Effect of TiO₂ on Plasma Sprayed Al₂O₃ Based Composite Coatings at 900°C in Molten Salt Environment

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Abstract

The present work investigates the effect of hot corrosion on ASTM-SA213-T-22 Steel with different coatings of Al₂O₃-TiO₂ at 900°C in molten salt environment (40wt%Na₂SO₄+60wt%V₂O₅). 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 (Fe₂O₃) as compared to coated substrate because of better adhesion of Al₂O₃ coating with base metal SA213-T22 due to presence of TiO₂. The presence of TiO₂ increased the strength and durability of Al₂O₃ 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 Na₂SO₄ and V₂O₅ in atmosphere with elevated temperature.

Na₂SO₄ + V₂O₅ → (Na₂O) . V₂O₅ + SO₃

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 Al₂O₃ 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 Al₂O₃-TiO₂ is used [8-10]. It is analyzed that the use of Al₂O₃-TiO₂ coating shows better results. The bilayer of TiO₂ with Al₂O₃ 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. TiO₂ is used along with fabrication of Al₂O₃ coating, TiO₂ helps in adhesion of coating with base metal [3]. It has been observed with analysis of various research papers that Al₂O₃ 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 Al₂O₃ and TiO₂ 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 Al₂O₃-TiO₂, 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%Na₂SO₄+60wt%V₂O₅). 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.

| Coating No. | Coating composition | Al₂O₃ | TiO₂ | Particle size |
|-------------|---------------------|-------|------|---------------|
| 1           | Al₂O₃               | 100   | 0    | 40±10μm       |
| 2           | Al₂O₃ - 3 wt.% TiO₂ | 97    | 3    | 40±10μm       |
| 3           | Al₂O₃ - 13 wt.% TiO₂| 87    | 13   | 40±10μm       |
| 4           | Al₂O₃ - 20 wt.% TiO₂| 80    | 20   | 40±10μm       |

| Parameters                  | Value |
|-----------------------------|-------|
| Plasma Current – A          | 600   |
| Plasma Voltage - V          | 50    |
| 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% Na2SO4+60wt% V2O5).

The behaviour of TiO2-Al2O3 coatings on T-22 boiler steel at 900°C in the molten salt environment (40wt% Na2SO4-60wt% V2O5) 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% Na2SO4-60wt% V2O5) 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% Na2SO4-60wt% V2O5) kept in silicon tube muffle furnace at 900°C. During the experiment, after the 4th cycle, the uncoated T-22 specimen started to change in brownish colour and after 15th cycles formation of cracks were started to develop near corners of the specimen as shown in (Fig. 1(a)). In the case of Al2O3 coated T-22 specimen, cracks were started to appear on the coated surface after 30th cycle. Minor spallation of scale was seen on the surface after 50th cycle as shown in (Fig. 1(b)). But in the case of other specimens coated with TiO2-Al2O3 composite coatings, no change in colour was observed and till 30th cycle, there was no development of cracks found even after 50 cycles as shown in images (Fig. 1(c-e)).
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$_2$SO$_4$-60wt%V$_2$O$_5$) 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$_2$O$_3$ 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](image)

![Figure 2. XRD diagrams showing phases present in different samples](image)
The XRD graph shows that, the uncoated T-22 Specimen shows the formation of Fe$_2$O$_3$ at oxide scales. The specimen with the coating of pure Al$_2$O$_3$ shows the Al$_2$O$_3$ peaks along with Na$_2$SO$_4$ and Fe$_2$O$_3$. The specimen containing Al$_2$O$_3$-3TiO$_2$ shows formation of TiO$_2$ and Al$_2$O$_3$, Na$_2$SO$_4$ and no presence of Fe$_2$O$_3$ is found on the surface of specimen. The specimen coated with Al$_2$O$_3$-13TiO$_2$ shows the peak of TiO$_2$, Na$_2$SO$_4$ and no presence of Fe$_2$O$_3$ is found on the surface and specimen coated with Al$_2$O$_3$-20TiO$_2$ shows presence of TiO$_2$, Na$_2$SO$_4$ and Al$_2$O$_3$ along with of V$_2$O$_5$ and no peak of Fe$_2$O$_3$ is found on coated surface of specimen. 

The XRD graph clearly shows that the uncoated specimen mostly affected by the formation of Fe$_2$O$_3$ and nearly no formation of Fe$_2$O$_3$ found on the surface of the specimen coated with TiO$_2$- Al$_2$O$_3$.

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$_2$O$_3$ and Cr$_2$O$_3$. SEM Micrograph shows the spallation in the coating layer. The Fe and O found along with small percentage of Cr. For Al$_2$O$_3$ 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$_2$O$_3$, Cr$_2$O$_3$ and Fe$_2$O$_3$. In case of coated specimens 3Wt% TiO$_2$-Al$_2$O$_3$, 13Wt% TiO$_2$-Al$_2$O$_3$ and 20Wt% TiO$_2$-Al$_2$O$_3$ respectively shows the morphology of surface coating of specimens and the EDS analysis shows the major formation of Al$_2$O$_3$ and TiO$_2$. The TiO$_2$ was well spotted with bright particle in darker region of Al$_2$O$_3$. The presence of Na and V might be due to the presence of molten salt elements in the oxide scale.
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 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$_2$O$_3$ on T-22 boiler steel was examined. Each specimen was kept in molten salt environment (40wt% Na$_2$SO$_4$-60wt% V$_2$O$_5$). 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 25$^{th}$ 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$_2$O$_3$ 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$_2$O$_3$ 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$_2$O$_3$, Cr$_2$O$_3$ and Fe$_2$O$_3$ oxide layers. The less mass gained by the specimen is might be due to the formation of Al$_2$O$_3$ and Cr$_2$O$_3$ which resist the corrosive element to attack the base metal. However, porosities in Al$_2$O$_3$ 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$_2$O$_3$ oxide layer.

After exposing the 3wt%TiO$_2$-Al$_2$O$_3$, 13wt% TiO$_2$-Al$_2$O$_3$ and 20wt%Ti-Al$_2$O$_3$ coated substrates in molten salt environment (40wt% Na$_2$SO$_4$-60wt% V$_2$O$_5$) at 900°C. These coatings were found safe to hot corrosion. There was no colour change found till 30$^{th}$ 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$_2$O$_3$ coating showed least mass gain. The mass gained by specimen coated with Al$_2$O$_3$-3TiO$_2$ was 40.06% less than that of uncoated T-22 steel. The specimen coated with Al$_2$O$_3$-13TiO$_2$ gained less mass by 54.18% and the specimen coated with Al$_2$O$_3$-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$_2$O$_3$, Cr$_2$O$_3$ 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$_2$O$_3$ might have helped to reduce the porosity in the coating layer. It is observed that the composition of Al$_2$O$_3$-20TiO$_2$ showed better results. It has been analyzed that by increase in percentage of TiO$_2$ with Al$_2$O$_3$ coating, the hot corrosion resistance increases. The TiO$_2$ along with Al$_2$O$_3$ 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$_2$O$_3$ < 3Wt% TiO$_2$-Al$_2$O$_3$ < 13Wt% TiO$_2$-Al$_2$O$_3$ < 20Wt%Ti-Al$_2$O$_3$

5. Conclusions

- Different coatings of 100Al$_2$O$_3$, 3TiO$_2$-Al$_2$O$_3$, 13TiO$_2$-Al$_2$O$_3$ and 20TiO$_2$-Al$_2$O$_3$ 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$_2$O$_3$ showed least mass change.
- The XRD and SEM/EDS analysis indicates that uncoated steel specimen contained Fe$_2$O$_3$ and Cr$_2$O$_3$ as major phase in oxide scale.
- In the case of coatings of 3TiO$_2$-Al$_2$O$_3$, 13TiO$_2$-Al$_2$O$_3$ and 20TiO$_2$-Al$_2$O$_3$, the major phases of TiO$_2$ and Al$_2$O$_3$ were found in XRD, SEM/EDS analysis.
- The better resistance was provided by Al$_2$O$_3$-20TiO$_2$ among all other coatings when reacted to molten salt environment (40wt% Na$_2$SO$_4$-60wt% V$_2$O$_5$) for 50 cycles at 900°C.
- The 100Al$_2$O$_3$, 3TiO$_2$-Al$_2$O$_3$, 13TiO$_2$-Al$_2$O$_3$ and 20TiO$_2$-Al$_2$O$_3$ 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$_2$O$_3$ specimens showed no formation of cracks after experimentation done in molten salt environment (40wt% Na$_2$SO$_4$-60wt% V$_2$O$_5$) at 900°C.
The sequence of the coating provided better resistance of corrosion in decreasing order is $\text{Al}_2\text{O}_3$-$20\text{TiO}_2$ coating $> \text{Al}_2\text{O}_3$-$13\text{TiO}_2$ coating $> \text{Al}_2\text{O}_3$-$3\text{TiO}_2$ coating $> 100 \text{Al}_2\text{O}_3$ coating $> \text{uncoated T-22}$.

REFERENCES

[1] P. Sassatelli, G. Boletti, 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$_7$C$_3$)-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$_2$SO$_4$–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] S. Yilmaz, M. Ipek, G. F. Celebi, and C. Bindal, "The effect of bond coat on mechanical properties of plasma-sprayed Al$_2$O$_3$ and Al$_2$O$_3$–15wt% 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$_2$O$_3$ 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$_2$O$_3$ 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$_2$O$_3$-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$_2$O$_3$/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. Sundarrajank, 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$_2$SO$_4$ 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$_2$O$_3$ 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$_2$O$_3$-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.