Universal Journal of Mechanical Engineering 7(5): 247-254, 2019 http://www.hrpub.org
DOI: 10.13189/ujme.2019.070501

Effect of TiO_2 on Plasma Sprayed Al_2O_3 Based Composite Coatings at 900°C in Molten Salt Environment

Gurdeep Singh[1], Khushdeep Goyal[1,*], Rakesh Goyal[2]

[1]Department of Mechanical Engineering, Punjabi University, India
[2]Chitkara University Institute of Engineering and Technology, Chitkara University, Punjab, India

Received June 28, 2019; Revised August 10, 2019; Accepted August 22, 2019

Copyright©2019 by authors, all rights reserved. Authors agree that this article remains permanently open access under the terms of the Creative Commons Attribution License 4.0 International License

Abstract The present work investigates the effect of hot corrosion on ASTM-SA213-T-22 Steel with different coatings of Al_2O_3-TiO_2 at 900°C in molten salt environment (40wt%Na_2SO_4+60wt%V_2O_5). The experimentation consisted of 50 cycles of heating coated and uncoated specimens for 1 hour at 900°C in muffle furnace and cooling for 20 minutes at ambient temperature. The corroded specimens were analyzed using visual examination, weight change measurement, X-ray diffraction technique and Scanning electron microscopy/Energy-disperse X-ray analysis. The results showed that the uncoated substrate had been more affected with corrosion and gained more mass due to formation of iron oxide (Fe_2O_3) as compared to coated substrate because of better adhesion of Al_2O_3 coating with base metal SA213-T22 due to presence of TiO_2. The presence of TiO_2 increased the strength and durability of Al_2O_3 coating to withstand with high temperatures.

Keywords Hot Corrosion, Boiler Steel, Composites, Thermal Spray, High Temperature

1. Introduction

The corrosion occurs at elevated temperatures due to exposure of steels and alloys in atmosphere, which causes formation of oxide layer, when the environmental oxygen reacts with ferrous metal, and is called hot corrosion [1-4]. The failure occurs in boiler tubes is due to the corrosion of base metal at elevated temperature in the molten salt environment which results in damage to the physical and chemical properties of the substrate [5-7]. This can be prevented by applying thin layer of coating on the surface of base metal by the various coating processes like plasma spray coating, high velocity oxy fuel (HVOF) and powder coating etc. As analyzed by literature survey, the alumina based coatings provide higher corrosion and wear resistance to steel alloys up to 900°C [8, 9]. The rate of corrosion is very fast in metals and alloys; this results in the formation of porous non-protective oxide layer on the surface of material [7, 10-12]. The corrosion rate is highly dependent on the presence of corrosive elements, such as Na_2SO_4 and V_2O_5 in atmosphere with elevated temperature.

$$Na_2SO_4 + V_2O_5 \rightarrow (Na_2O) .V_2O_5 + SO_3$$

In this reaction, the sodium sulphate and vanadium pentoxide results in formation of Sodium oxide and sulfur tri-oxide which is known as corrosive agent [4, 13]. To coat the substrate, various coating process are used such as Plasma spray coating, High Velocity Oxy Fuel (HVOF) coating and D-gun spray coating, to decrease the rate of corrosion. Goya et al [14] all stated that all coatings are porous, due to the porosity at microscopic level in coating, allows oxygen to react with the base metal through pores and cause formation of oxide layer under the coating region in molten salt environment. Due to oxide layer formation between the coating and base metal boundaries spallation takes place which results in erosion in between the coating and the surface of substrate [15-20]. Hot corrosion is of two types; high temperature hot corrosion (HTHC) – above750°C and low temperature hot corrosion (LTHC) – 550-750°C. The high rate corrosion occurs with the reaction of sulfur, sodium, potassium, lead and vanadium, usually having low melting points. The rate of corrosion is highly dependent on partial pressure of oxygen present in atmosphere [21-24]. Various coatings are used to prevent the rate of corrosion, as per analysis, the Al_2O_3 is more protective in prevention of oxidation rate, formation of cracks and spallation caused by oxides of molybdenum after repetitive cycle at elevated temperature in molten salt environment. It is observed from literature study that various types of coatings are used on the substrates with different deposition method. To reduce this effect of coating, bi-layered coating of Al_2O_3-TiO_2 is used [8-10]. It is analyzed that the use of Al_2O_3-TiO_2 coating shows better results. The bilayer of TiO_2 with Al_2O_3 sprayed with plasma coating helps to reduce pores so that the electrolyte and other corrosive elements could not react with the base metal of substrate. It also increases the properties of substrate to withstand with high temperature, wear and corrosion. TiO_2 is used along with fabrication of Al_2O_3 coating, TiO_2 helps in adhesion of coating with base metal [3]. It has been observed with analysis of various research papers that Al_2O_3 enhance the properties of material by both physically or chemically to prevent the rate of corrosion at 900°C [17, 18]. The aim of this experiment is to slow down the rate of corrosion at elevated temperatures in molten salt environment by using the reinforced coating of Al_2O_3 and TiO_2 with different weight percentage composition, exposed to molten salt environment at 900°C. This experiment defines the behavior of hot corrosion on SA213-T22 boiler steels coated with Al_2O_3-TiO_2, with different weight-percent combinations, in silicon tube furnace at 900°C for 50 cycles consisting of one hour heating followed by 20 minutes of cooling in molten salt (40wt%Na_2SO_4+60wt%V_2O_5). XRD, SEM/EDS is undertaken to obtain various results.

2. Experimental Procedure

2.1. Basic Composition of SA213-T22 Material

ASTM-SA213-T-22 Steel is used as base material, obtained from Guru Gobind Singh Thermal Power station, Rupnagar, Punjab. Detailed specifications are given in Table 1.

2.2. Preparation of Coatings

The coating was sprayed on steel specimens at Metallizing Equipment Corporation Private Ltd. Jodhpur, Rajasthan. The size of each specimen was 20 mm x 15 mm x 5 mm. Table 2 shows the composition of coatings obtained, and Table 3 shows the parameters employed in plasma spraying process.

Table 1. Composition of SA213-T22 steel boiler tubes

Type of steel	ASME code	Composition	C	Mn	Si	S	P	Cr	Mo	K	Fe
T-22	SA213 T-22	Actual	0.15	0.60	0.48	0.01	0.02	2.6	1.13	0.02	Bal.

Table 2. Composition of SA213-T22 material

Coating No.	Coating composition	Al_2O_3	TiO_2	Particle size
1	Al_2O_3	100	0	40±10μm
2	Al_2O_3 - 3 wt.% TiO_2	97	3	40±10μm
3	Al_2O_3 - 13 wt.% TiO_2	87	13	40±10μm
4	Al_2O_3 - 20 wt.% TiO_2.	80	20	40±10μm

Table 3. Parameters used for plasma spray coating

Parameters	Value
Plasma Current – A	600
Plasma Voltage - V	50
Carrier gas flow (g-min)	50
H_2 Gas flow pressure- psi	62
Argon Gas flow pressure - psi	50
Spray distance – mm	50
Spray passes	5

2.3. Formulation of Coating

Experimental studies are undertaken in molten salt environment (40wt%Na_2SO_4+60wt% V_2O_5).

The behaviour of TiO_2-Al_2O_3 coatings on T-22 boiler steel at 900°C in the molten salt environment (40wt% Na_2SO_4-60wt% V_2O_5) was examined. The experiment was consisted of 50 cycles. Each cycle consisted of 1 hour heating in a silicon tube muffle furnace followed by 20 minutes of cooling in room temperature. Before conducting the experiment, the physical dimensions of each specimen was measured with the help of vernier caliper. The de-burring operation was performed on each surface to remove any foreign particles at the microscopic level. The plasma spray coating was performed before the application of molten salt on the surface of specimens. The (40wt% Na_2SO_4-60wt% V_2O_5) salt was mixed with distilled water and was applied on each face of the specimen after washing all specimens with acetone. The layer of molten salt was applied gently on each face of specimen with the help of camel hair brush. To make the proper adhesion of molten salt on each surface of the specimen, all specimens were heated up to 250°C in the oven. The molten salt environment becomes more aggressive to react with metals with the increase in temperature and the rate of reaction also increases. The increase in temperature causes the faster rate of corrosion on the surface of the metal. The samples were kept in alumina boats in a muffle furnace at 900°C with 50 repetitive cycles of 1-hour heating followed by 20 minutes of cooling at room temperature. The aggressiveness of corrosion was examined with a number of repetitions in cycles. After the experimentation, all the specimens were analyzed by the X-ray diffraction, SEM and EDS. The experiment was performed in metallurgy laboratory of Chandigarh Engineering College, Landran (Mohali), Punjab.

3. Results

3.1. Visual Examination

Before conducting the experiment, all samples were in physically perfect condition. The experiment was conducted in a molten salt environment (40wt% Na_2SO_4-60wt% V_2O_5) kept in silicon tube muffle furnace at 900°C. During the experiment, after the 4^{th} cycle, the uncoated T-22 specimen started to change in brownish colour and after 15^{th} cycles formation of cracks were started to develop near corners of the specimen as shown in (Fig. 1(a)). In the case of Al_2O_3 coated T-22 specimen, cracks were started to appear on the coated surface after 30^{th} cycle. Minor spallation of scale was seen on the surface after 50^{th} cycle as shown in (Fig. 1(b)). But in the case of other specimens coated with TiO_2-Al_2O_3 composite coatings, no change in colour was observed and till 30^{th} cycle, there was no development of cracks found even after 50 cycles as shown in images (Fig. 1(c-e)).

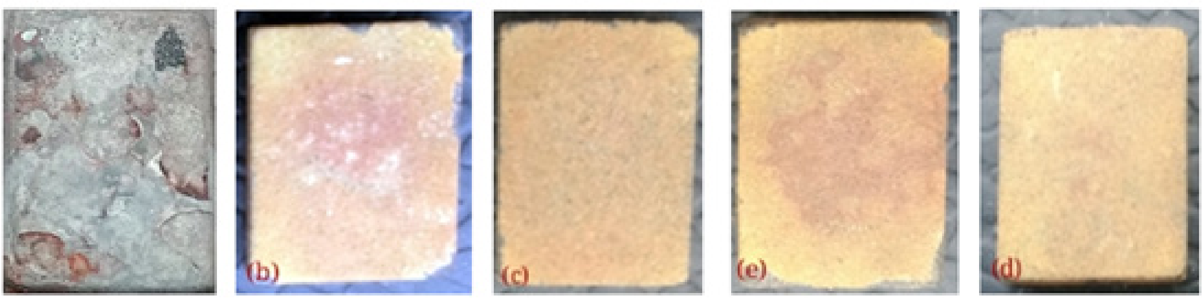


Figure 1. Visual inspected images of (a) uncoated, (b) Al_2O_3 (c) Al_2O_3 - 3 wt.% TiO_2, (d) Al_2O_3 - 13 wt.% TiO_2, and (e) Al_2O_3 - 20 wt.% TiO_2 coated substrates

3.2. Mass Change Observations

The thermo gravimetric study was done to find the mass change characteristics showed by coated and uncoated T-22 boiler steel. The change in mass of uncoated and coated T-22 steels were analyzed after exposing each specimen in the molten salt environment (40wt%Na_2SO_4-60wt%V_2O_5) for 50 cycles at 900°C. The change in mass showed the kinetics of corrosion. The high mass gain is identified as a high rate of corrosion. The graph shows that uncoated specimen showed the higher mass gain, the specimen coated with Al_2O_3 shows a little less mass gain than uncoated specimen.

The mass change is observed after each complete cycle shown in. (Fig 2)

3.3. XRD Analysis

X-Ray diffraction tests are conducted to figure out the nature of metallurgy of material affected due to high temperature and corrosive environment.

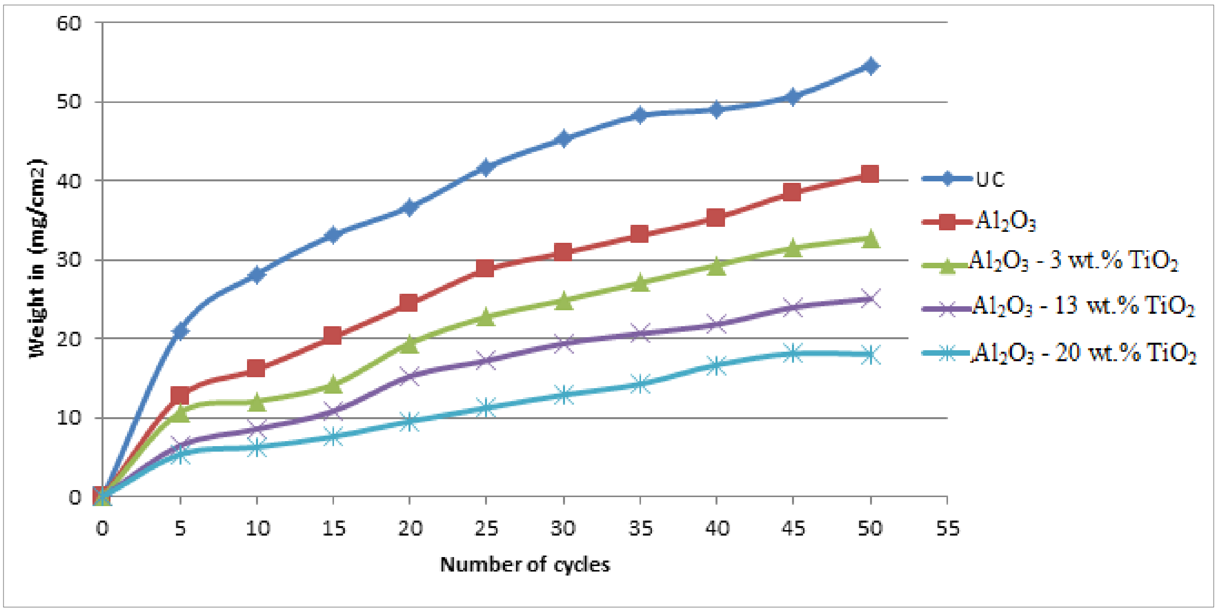


Figure 2. Weight gain in (mg/cm^2) for uncoated and coated substrates

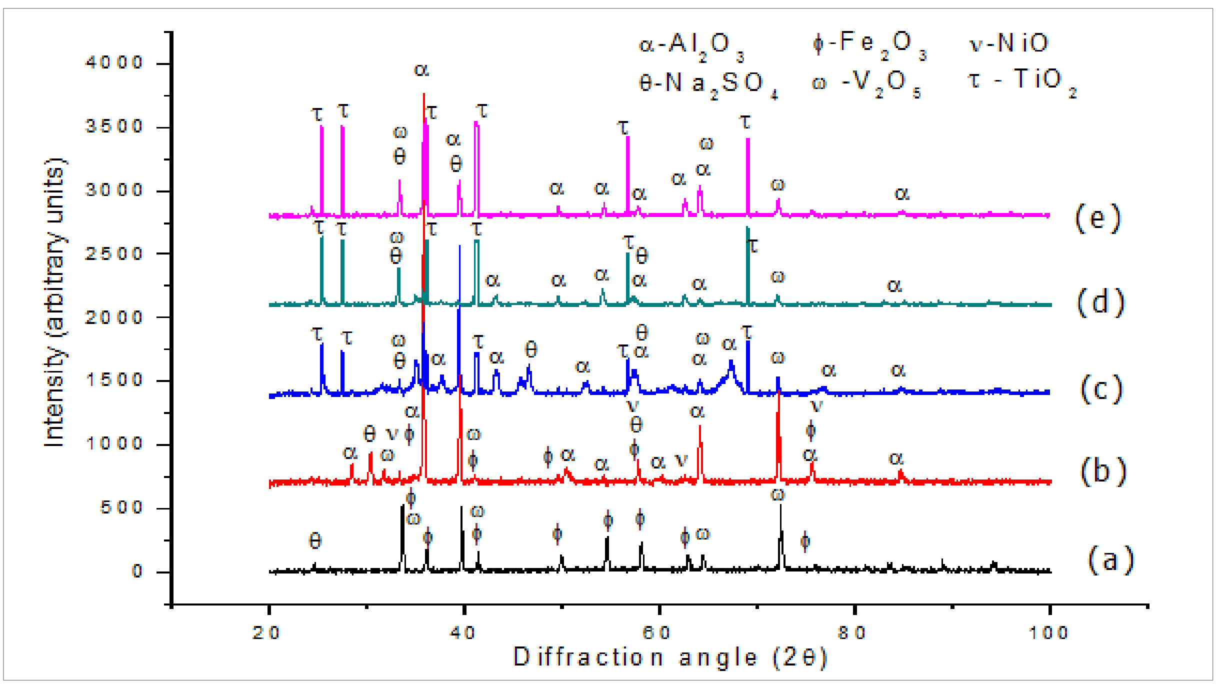


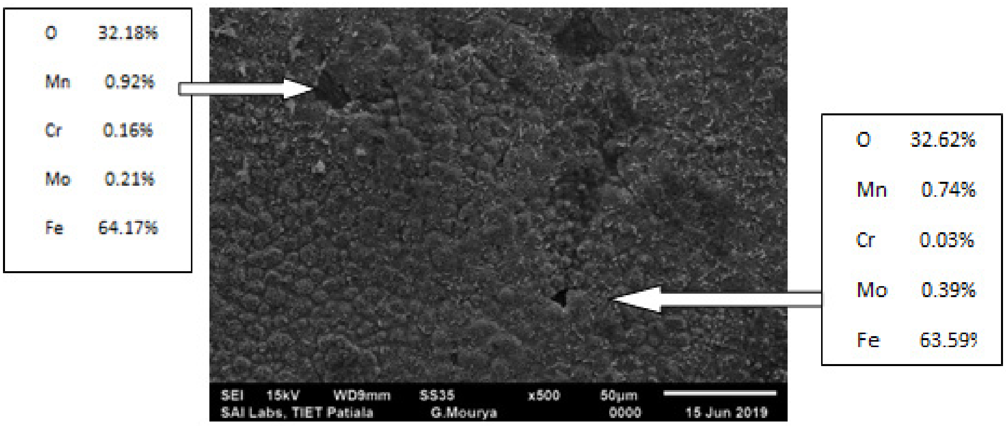
Figure 3. Xrd spectrum of (a) uncoated, (b) Al_2O_3 (c) Al_2O_3 - 3 wt.% TiO_2, (d) Al_2O_3 - 13 wt.% TiO_2, and (e) Al_2O_3 - 20 wt.% TiO_2 coated substrates

The XRD graph shows that, the uncoated T-22 Specimen shows the formation of Fe_2O_3 at oxide scales. The specimen with the coating of pure Al_2O_3 shows the Al_2O_3 peaks along with Na_2SO_4 and Fe_2O_3. The specimen containing Al_2O_3-$3TiO_2$ shows formation of TiO_2 and Al_2O_3, Na_2SO_4, and no presence of Fe_2O_3 is found on the surface of specimen. The specimen coated with Al_2O_3-$13TiO_2$ shows the peak of TiO_2, Na_2SO_4 and no presence of Fe_2O_3 is found on the surface and specimen coated with Al_2O_3-$20TiO_2$ shows presence of TiO_2, Na_2SO_4 and Al_2O_3 along with of V_2O_5 and no peak of Fe_2O_3 is found on coated surface of specimen.

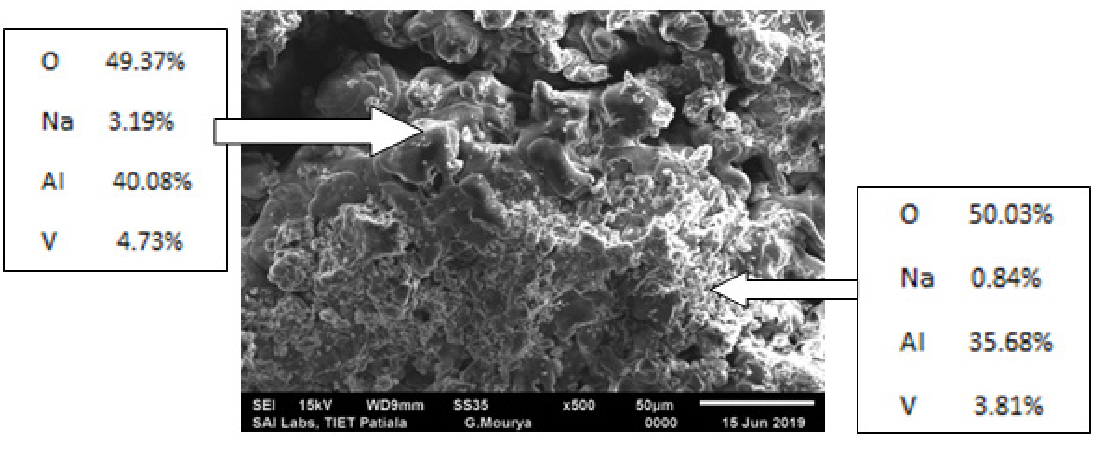
The XRD graph clearly shows that the uncoated specimen mostly affected by the formation of Fe_2O_3 and nearly no formation of Fe_2O_3 found on the surface of the specimen coated with TiO_2- Al_2O_3.

3.4. SEM/EDS Analysis

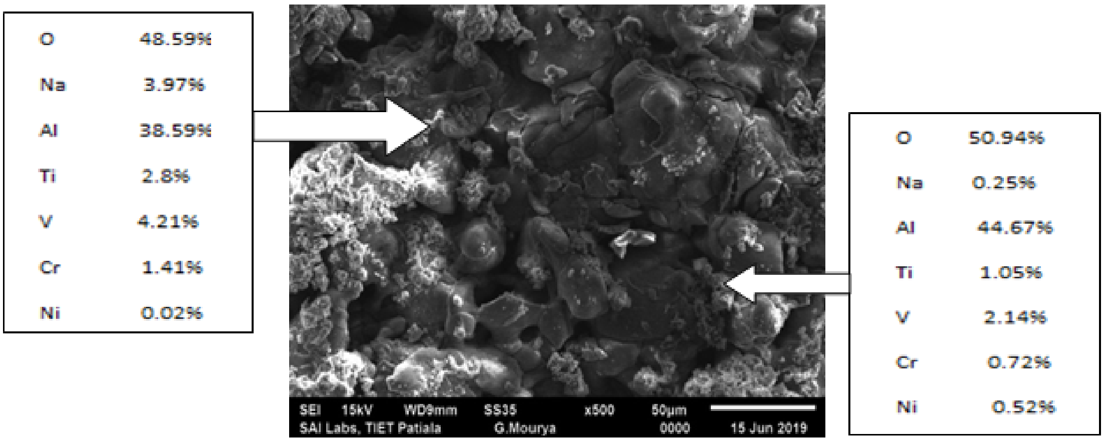
Figure 4 shows the SEM micrograph of T-22 uncoated steel substrate after exposing it in molten salt environment for 50 cycles of heating inside a silicon tube muffle furnace. The EDS analysis on spectrum indicates the presence of Fe and Cr which might be the reason of formation of Fe_2O_3 and Cr_2O_3. SEM Micrograph shows the spallation in the coating layer. The Fe and O found along with small percentage of Cr. For Al_2O_3 coated T-22 specimen the EDS analysis spectrum shows the presence of Al, O, Cr and Fe. The presence of Al and Fe might cause the formation of Al_2O_3, Cr_2O_3 and Fe_2O_3. In case of coated specimens 3Wt% TiO_2-Al_2O_3, 13Wt% TiO_2-Al_2O_3 and 20Wt% TiO_2-Al_2O_3 respectively shows the morphology of surface coating of specimens and the EDS analysis shows the major formation of Al_2O_3 and TiO_2. The TiO_2 was well spotted with bright particle in darker region of Al_2O_3. The presence of Na and V might be due to the presence of molten salt elements in the oxide scale.



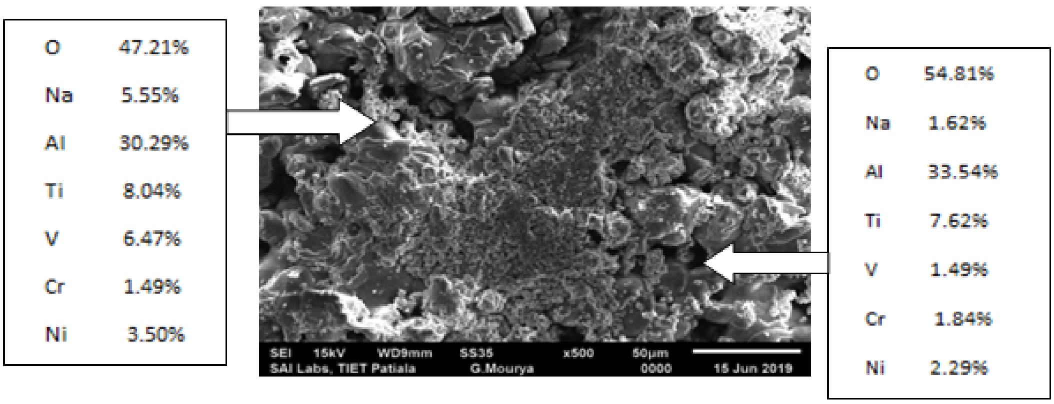
Uncoated T-22



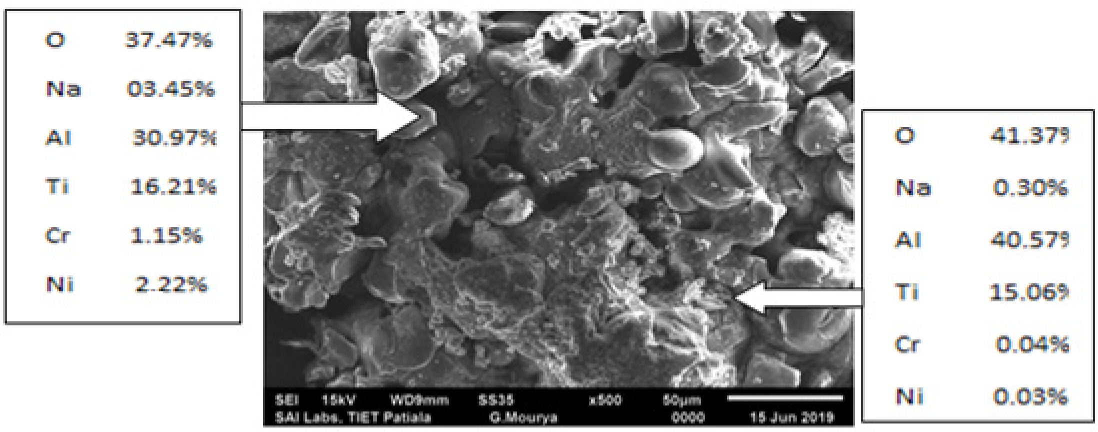
T-22 Al_2O_3



T-22 Al_2O_3+3TiO2



T-22 Al_2O_3+13TiO_2



T-22 Al_2O_3+20TiO_2

Figure 4. SEM/EDAX results of different corroded specimens

The SEM/EDS result showed that the coated specimens formed preventive elements such as Al, Cr and Ti on their surface, but in uncoated specimen the formation of Fe and Mo was found. The presence of Fe and Mo on the surface of uncoated specimen, might have caused the formation of iron oxide layer on the surface, and led to maximum mass gain. The corrosion occurred at very early stages of the cycles in molten salt the environment at 900°C. On the other hand, the coated specimen showed absence of Fe and molybdenum.

4. Discussion

In this experiment, the hot corrosion behaviour of different reinforced coatings of TiO_2-Al_2O_3 on T-22 boiler steel was examined. Each specimen was kept is molten salt environment (40wt% Na_2SO_4-60wt% V_2O_5). After the successful completion of experiment the result were obtained.

The macrograph showed the rate of corrosion was high in uncoated T-22 specimen as compared to coated specimens. The change in colour to brownish was found in early stage in uncoated T-22 specimen. After 25th cycle the development of cracks were observed on the corner of uncoated specimen in visual observations. The thermo gravimetric study revealed that the uncoated specimen gained maximum mass in the experiment as compared to other specimens. The change in mass showed the kinetics of corrosion in the molten salt environment at elevated temperature. The thermo gravimetric graph (Fig. 2) showed that mass gained by the uncoated specimen was 54.61mg/cm^2. The XRD (Fig. 3) graph indicated the formation of Fe_2O_3 in oxide scale on the surface of uncoated specimen. The SEM/EDS analysis indicated the presence of Fe, Mo and V on the surface of uncoated T-22 specimen (Fig. 4). These elements are highly responsible for the hot corrosion [2]. The molybdenum oxide is found in molten state at 550°C. At 900°C the liquid molybdenum oxide dissolves the protective layer of chromium, which causes corrosion on the surface of substrate. The protective oxide layer of chromium helps to resist the corrosive species to react with the surface of metal [9]. The iron oxide reacts with the base metal with time, due to this the mass of substrate increases with respect to time. The thick iron oxide layer forms on the surface of specimens which is responsible for corrosion [13].

Al_2O_3 coated specimen showed 25.41% less mass gain as compared to uncoated specimen. Small pores were noticed on the surface of the specimen after exposing it to the molten salt environment for 50 cycles. XRD graph indicated the presence of Al_2O_3, Cr_2O_3 and Fe_2O_3 oxide layers. The less mass gained by the specimen is might be due to the formation of Al_2O_3 and Cr_2O_3 which resist the corrosive element to attack the base metal. However, porosities in Al_2O_3 coatings might have abled the corrosive elements to attack the base metal. SEM/EDS analysis also showed presence of Al, Cr and Fe which validated the XRD results. The spallation produced on the specimen was might be due to the formation of Fe_2O_3 oxide layer.

After exposing the 3wt%TiO_2-Al_2O_3, 13wt% TiO_2-Al_2O_3 and 20wt%Ti-Al_2O_3 coated substrates in molten salt environment (40wt% Na_2SO_4-60wt% V_2O_5) at 900°C. These coatings were found safe to hot corrosion. There was no colour change found till 30th cycle and no cracks were visualized in the coated specimen after completion of all 50 cycles in molten salt environment at elevated temperature. The specimen coated with 20TiO_2-Al_2O_3 coating showed least mass gain. The mass gained by specimen coated with Al_2O_3-3TiO_2 was 40.06% less than that of uncoated T-22 steel. The specimen coated with Al_2O_3-13TiO_2 gained less mass by 54.18% and the specimen coated with Al_2O_3-20TiO_2 showed least mass gain of 18.01 mg/cm^2 and gained 67.02% less mass as compared to uncoated specimen showed by thermo gravimetric method shown in. The XRD graph showed the presence of Al_2O_3, Cr_2O_3 and TiO_2 oxides on the surface of coated specimens. These elements are corrosion resistant in nature. In SEM/EDS analysis, the coated specimen showed the presence of Ti, Al in major phase. There were no traces of Fe and Mo found on the surface of coated specimens even after 50 numbers of cycles in molten salt environment at elevated temperatures.

This reinforcement of TiO_2 in Al_2O_3 might have helped to reduce the porosity in the coating layer. It is observed that the composition of Al_2O_3-20TiO_2 showed better results. It has been analyzed that by increase in percentage of TiO_2 with Al_2O_3 coating, the hot corrosion resistance increases. The TiO_2 along with Al_2O_3 showed better adhesion properties with base metal and found preventive from hot corrosion. The rate of hot corrosion resistance showed the following trend:

Uncoated T-22 steel < Al_2O_3 < 3Wt% TiO_2-Al_2O_3 < 13Wt% TiO_2-Al_2O_3 < 20Wt%Ti-Al_2O

5. Conclusions

- Different coatings of 100Al_2O_3, 3TiO_2-Al_2O_3, 13TiO_2-Al_2O_3 and 20TiO_2-Al_2O_3 were deposited on SA213-T22 with plasma spray coating technique.
- The uncoated specimen showed maximum mass change where as the specimen coated with TiO_2-Al_2O_3 showed least mass change.
- The XRD and SEM/EDS analysis indicates that uncoated steel specimen contained Fe_2O_3 and Cr_2O_3 as major phase in oxide scale.
- In the case of coatings of 3TiO_2-Al_2O_3, 13TiO_2-Al_2O_3 and 20TiO_2-Al_2O_3, the major phases of TiO_2 and Al_2O_3 were found in XRD, SEM/EDS analysis.
- The better resistance was provided by Al_2O_3-20TiO_2 among all other coatings when reacted to molten salt environment (40wt% Na_2SO_4-60wt% V_2O_5) for 50 cycles at 900°C.
- The 100Al_2O_3, 3TiO_2-Al_2O_3, 13TiO_2-Al_2O_3 and 20TiO_2-Al_2O_3 coated specimen indicated the mass gain reduction by 25.41%, 40.06%, 54.18% and 67.02 % respectively, as compared to uncoated specimen.
- The TiO_2-Al_2O_3 specimens showed no formation of cracks after experimentation done in molten salt environment (40wt% Na_2SO_4-60wt% V_2O_5) at 900°C.

- The sequence of the coating provided better resistance of corrosion in decreasing order is Al_2O_3-20TiO_2 coating > Al_2O_3-13TiO_2 coating > Al_2O_3-3TiO_2 coating > 100 Al_2O_3 coating > uncoated T-22

REFERENCES

[1] P. Sassatelli, G. Bolelli, M. L. Gualtieri, E. Heinonen, M. Honkanen, L. Lusvarghi, "Properties of HVOF-sprayed Stellite-6 coatings," *Surface and Coatings Technology,* Vol. 338, pp. 45-62, 2018.

[2] V. P. S. Sidhu, K. Goyal, and R. Goyal, "Hot corrosion behaviour of HVOF-sprayed 93 (WC-Cr_3C_2)-7Ni and 83WC-17Co coatings on boiler tube steel in coal fired boiler," *Australian Journal of Mechanical Engineering,* Vol. 17, No. 2, pp. 127-132, 2017.

[3] G. Singh, K. Goyal, and R. Bhatia, "Hot corrosion studies of plasma-sprayed chromium oxide coatings on boiler tube steel at 850 C in simulated boiler environment," *Iranian Journal of Science and Technology, Transactions of Mechanical Engineering,* Vol. 42, No. 2, pp. 149-159, 2018.

[4] R. Taylor, J. Brandon, and P. Morrell, "Microstructure, composition and property relationships of plasma-sprayed thermal barrier coatings," *Surface and Coatings technology,* Vol. 50, No. 2, pp. 141-149, 1992.

[5] S. Sampath, "Thermal sprayed ceramic coatings: fundamental issues and application considerations," *International Journal of Materials and Product Technology,* Vol. 35, No. 3-4, pp. 425-448, 2009.

[6] B. A. Shaw and R. G. Kelly, "What is corrosion?," *Interface-Electrochemical Society,* Vol. 15, No. 1, pp. 24-27, 2006.

[7] V. P. S. Sidhu, K. Goyal, and R. Goyal, "An investigation of corrosion resistance of HVOF coated ASME SA213 T91 boiler steel in an actual boiler environment," *Anti-Corrosion Methods and Materials,* Vol. 64, No. 5, pp. 499-507, 2017.

[8] B. S. Sidhu and S. Prakash, "Performance of NiCrAlY, Ni–Cr, Stellite-6 and Ni 3 Al coatings in Na_2SO_4–60% V_2 O_5 environment at 900° C under cyclic conditions," *Surface and Coatings Technology,* Vol. 201, No. 3, pp. 1643-1654, 2006.

[9] Ş. Yılmaz, M. Ipek, G. F. Celebi, and C. Bindal, "The effect of bond coat on mechanical properties of plasma-sprayed Al_2O_3 and Al_2O_3–13wt% TiO 2 coatings on AISI 316L stainless steel," *Vacuum,* Vol. 77, No. 3, pp. 315-321, 2005.

[10] V. P. S. Sidhu, K. Goyal, and R. Goyal, "Comparative study of corrosion behaviour of HVOF-coated boiler steel in actual boiler environment of a thermal power plant," *Journal of the Australian Ceramic Society,* Vol. 53, No. 2, pp. 925-932, 2017.

[11] L. Singh, N. K. Grover, V. Chawla, and J. Grewal, "Microstructure and Characterization of Detonation Gun Sprayed Al_2O_3 Coating," *Asian Journal of Engineering and Applied Technology,* Vol. 5, No. 1, pp. 15-17, 2016.

[12] K. Goyal, H. Singh, and R. Bhatia, "Current status of thermal spray coatings for high temperature corrosion resistance of boiler steel," *Journal of Material & Metallurgical Engineering,* Vol. 6, No. 1, pp. 29-35, 2016.

[13] V. P. Singh Sidhu, K. Goyal, and R. Goyal, "Corrosion behaviour of HVOF sprayed coatings on ASME SA213 T22 boiler steel in an actual boiler environment," in *Advanced Engineering Forum*, 2017, pp. 1-9.

[14] K. Goyal, H. Singh, and R. Bhatia, "Effect of Carbon Nanotubes on Properties of Ceramics Based Composite Coatings," in *Advanced Engineering Forum*, 2018, pp. 53-66.

[15] E. Irissou, J.-G. Legoux, B. Arsenault, and C. Moreau, "Investigation of Al-Al_2O_3 cold spray coating formation and properties," *Journal of Thermal Spray Technology,* Vol. 16, No. 5-6, pp. 661-668, 2007.

[16] R. Jones, "Hot Corrosion in Gas Turbines," DTIC Document1983.

[17] A. Keyvani and M. Bahamirian, "Oxidation resistance of Al_2O_3-nanostructured/CSZ composite compared to conventional CSZ and YSZ thermal barrier coatings," *Materials Research Express,* Vol. 3, No. 10, p. 105047, 2016.

[18] A. Keyvani and M. Bahamirian, "Hot corrosion and mechanical properties of nanostructured Al_2O_3/CSZ composite TBCs," *Surface Engineering,* Vol. 33, No. 6, pp. 433-443, 2017.

[19] K. Goyal, H. Singh, and R. Bhatia, "Mechanical and microstructural properties of carbon nanotubes reinforced chromium oxide coated boiler steel," *World Journal of Engineering,* Vol. 15, No. 4, pp. 429-439, 2018.

[20] K. Goyal, H. Singh, and R. Bhatia, "Experimental investigations of carbon nanotubes reinforcement on properties of ceramic-based composite coating," *Journal of the Australian Ceramic Society,* Vol. 55, No. 2, pp. 315-322, 2018.

[21] M. A. Khan, S. Sundarrajan, and S. Natarajan, "Hot corrosion behaviour of Super 304H for marine applications at elevated temperatures," *Anti-Corrosion Methods and Materials,* Vol. 64, No. 5, pp. 508-514, 2017.

[22] S. K. Kim and Y. S. Hwang, "Hot Corrosion of T22, T23, and T91 Steels in Na_2SO_4 Salts at 800 and 900°C," *Journal of the Korean Institute of Metals and Materials,* Vol. 51, No. 12, pp. 849-856, 2013.

[23] K. Goyal, H. Singh, and R. Bhatia, "Behaviour of carbon nanotubes-Cr_2O_3 thermal barrier coatings in actual boiler," *Surface Engineering,* pp. 1-11, 2019, published online, https://doi.org/10.1080/02670844.2019.1584966

[24] K. Goyal, H. Singh, and R. Bhatia, "Hot-corrosion behavior of Cr_2O_3-CNT-coated ASTM-SA213-T22 steel in a molten salt environment at 700° C," *International Journal of Minerals, Metallurgy, and Materials,* Vol. 26, No. 3, pp. 337-344, 2019.