Coating Process on Inconel Super alloy Substrates: A Review

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Abstract. This study reviews a variety of coating types, which include, alloys, nickel, palladium, nickel alloys and composite coatings, on the super-alloy substrates with the use of the Slurry Coating approach. Attempts have been performed for representing a general view of the conditions of plating and highlighting the significance of the layer concerning the efficiency of the high-temperature coatings that are applied on the super alloys that are utilized extensively on the components of the gas-turbine.

1. Introduction

Nickel-based super-alloys that are utilized extensively in the components of the gas-turbine engine, need the protection from the high-temperature oxidation throughout the operation. For the purpose of protecting the nickel-based super-alloys from the hot corrosion and oxidation, diffusion aluminide coatings are commonly utilized.1,2 Being utilized since the 1950s, the aluminide coatings that are based upon NiAl phase that are deposited by the approach of the chemical vapor deposition (CVD) don’t satisfy the oxidation resistance requirements at the high temperatures [1].

In the present day, coatings for the applications of high temperature fundamentally include the overlay coatings diffusion coatings, and the thermal barrier coatings (TBC). The diffusion coating protective character results from the protective natures of Cr2O3, Al2O3, and SiO2 scale formed on the chrominide, aluminide or silicides respectively at very high degrees of the temperature. The diffusion coatings were developed first and remain the most commonly utilized coating types. The Aluminide diffusion coatings have been proven as a cost-effective solution for the oxidation of high temperature, which are commonly utilized for the protection of the turbine blades and vanes. The aluminide coating characteristics are dependent upon process methods that have been utilized for depositing the coating, the composition of the substrate as well as the successive treatments. The rate and morphology of the coating deposition are dependent upon the time and temperature of process. The temperature of the processing affects the diffusion rate at which the elements of the alloy may be diffusing and surface compound metallurgy could be formed, which is why, it’s one of the critical parameters in manufacturing and processing the diffusion coating. The coating time at the temperature defines the formed coating thickness throughout the step of the diffusion. The coating thickness has also been defined as one of the key factors of the protection of coating properties [2,3].

Wang, et. al. [4] had been deposited a NiCoCrAlY(SiB) coating upon nickel base super-alloys DZ-125 and DSM-11 through the arc ion plating (AIP). The corrosion behaviors of bare alloys and protective coating in the molten 75wt. % Na2SO4 + 25wt. % K2SO4 at 900oC in the air has been tested for 90h.
Results have shown that the DZ-125 super-alloy had suffered from the disastrous corrosion after a 5h exposure and a thick porous oxide scale (500Am–600Am) that has been interspersed with the Ni3S2 and the alloy particles that have been formed on alloy. For Cr-rich DSM-11 alloy, there has been a mild corrosion attack, however, internal severe Al-rich oxidations had happened within alloy. With the NiCoCrAlYSiB coating and NiCoCrAlY coating, the systems’ hot corrosion resistance has been enhanced because of the formation of a-Al2O3 scale. The coatings’ hot corrosion resistance with additions of B and Si may be enhanced through the promotion of the growth of continuous and dense layer of a-Al2O3 in initial stage and enhancing the oxide scale adherence to coating in successive process of hot corrosion. The mechanism of the hot corrosion degradations of the NiCoCrAlYSiB coating and impact of substrate materials upon entire system’s behavior have been researched as well.

Figure 1. Surface morphology (a) and XRD patterns (b) of NiCoCrAlY coating that have been deposited by the AIP and after the heat treatments by the vacuum.

Xin Ren and Fuhui Wang [5] had been deposited a nano-crystalline Ni–30 Cr–8 Al–0.50Y coating upon an Ni-base super-alloy through the sputtering of the magnetron. The post-aluminizing has been carried out upon sputtered coating for the purpose of improving corresponding characteristics of high-temperature. The behavior of the isothermal oxidation at 1000oC–1100oC and the behavior of the hot-corrosion in presence of 75wt.% Na2SO4+25wt.% K2SO4/NaCl film at 900oC of sputtered coatings with and with no aluminizing were researched with the use of the TGA, XRD, SEM/EDS, and EPMA. Results have shown that sputtered NiCrAlY coatings had very good resistance to the oxidation at 1000oC as a result of the existence of a very high amount of the chromium and sufficient aluminum amount. Due to excessive Al consumption in coatings, it had lost protection at the temperature of 1100oC. The aluminized NiCrAlY coating mass gain has been a little bit higher compared to that of sputtered coating as a result of the formation of rapid growth θ-Al2O3 phase at a temperature of 1000oC. At 1100oC the latter’s oxidation resistance has been more sufficient compared to the oxidation resistance of former. Sputtered coating provided a limited level of the protection at transient hot-corrosion phase in film of molten salt and de-generated entirely with the time. Conversely,
aluminized NiCrAlY coating has shown considerably more sufficient resistance to the hot-corrosion in the presence of 75wt.% Na2SO4+K2SO4/NaCl film due to the formation of protective and continuous Al2O3 scale.

\[ \text{Figure 2. Curves of the oxidation kinetics of coatings and alloy, (a) 1000°C, (b) 1100°C.} \]

\[ \text{Fig3. Cross-section morphology of cast alloy following the oxidations, (a) 1000°C for 300h; (b) 1100°C for 300h.} \]

Deodeshmukh, et. al. [6] had been developed a new Pt+Hf-modified γ'-Ni3Al+γNi-based coating type, where the deposition includes the Pt electro-plating, which is succeeded by the combined hafnizing and aluminizing, with the use of a process of pack cementation. The testing of the cyclic oxidation for the Pt+Hf-modified γ'+γ as well as the Pt-modified β-NiAl coating at 1150°C (2102°F), in the air, had led to the formation of an adherent and continuous αAl2O3 scale; none-the-less, the latter had developed unwanted surface undulation following the thermal cycling. Type I (in other words, 900°C/1652°F) and Type II (in other words, 705°C/1300°F) hot corrosion behaviour of Pt+Hf-modified γ'+γ coating have been researched and comparisons have been made to the γ+β-CoCrAlY and Pt-modified β coatings. The two hot corrosion condition types have been simulated through the deposition of the Na2SO4 salt upon coated samples and after that, exposing samples to lab-based furnace rig. It has been discovered that Pt-modified β and Pt+Hf-modified γ'+γ coatings have shown a better Type II hot corrosion resistance in comparison with γ+β-CoCrAlY coating; whereas γ+β-CoCrAlY and Pt+Hf-modified γ'+γ coatings have shown enhanced Type I hot corrosion performance compared to Pt-modified β.
Figure 4. Cross-section SEM micro-graphs of (a) Pt-modified β (b) Pt+Hfmodified γ′ +γ coating after 1000h of the cyclic oxidations tests at a temperature of 1150°C.

Orlov [7] the impact of the liquid nickel sulfide eutectic in corrosive damages mechanisms has been specified through the researches of a high temperature oxidation products and super-alloys’ corrosion by using Xray spectroscopy, SEM and X-ray structural analysis. It has been discovered that the rate of the sulfide corrosion has been regulated through the procedure of diluting the nickel alloy of high temperature in liquid nickel sulfide eutectic, diffusions of the alloy’s alloying constituents in liquid phase, and their successive oxidations.

Figure 5. Damages to the hightemperature protective coatings at inlet edge’s exterior surface of singlecrystal rotor blade of ZhS26VI alloy for 1st turbine stage of GTE due to hightemperature oxidationand corrosion.

Sidhu, et. al. [8] supposed that there aren’t any alloys that have indefinite immunity to the hot corrosion attacks. The coatings may result in extending lives of the substrate materials that have been utilized at higher temperature levels in the corrosive environments through the formation of the layers of protective oxides, which have been reasonably sufficient for the long-term application. This study has been concerned with investigating efficiency of the high velocity oxy fuel (HVOF) sprayed NiCrBSi, Ni-20Cr, Cr3C2-NiCr, and Stellite-6 coating upon Ni-base super-alloy at a temperature of
900°C in environment of molten salt (Na2SO4-60%V2O5) under the conditions of the cyclic oxidation. Thermo-gravimetric approach has been utilized for establishing the corrosion kinetics. Optical microscope, XRD, electron probe microanalysis (EPMA), and SEM/electron dispersive analysis by x-ray (SEM/EDAX) approaches have been utilized for the characterization of as-sprayed coating and corrosion products. Bare super-alloy had suffered a degree of acceleration in the corrosion in specified environmental conditions, while the hot corrosion resistance of all of coated super-alloys has been discovered to be more sufficient. Amongst the researched coatings, Ni-20 Cr coated super-alloy imparted maximal resistance to the hot corrosion, while Stellite-6 coated indicated minimal resistance. Hot corrosion resistance of all the coating types can be a result of formations of the oxides as well as the spinels of nickel, cobalt or chromium.

Figure 6 SEM/EDAX analyses of as-sprayed coatings upon super-alloy Superni601. Original magnification: 400x. (a) Cr3C2-NiCr coatings. (b) NiCrBSi coatings. (c) Stellite6 coating. (d) Ni20Cr coatings.

Jintao Lu, et. al. [9] have discussed the aluminide coating, which has been intended for the applications in the ultra-supercritical boilers with a 650°C steam temperature, has been deposited on Super 304 H steel tube’s inner surface, combined with the heat treatment. The relevant thermophysical, mechanical and chemical characteristics of the aluminized Super 304H have been identified. Results have shown that aluminide coating has resulted in a significant improvement of the resistance of the Super 304H steam oxidation through the formation of a very thin scale of the Al2O3. Which has been better that the shot-peening treatments and using steel that have higher chromium content. Aluminide coating has shown quite limited effect upon thermophysical characteristics of matrix alloy as a result of its thin nature. Creep-rupture and tensile strength characteristics of Super 304H have all been within allowed range for the Super 304H steel based on ASME code. The FeAl inter-metallics’ high intrinsic strength has resulted in a slight improvement of yield strength of the aluminized Super 304H and micro-cracks resulted in relieving stress in coating, thereby resulting in a creep fracture on uncoated sample side. Their study has proposed that the slurry aluminide coating may be considered as
one of the viable options for the applications of the Super 304H steel in the super-critical boilers with greater temperatures of the steam.

Figure 7. Coating deposition device diagram.

Khorsand, et. al. [10] had studied the corrosion resistance of the Inconel625 Ni-based super-alloy in molten nitrate salt that consists of 40KNO3–60NaNO3 (wt. %) at 500o and 600oC. The open-circuit potential, electro-chemical impedance spectroscopy, potentiodynamic polarization, and gravimetric tests have been utilize for the evaluation of the alloy’s corrosion behavior and degradation mechanism. Chemical analysis and surface morphology of the products of the corrosion have been identified through the use of the SEM and energy-dispersive XRD. The curves of the weight-loss have shown that by increasing temperature, the mass gain and rate of oxidation have been increased; correlation between mass gain and time has been near the law of parabolic oxidation. Results of electro-chemical corrosion have confirmed the fact that throughout Inconel 625 alloy’s exposure to molten salts, the nickel dissolved due to the formed non-protective layer of NiO. Formation of non-protective layer of the oxide with a characteristic of the low barrier has been responsible for the observation of the alloy’s weak resistance to the corrosions at the high temperature degrees (500o and 600oC). The tests of the cyclic polarization have shown some positive hysteresis that confirms the growth and nucleation of the stable pits on Inconel625 surface at high anodic over-potentials. NaN2 plays the role of efficient inhibitor of pitting for that case. In such way, NaN2 with a 0.10molal concentration has been discovered to have optimal effect of inhibition on the pit nucleation at a temperature of 600oC.

Figure 8. A. Measured open-circuit potential values and B. potentiodynamic curves of polarization of the In 625 alloy in molten nitrate salts at 500o & 600oC.
Nickel-based super-alloy grade IN 738 is of a better creep resistance, none-the-less, the resistance to the oxidation represents the fundamental drawback of the alloy for the practical application at the high temperatures. Nickel aluminide compound coating with high resistance to the oxidation on IN-738 alloy surface may result in remarkable increases of oxidation resistance through forming the film of Al2O3 as protective layer. Aluminizing through the approaches of the powder liquid coating has been applied in the present study. Mixed Al and Al2O3 powder slurries have been pasted onto IN738 samples and have been heated at 1273K in the argon atmosphere for 3.60ks to 14.40ks (1h to 4h). Slurries may be categorized to 4 different Al ratios: Al2O3: 5:5, 3:7, 10:0, and 7:3. Micro-structure has been studied through the optical microscope and SEM. The phases in coated layer have been identified through the Electron Probe Micro Analysis (EPMA) and Glancing Incident-angle Xray Diffractometer (GIXD). Results have shown that coated layer has been produced through the dissolution of the Ni to liquid Al at aluminizing temperature that results in forming inter-metallic compound layer. Coated layer includes Ni2Al3 as one of the key phases with small AlCr2 and NiAl3 amount. AlCr2 mainly exists at a layer that is adjacent to top surface. For 8.1ks and 14.4ks (2.25h & 4h) holding time, AlCr2 formation at coated layer and matrix interface takes place as a result of the aluminum diffusion from the coated layer to the nickel matrix. The time effects show that more extended aluminizing time results in forming an even coated layer. Al : Al2O3 ratio of either 7 : 3 or 10 : 0 would result in the creation of an even coated layer that is over 200mm thick.

Figure 9 SEM images of In 625 alloy following the polarization reading at 500°C, a SE and b BSE and at 600°C, c) SE and d BSE

Patama Visuttipitkul, et. al. [11]
Figure 10. GIXD profile of IN 738 aluminized at 1273K for 3.60ks with a variety of the Al : Al2O3 ratios.

Figure 11 GIXD profile of specimen that has been aluminized at 1273K for 3.6ks using Al : Al2O3 ratio of 10 : 0 at a variety of depth values from surface.

Figure 12 Cross-section micro-structure of (a) coating layer (b) enlarged image of the layer of coating (c) enlarged image at the interface between the coating layer and the matrix.
Himanshu Saini, et. al. [12] had made a review and concluded that the hot corrosion is one of the serious problems in the boilers, power plants, internal combustion engines and gas turbines. There is a number of the alloys and super alloys that have the ability of the protection of components in a specific limit. Which is why, numerous coatings are commonly utilized for improving the components’ service life through the provision of a more sufficient resistance to the erosion-corrosion to substrates. This review has been mainly based upon hot corrosion behavior of the conventional as well as the Nanostructured Cr3C2-NiCr coatings that have been deposited with a number of the thermal spray approaches. The study has been carried out for summarizing a variety of the characteristics of the Chrome carbide nickel chrome coatings that have been deposited by a variety of approaches and the behavior of the hot corrosion of the conventional as well as the Nanostructured coatings in the molten salts environment. The spraying approach of High-velocity oxy-fuel (HVOF) has been considered as one of the efficient methods for the deposition of the dense coatings with lower porosity, however, a new approach was advanced and was known as the Detonation gun (DGun) coatings, which has been deposited by the Dgun is of a lower porosity and higher bond strength compared with HVOF. Plasma spray can be defined as a thermal spray approach that has higher bond strength, lower level of porosity, sufficient abrasive and wear resistance and high value of hardness, however, the equipment costs are quite high, which represents this approach’s limitation. The key objective of this review has been summarizing the efficiency of the Cr3C2-NiCr coating in a variety of the environments and studying the effects of the parameters of coating like its porosity and thickness on the behavior of the hot corrosion.

Masallb, et al., [13], made an attempt to develop Ni-based super alloy through the use of the pack cementation procedure. Results showed that the micro-structure of the coatings consisted of 2 layers: an outer layer and an inter-diffusion zone. The increase in the coating thickness with increasing coating process time up to 234 µm and 153 µm at 8 h for 2 coating types. The decrease of the value of the micro-hardness from the outer layer towards the substrate core. The high value of the micro-hardness is 823Kg/mm2 at 8 h for type I and 902Kg/mm2 at 8 h for the type II of coating. Results of the X-ray have shown different inter-metallic compound that has been formed after the coatings have been Ni2Al3, Ni2Si, Fe3Si, YNi10Si2, Ni3Si2, and Al1.1Ni0.9.

| Coating time (hr) | Outer layer(µm) | Inter-diffusion zone(µm) |
|------------------|-----------------|--------------------------|
| 2                | 110             | 22                       |
| 4                | 145             | 25                       |
| 6                | 198             | 27                       |
| 8                | 205             | 29                       |

Agüero, Blanco, et. al. [14] had been studied Al slurry coating for Cd substitute for the aircraft components, they show that commercial aluminum slurry coatings have been deposited and subjected to a series of tests. Glass beading after coating application is required in order to reduce porosity. Preliminary testing studies indicate that Al slurry coatings have potential to replace Cd in aircraft components. Further tests, including axial fatigue, embrittlement and re-embrittlement, and electrochemical analyses are ongoing or scheduled.
In order to reduce porosity the coating was subjected to glass beading. Figure 14 shows the resulting microstructure. The coating thickness has been decreased to approximately 70μm.

Min Qiao and Chungen Zhou [15], had investigated the corrosion behavior and the microstructure for a Co modified coating of NiAl that has been formed on super-alloy DZ-125 through the use of the pack cementation procedure. Kinetics of hot corrosion have shown that the coated specimen’s mass gain has been 3 magnitude orders lower than that of uncoated sample at 1,173K up to 100hrs. The formed product of the corrosion on the coating surface fundamentally included a protective film of a-Al2O3. The existence of the Co in a coating might result in the promotion of establishing a protective scale of the Al2O3 on coating and restraining internal diffusion of the sulphur in coating. The cross-sectional micro-structure of a coated specimen has been illustrated in Fig15.
The change in the weight of coated and uncoated specimens has been depicted in Fig16. Kinetics of corrosion have shown that uncoated specimens had insufficient resistance to the hot corrosion. In initial stage of up to 10hr corrosion, uncoated samples had a fast mass gain with no evident period of incubation that has been succeeded with a faster mass gain rate at corrosion time of about 100hr.

Zhang, et al. [16], had deposited an NiCrAlYSi coating with the arc ion plating upon a cobalt-base super-alloy K40S for improving its resistance to the hot corrosion at 1173K in the air. K40S suffered from the acceleration in the corrosion, in addition to the formation of non-protective scale with insufficient adherence in the case where its surface has been underneath Na2SO4 and Na2SO4 that contains 25wt.% deposits of NaCl salt. After K40S has been coated by the NiCrAlYSi, a protective a-Al2O3 scale has been formed on coating. Even though NiCrAlYSi coating transformed to NiCoCrAlYSi throughout the procedure of the corrosion, it remained possessing good resistance to the corrosion. Moreover, mechanisms of corrosion have been discussed according to the fundamental model of fluxing.

Figure 17 has shown XRD and cross sectional morphology results of arc ion plating NiCrAlYSi coating upon K40S following every one of the heat treatments in the pure Ar at 1,173K for 4hr. Coating cross-section has been an indication of the fact that it has been rather dense and evenly structured without any cracks, and it had a sufficient adhesion to substrate. The coating thickness has been approximately 50 lm.
Figure 17. Cross section morphology (a) X-RD results (b) of arc ion plating NiCrAlYSi coatings upon K40S after the heat treatment in the pure Ar at 1,173K for 4hr.

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