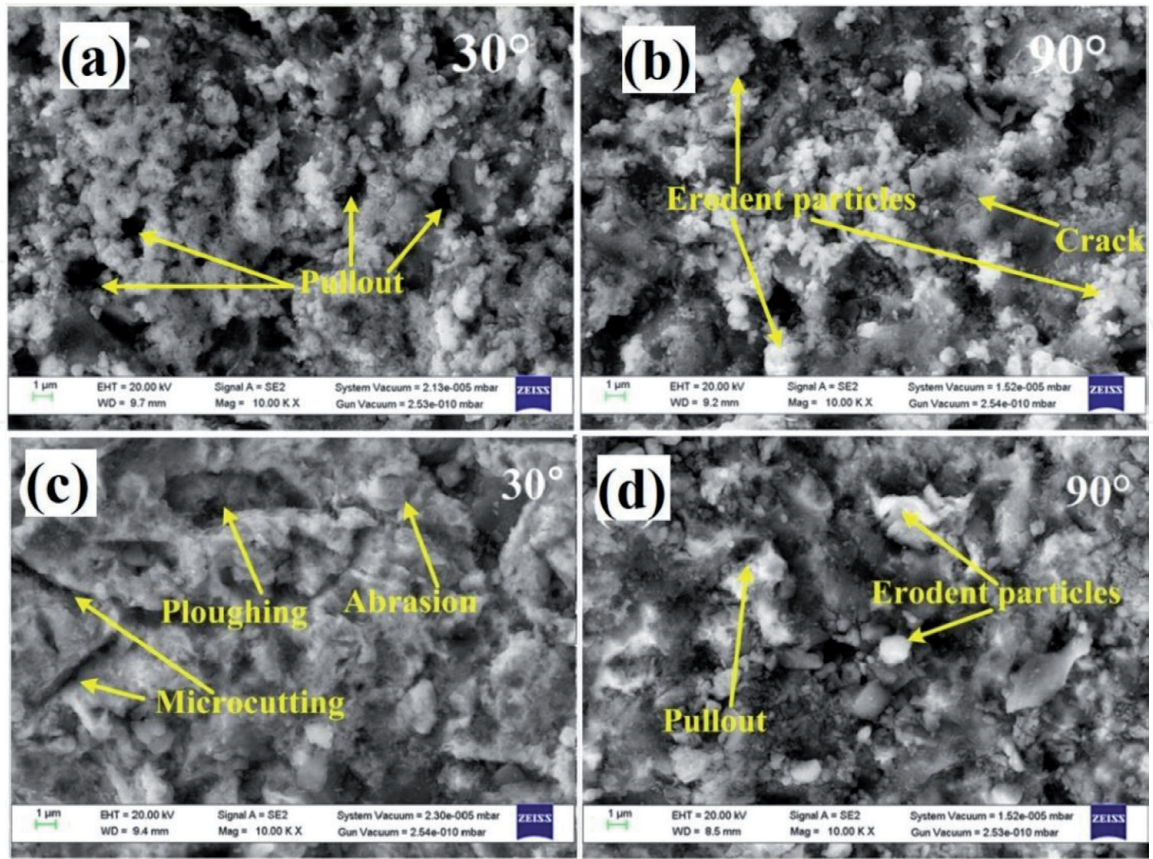


Figure 9. Surface topology of eroded GCI at (a) at 30° impact angle (b) at 90° impact angle. Surface topology of eroded Alloy-718/NiCrAlY coating (c) at 30° impact angle (d) and at 90° impact angle [30].

at 90° impact angle [27]. The GCI showed the micro-cutting marks along with some craters formed on the surface due to impact of erodent particles at 30°.

In case of Alloy-718/NiCrAlY coating, some cavities were formed and micro-cutting marks were seen in case of erosion conducted at 30° impact angle. The topology of coated samples showed the micro-cutting and abrasion marks along with lip formation in the periphery of craters at 30° impact angle. Hence, the abrasion and plastic deformation of coating surface is responsible for erosion of material in ductile mode at 30° impact angle. The Alloy-718/NiCrAlY coating also showed the presence of fine cracks, material pullout and some erodent particles embedded on the surface due to the repetitive impacts at 90° impact angle [28, 29].

4. Summary

The successful deposition of bi-layer Alloy718/NiCrAlY coating on the GCI substrate was carried out using HVOF process. The coatings were further characterized in terms of their microstructure, micro-hardness, high temperature erosion and oxidation behaviour. The following conclusions have been drawn from the present study:

As-sprayed Alloy718/NiCrAlY coating showed well bonded interfaces due to the well-defined inter-splat bonding of splats.

The Alloy718/NiCrAlY coating showed the increased micro-hardness as compared to GCI; the high hardness of the Alloy-718 coatings was due to solid solution hardening provided by various alloying elements and presence of various oxides such as Cr₂O₃ and Al₂O₃ in the coatings.

High temperature oxidation resistance of the bilayer Alloy718/NiCrAlY coating is attributed to the formation of protective oxides such as NiCr₂O₄, Cr₂O₃, Al₂O₃, and TiO₂ in the coating.

The micro-cutting, ploughing, brittle fracture and formation of craters were the different erosion wear mechanisms.

The brittle and ductile modes of erosion were observed for GCI and Alloy718/NiCrAlY coating, respectively.

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