M. KUMAR*, H. SINGH*, N. SINGH**

STUDY OF Ni-20Cr COATINGS FOR HIGH TEMPERATURE APPLICATIONS – A REVIEW

BADANIA POWŁOK Ni-20Cr DO ZASTOSOWAŃ WYSOKOTEMPERATUROWYCH – PRZEGŁĄD LITERATURY

Hot corrosion is a serious problem in various high temperature applications. The thermal spray coatings provides possible solution to counter the problem of hot corrosion in high temperature environment and enhances the life of equipment. Ni-20Cr alloy compositions require long initiation time at which the hot corrosion process moves from the initiation stage to the propagation stage. In this review, the performance of Ni-Cr coatings by different investigators has been presented to understand the mechanism of hot corrosion under different environments.

Keywords: hot corrosion, nickel-chromium coatings, surface engineering, boilers

Wysokotemperaturowa korozja jest poważnym problemem w zastosowaniach wysokotemperaturowych. Możliwym rozwiązaniem problemu korozji w warunkach wysokiej temperatury poprzez zwiększenie żywotności urządzeń jest zastosowanie termicznych powłok natryskowych. Stopy o składzie Ni-20Cr wymagają długiego czasu inicjacji, po którym proces korozji wysokotemperaturowej z etapu inicjacji przechodzi do etapu propagacji. W tym przeglądzie zostały zaprezentowane badania zachowania powłok niklowo-chromowych wykonane przez różnych badaczy, żeby zrozumieć mechanizm korozji wysokotemperaturowej w warunkach różnych środowisk.

1. Introduction

Corrosion is a natural occurrence commonly defined as the deterioration of a substance (usually metal) or its properties as a consequence of its reaction with the environment. The direct cost of metallic corrosion in the U.S. is $276 billion—which is 3.1% of the Nation’s Gross Domestic Product (GDP) [1]. So it is important to understand the nature of all types of degradation of metals and alloys so that preventive measures can be economically devised against metal loss to ensure safety and reliability in the use of metallic components. Corrosion draws the attention of researchers in the field of environmental degradation of metals [2]. The power plants suffered major loss due to hot corrosion resulting in substantial economic loss [3]. The temperature of steam produced in boilers depends on corrosion and creep resistance of boiler components, both the factors effects the thermal efficiency of the boilers. Consequently, the thermal efficiency decreases and hence electricity production is reduced [3].

Hot corrosion is a serious problem in high temperature applications such as boilers, gas turbines, waste incinerations, diesel engines, coal gasification plants, chemical plants [4]. It is accelerated oxidation of materials, at elevated temperatures, induced by a thin film of fused salt deposit [5]. The fireside corrosion in a boiler occurs because of the reaction of the sulphur species in the gas phase with metal surfaces [6]. The sulphur present in the coal and fuel oils, especially in low-grade fuels, yield SO$_2$ on combustion which is partially oxidized to SO$_3$.

The power plants boiler tubes of coal fires boilers suffers big economic losses due to high rate of corrosion, erosion-corrosion of boiler tubes. To overcome this problem the use of thin anti-wear and anti-erosion-corrosion thermal spray coatings is the perfect choice there is an increasing trend in the deposition of Ni based metallic alloy coatings such as Ni-20 wt.% Cr for protection against hot corrosion using thermal spray processes. This is because of high resistance offered by chromium, nickel-chromium alloys against high-temperature oxidation and corrosion. This makes Ni-Cr coatings widely used as welded and thermally sprayed coatings in fossil fuel-fired boilers, waste incineration boilers, and electric furnaces [7].

Oxidation behavior of Ni-20Cr metallic coatings using high-velocity oxy-fuel (HVOF) and air plasma spray process on 9Cr-1Mo substrate steel was observed in the temperature range of 600-750°C [8]. The kinetics of hot corrosion like formation of protective oxide scale of Cr$_2$O$_3$, diffusion of nickel from the coatings to the substrate and the diffusion of iron from the substrate to the coatings for longer exposures to steam oxidation was investigated. The trend of formation of scale initiation with temperature and time duration was also observed at the interface between the coating and the substrate in case of

* SCHOOL OF MECHANICAL ENGINEERING, MATERIALS & ENERGY ENGINEERING, INDIAN INSTITUTE OF TECHNOLOGY ROPAR, NANGAL ROAD, RUPNAGAR, PUNJAB, INDIA, 140001
** DEPARTMENT OF CHEMISTRY, INDIAN INSTITUTE OF TECHNOLOGY ROPAR, NANGAL ROAD, RUPNAGAR, PUNJAB, INDIA, 140001
of coated samples was tested in actual refuse incineration conditions. In coal based power plants, fireside corrosion involves high temperature oxidation and corrosion by a high temperature melt. Acidity increases as the pressure of SO₃ decreases, and the requirement of SO₃ is about 2500 ppm. Once the pyrosulphates are formed, the complex mixture of the two melts at about 451°C has a high activity of oxide ions in the melt. Acidity increases as the SO₃ pressure is increased. Acidity is not controlled by the SO₃ in the gas alone when there are other gradients in the system. For example, V₂O₅ can react with Na₂SO₄ to increase the acidity of the melt via reaction given below:

\[ \text{Na}_2\text{SO}_4 + \text{V}_2\text{O}_5 \rightarrow 2\text{NaVO}_3 + \text{SO}_3 \]

3. Deposition of Ni-20Cr coatings using various thermal spray processes

Ni-20Cr, Ni-50Cr and 100% Cr powders were deposited on Ni base alloys and steels using detonation spraying, HVOF spraying and plasma spraying [20]. The hot corrosion behavior of coated samples was tested in actual refuse incineration conditions.
plant. It was inferred that Ni-50Cr sprayed coating by detonation gun remained in excellent condition even after 7 years and thickness lost was 1/37 of carbon steel.

Ni-20Cr powder using HVOF spraying was deposited on stainless steel samples. XRD revealed that the coating had Ni, Cr3C2, Cr-Ni, Fe0.9Ni0.05Cr, Ni-Cr-Fe and Fe-Cr phases in as-sprayed condition. The microhardness of the coatings was found dependent on porosity oxide, un-melted, semi-melted particles and inclusions, which contributed in decreasing the hardness values [21].

NiCrAlY, Ni-20Cr, Ni3Al and Stellite-6 metallic coatings were deposited on Fe-based super alloy (32Ni-21Cr-0.3Al-0.3Ti-1.5Mn-1.0Si-0.1C-Bal Fe) using plasma spraying [22]. Hot corrosion studies were conducted on uncoated as well as plasma spray coated superalloy specimens after exposure to molten salt at 900°C under cyclic conditions, which revealed the following trend of protection NiCrAlY coating>Ni-20Cr coating>Ni3Al coating>Stellite-6. The XRD, SEM/EDAX and electron probe microanalysis (EPMA) were used as characterization techniques to analyze the corrosion products. It was concluded that the formation of oxides and spinels of nickel, aluminium, chromium or cobalt contributed to development of hot corrosion resistance in the coatings.

NiCrAlY, Ni-20Cr and Ni3Al metallic coatings were deposited on Ni based super alloy (superni 718-Inconel 718) by Shrouded Plasma Spray Process. It was found that coatings have lamellar structure with distinctive boundaries along with the presence of some porosity. The microhardness trend of the coatings was found to Ni-20Cr >NiCrAlY >Ni3Al with the distance from the coating-substrate interface. The XRD characterization of the coatings revealed the formation of solid solutions [23].

Ni-Cr (Ni-45Cr-4Ti) and FeCrAl coatings were deposited on water-wall tubes of boilers using high-velocity electric-arc-sprayed (HVAS). Ni-Cr coatings showed the best anti-corrosion results. It was found that Ni-Cr coatings had slightly lower pores than FeCrAl coatings [24].

Ni-20Cr, Stellite-6 powders were deposited on ASTM-SA210-grade A1, ASTM-SA213-T-11 and ASTM-SA213-T-22 using shrouded plasma spray process. It was found that considerable reduction in the micro-hardness and porosity after laser re-melting of the coatings occurred which contributed to significant dilution of coating due to inter diffusion of atoms [25].

NiCrBSi, Cr3C2-NiCr, Ni-20Cr, and Stellite-6 coatings were done on Fe-based super alloy using HVOF thermal spray process. The salt tests were conducted at 900°C under cyclic conditions to study the hot corrosion behavior of the coatings in an aggressive environment of Na2SO4-60%V2O5. The kinetics of corrosion was studied from the thermo gravimetric technique. The following trend of protection of super alloy was obtained Ni-20Cr >Cr3C2-2NiCr >NiCrBSi >Stellite-6. It was found that the formation of oxides and spinels of nickel, chromium, or cobalt contributed to the development of hot corrosion resistance in the coatings [26].

Ceramic (Al2O3), metallic (Ni-20 wt% Cr), and cermets (WC-12 wt% Co) powders were deposited using detonation spray technique. The effect of particle size and its distribution on the coating properties were studied. The increasing trend of surface roughness and porosity with increasing powder particle size was observed. The fine and narrow size range WC-Co coating exhibited superior wear resistance. The coarse and narrow size distribution Al2O3 coating exhibited better performance under abrasion and sliding wear modes however under erosion wear mode the as-received Al2O3 coating exhibited better performance. In the case of metallic (Ni-Cr) coatings, the coatings deposited using coarser powder exhibited marginally lower-wear rate under abrasion and sliding wear modes. However, under erosion wear mode, the coating deposited using finer particle size exhibited considerably lower wear rate [27].

The high-velocity air-fuel (HVAF) and HVOF coatings were heat treated for up to 30 days at 900°C to generate a range of coating microstructures up to a steady state. Erosion was performed under the same conditions. Heat treatment increased the ductility of the NiCr phase, enabling ductile erosion deformation to occur. Intersplat sintering reduced the significance of splat based erosion mechanisms and forced mass loss to become dictated by the phase microstructure. Such developments improved the quantified erosion resistance of both coating systems relative to the as-sprayed conditions. The coating microhardness was shown to be a poor indicator of erosion response across the range of coating microstructures investigated [28].

Bala 2009 et al. [29] studied the high-temperature oxidation behavior of cold-sprayed Ni-20Cr and Ni-50Cr coatings on SAE 213-T22 boiler steel at 900°C in air under cyclic heating and cooling conditions for 50 cycles. The kinetics of oxidation of coated and bare boiler steel was established with the help of weight change measurements and it was found that all the coated and bare steels obeyed parabolic rate law of oxidation. The uncoated steel suffered corrosion in the form of intense spalling and peeling of its oxide scale, which was perhaps due to the formation of un-protective Fe2O3 oxide scale. The trend of protection of coatings against hot corrosion is Ni-50Cr >Ni-20Cr.

Deposition of Ni-20Cr coating on molybdenum substrate by laser cladding was studied. The coating was found free of cracks and pores, and strongly bonded to the substrate. The oxidation behavior of the coating indicates that the laser clad Ni-20Cr coating can effectively prevent oxidation of molybdenum at 600°C in air. The oxide scale formed on the coating surface by oxidation in air is composed of NiO, Cr2O3 and NiMoO4 [30].

Ni-20Cr coatings on boiler steel ASTM A213, 347H using HVOF technique were studied in actual boiler environment at 700°C and 900°C under cyclic conditions to ascertain their erosion-corrosion (E-C) behavior. The kinetics of the hot corrosion was studied using mass change and thickness loss data. It was observed that overall mass loss was reduced by 31% and thickness loss by 44% after the application of the coating. During air oxidation exposures, the coating was found to be intact with only marginal spallation of its oxide scales, which is an indicator of good adhesion between the coating and substrate steel. The air oxidation mass change data revealed that the coating enhanced the oxidation resistance of the steel by 85% [31].

NiCrAlY + CeO2 alloy coatings on three different super alloys using detonation gun spraying were studied [32].
Average porosity on three substrates was less than 0.58% and surface roughness of the coatings was in the range of 6.17-6.94 \( \mu m \). Average bond strength and microhardness of the coatings were found to be 58 MPa and 697-920 HV, respectively.

Ni-20Cr coatings on ASTM-SAE 213-T22 using HVOF spray and detonation-gun (D-gun) spray techniques were deposited and studied. The salt (\( Na_2SO_4\)-60%\( V_2O_5 \)) studies were carried out at 900\( ^\circ \)C for bare and coated samples to access the kinetics of hot corrosion. Specimens were also exposed to the superheater zone of a thermal power plant boiler at an average temperature of 700\( ^\circ \)C under cyclic conditions to ascertain their erosion-corrosion (E-C) behavior. The micro structural study revealed HVOF-sprayed coating intact during exposure to both given environments; whereas the D-gun coating showed spallation of its oxide scale during exposure to the molten salt environments. HVOF-sprayed Ni-20Cr coating offered better hot corrosion resistance in comparison to D-gun sprayed coatings in boiler applications [33].

Bala et al. [34] investigated the deposition of Ni-20Cr powder on T-22 boiler steel using HVOF and cold spray processes. To evaluate the performance of the coatings in actual conditions the bare as well as the coated steels were subjected to cyclic exposures in the super heater zone of a coal fired boiler for 15 cycles. It was found that the HVOF sprayed coating performed better than its cold sprayed counterpart in actual boiler environment.

Table 1 gives the summary of the investigations by various researchers on Ni-Cr coatings for high temperature applications using thermal spray processes.

### Table 1

Summary of the investigations on Ni-Cr coatings using thermal spray process

<table>
<thead>
<tr>
<th>Author name</th>
<th>Coating material</th>
<th>Substrate</th>
<th>Thermal Spray Process</th>
<th>Testing Environment</th>
<th>Important Findings</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>2</td>
<td>3</td>
<td>4</td>
<td>5</td>
<td>6</td>
</tr>
<tr>
<td>Yamada et al. [20]</td>
<td>Ni-20Cr, Ni-50Cr and 100%Cr</td>
<td>Ni base alloys and steels</td>
<td>Detonation spraying, HVOF spraying and Plasma spraying</td>
<td>Actual refuse incineration plant</td>
<td>Ni-50Cr sprayed coating by detonation gun found to have longer sustainability, 1/37 of thickness is lost after 7 years.</td>
</tr>
<tr>
<td>Ak et al. [21]</td>
<td>Ni-20Cr</td>
<td>Stainless steel</td>
<td>HVOF spraying</td>
<td></td>
<td>The formation porosity oxide, un-melted and semi-melted particles and inclusions decreased the hardness values.</td>
</tr>
<tr>
<td>H Singh et al. [22]</td>
<td>NiCrAlY, Ni-20Cr, Ni(_3)Al and Stellite-6</td>
<td>Fe-based Super alloy (32Ni-21Cr-0.3Al-0.3Ti-1.5Mn-1.0Si-0.1C-Bal Fe)</td>
<td>Plasma sprayed</td>
<td>Na(_2)SO(_4)-60%( V_2O_5 ) under laboratory conditions</td>
<td>Resistance to hot corrosion follows the trend NiCrAlY coating &gt;Ni-20Cr coating &gt;Ni(_3)Al coating &gt;Stellite-6 coating</td>
</tr>
<tr>
<td>S B Mishra et al. [23]</td>
<td>NiCrAlY, Ni-20Cr and Ni(_3)Al metallic coatings</td>
<td>Superni 718-Inconel 718</td>
<td>Shrouded plasma sprayed</td>
<td>Power plant boilers</td>
<td>Ni-20Cr &gt;NiCrAlY &gt;Ni(_3)Al</td>
</tr>
<tr>
<td>Lianyong et al. [24]</td>
<td>Ni-Cr (Ni-45Cr-4Ti) and FeCrAl coatings</td>
<td></td>
<td>HVAS sprayed</td>
<td>Power plant boilers</td>
<td>Ni-Cr coatings had slightly lower pores than FeCrAl coatings</td>
</tr>
<tr>
<td>T S Sidhu et al. [26]</td>
<td>NiCrBSi, Cr(_2)C(_2)-NiCr, Ni-20Cr, and Stellite-6</td>
<td>Fe-based super alloy</td>
<td>HVOF</td>
<td>Na(_2)SO(_4)-60%( V_2O_5 ) at 900( ^\circ )C</td>
<td>Ni-20Cr &gt;Cr(_2)C(_2)-NiCr &gt;NiCrBSi &gt;Stellite-6</td>
</tr>
<tr>
<td>P Suresh Babu et al. [27]</td>
<td>Ceramic (Al(_2)O(_3)), metallic (Ni-20 wt% Cr), and cermet (WC-12 wt% Co)</td>
<td>Mild steel specimens</td>
<td>Detonation spraying</td>
<td>Power plant boilers</td>
<td>The marginal influence of powder particle size on coating properties and performance.</td>
</tr>
</tbody>
</table>
4. Summary and Conclusion

Hot corrosion poses a serious problem in high temperature applications like power plant boilers, gas turbines, waste incinerations, aircraft, and in other energy conversion and chemical process systems. Severity of this problem rises further when fuel of low grades is used in the power plant boilers because of the non-availability of high grade fuel and cost involved in procurement. The only solution to enhance the life of boiler tubes is to use the thermal spray coatings to counter the problem of hot corrosion. It has been concluded after reviewing the literature that Ni-20Cr coatings can be successfully deposited on different boiler steels using various thermal spray processes. Further it is observed nickel alloyed with chromium (Ni-20Cr) oxidizes to Cr₂O₃, and other protective spinel phases such as NiCr₂O₄, which makes it suitable for use up to 950°C to counter hot corrosion in different environments.

Acknowledgements

Authors thankfully acknowledge the research Grant from Department of Science & Technology, New Delhi for carrying out the R & D work on “Surface Engineering to Control Erosion-Corrosion of Steam Generating Plants by Nano-particle Coatings”.

REFERENCES

Received: 20 September 2012.