High temperature oxidation and erosion-corrosion behaviour of wire arc sprayed Ni-Cr coating on boiler steel

Santosh Kumar1,2, Manoj Kumar3 and Amit Handa1

1 Department of Mechanical Engineering, I K G Punjab Technical University, Kapurthala, Punjab, India
2 Department of Mechanical Engineering, Chandigarh Group of Colleges, Landran, Mohali, Punjab, India
3 Department of Mechanical Engineering, Chandigarh University, Gharuan, Mohali, Punjab, India

E-mail: manojsingla77@gmail.com and manoj.me@cumail.in

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Abstract

In the current investigation, oxidation and erosion corrosion performance of wire arc sprayed Ni-20Cr coating on SA516 and T-22 boiler steel was studied at high temperature. The air oxidation kinetics of wire arc sprayed samples was established on the basis of weight change values for 50 cycles at 900 °C. Each cycle consists of 1 h of heating, followed by 20 min of cooling in air. The erosion corrosion performance of samples was determined by exposing them to the super heater zone of coal fired boiler for 15 cycles at 750 °C, where each cycle consists of 100 h of heating, followed by 1 h of air cooling. Then, the kinematics of erosion corrosion were established using thickness loss and weight change value of the exposed samples. The distinct characterization techniques (XRD, SEM and EDS) were utilized to examine the oxidized and eroded corroded products. Experimental results reveal that both the coated samples offered more oxidation and erosion corrosion resistance. However, Ni-20Cr coating on SA516 steel perform better than T-22 steel. The Ni-20Cr coated SA516 and T-22 steel reduced the weight gain by 99% and 90% respectively in laboratory environment. Moreover, the Ni-20Cr coating reduced the erosion corrosion rate of SA516 and T-22 steel by 98.04% and 88.23% respectively in terms of thickness loss. The higher resistance against erosion corrosion and oxidation is due to the development of Cr2O3 phase, higher micro hardness and less porosity of the coating.

1. Introduction

To increase the efficiency and reduce the emission of coal fired boiler is one of the major challenge for thermal power plant [1]. Therefore, steam at high temperature and pressure is required to attain higher efficiency. However, this leads to different types of material degradations like high temperature oxidation, erosion-corrosion (E-C), solid particle abrasion, wear and overheating etc. High temperature corrosion (hot corrosion) of boiler tubes has been recognized as a serious problem, resulting in the tube wall thinning and premature failure [2]. However, the degraded or worn out parts (boiler tubes) can be replaced, which enhance the cost and decrease the efficiency of the plant. Thus, to diminish these big economic losses, mainly in boiler tubes, coating by thermal spray techniques is one of the best and most effective method. Since, thermal spray coatings have the ability to safeguard the material of desired type without changing other characteristics of the base material [3]. In addition, it provides excellent mechanical properties like high strength, hardness, scratch resistance and improve wear resistance [4, 5].

In the past decade, a distinct thermal spray coating (Ni–Cr–Mo, Ni–Cr–B–Si, Ni–Cr–Ti, Ni–Cr, Cr3C2 / Ni–Cr and Ni–Cr–Al–Y) have been sprayed using Plasma Arc Spray, Detonation—Gun Spray, Cold Spray, High Velocity Oxy Fuel and Wire Arc Spray etc to prevent the boiler tubes from E-C and oxidation [4,6–12]. Among distinct aforementioned coating techniques, wire arc spray (WAS) is gaining higher potential owing to its low power input, low cost, high deposition efficiency, feasibility to spray two dissimilar wires, high spraying rate, flexibility, simplicity, offers more coarse coating than Plasma or HVOF coating method and imparts an on-site solution for restoration of corroded parts. Due to these characteristics, wire arc spray coating technique is most
widely used to decrease the corrosion of bridge decks, piston rings, welded tube seams, transport pipes and boiler walls etc. [13–15]. Shukla et al. [16] studied the degradation behavior of FeCrBSiMn coating on 310 s stainless steel in Na2SO4–82%Fe3(SO4)3 environment at 900 °C for 50 cycles. The structure of the coating was identified to be dense and globular as represented by SEM image. The coated sample showed higher resistance to corrosion than bare steel due to the development of chromium oxide phase. Li et al. [17] adopted wire arc spray technique to deposit Fe–Cr–Al and Fe–Cr–Al–B coatings on SA213–T–22 steel to evaluate the cyclic corrosion behavior at 650 °C in the molten salt environment. The results indicate that Fe–Cr–Al–B coating offered higher hardness and better corrosion resistance than Fe–Cr–Al. Qin et al. [18] deposited FeCrBSi coating on 316 l steel using twin wire arc spray technique for corrosion and wear resistance. The roughness, porosity, hardness and bond strength of as sprayed coating was found to be 35 μm, 2.6%, 8 GPa and 41 MPa. The test in sludge incineration boilers shows that the coating thickness loss is only half of that of the uncoated tubes. This shows that wire arc spray coating is an economical method to protect the sewage sludge boiler tubes from wear, hot corrosion and erosion. Steffens et al. [19] studied the recent trends in wire arc spraying techniques and material. Author reported that wire arc spraying is a better choice to resist wear and corrosion than D-Gun, Plasma spray, HVOF, etc due to its economic benefits. In addition, by adopting this method, almost all types of material (metal, alloys, carbides and borides) can be sprayed for distinct engineering applications. Hence, an effort must be made to use the potential of wire arc spraying methods. Li et al. [20] investigated the high temperature oxidation behavior of Fe–xCr (x = 15, 20, 25, 30 and 40% by weight) coatings on SA213–T2 low carbon steel using wire arc spray process. From the weight change data, it was observed that Fe–xCr coatings reduced more weight gain than bare steel. Since, with the increase in chromium content, the thickness of oxide scales reduced, which result in enhanced oxidation resistance.

Fournier et al. [21] used nickel based coating of distinct Ni/Al ratios on mild steel using wire arc spray for hydrogen evolution reaction in alkaline (1 M NaOH) solution at 25 °C. At low voltage (179 mV at 0.25 A cm−2) better mechanical electrode stability was noticed and it provides many benefits for processing of electrode material at low cost. Liu et al. [22] examined the erosion characteristics of TiAl3, TiAl, Ti3Al and Cr3C2 wire arc sprayed coating on low carbon steel by wire arc spray technique. From the result, the erosion resistance of the coatings was observed to be in the order of TiAl3 < Cr3C2 < TiAl < Ti3Al. The as sprayed samples showed laminar microstructure. The erosion mechanism of the aforementioned coatings may be due to fatigue spalling, brittle breaking, cutting and ploughing. Kawahara et al. [23] clear that NiCr based coating possesses higher resistance to oxidation, wear and corrosion thus makes it suitable for different applications. Sundararajan et al. [24] investigated the oxidation resistance of 80%Ni–20%Cr coatings on 9Cr–1Mo steel between 600 °C–750 °C by using HVOF and air plasma spray process. The HVOF sprayed coating has superior steam oxidation resistance as compared with thin porous air plasma spray coatings. Kaushal et al. [25] employed distinct thermal spray processes (CS, HVOF and D-Gun) to compare the high temperature corrosion performance of Ni–20Cr coatings on T–22 steel. From the result of XRD, SEM/EDS and x-ray mapping of samples, it was established that D-Gun spray coating provides maximum erosion-corrosion resistance owing to its dense microstructure, formation of Cr2O3 protective phase along with NiCr2O4 in its oxide scale. Kumar et al. [26] used Ni based wire arc sprayed coating on boiler steel to combat high temperature oxidation. The result indicates that Ni-20Cr coating offered higher resistance to oxidation than Ni-5Al coating due to the formation of strong protective oxide phase of chromium and nickel (Cr2O3, NiO and NiCr2O4). Kumar et al. [27] deposited Ni-5Al and Ni–20Cr coatings on T–11 and Gr A1 steel by using wire arc sprayed (WAS) method in molten salt (Na2SO4–60%V2O5) environment to investigate the corrosion performance of the coatings. The Ni–20Cr coating on Gr A1 and T–11 boiler steel exhibited 75% and 87% higher resistance to corrosion than the uncoated steel, while the Ni–5Al coating on the same substrate imparts 86% and 73% higher resistance to corrosion.

Although, in the previous study the author summarized the results of the several authors working in the field of erosion, corrosion, oxidation and hot corrosion of boiler tubes. From the results, the author concluded that among distinct coating materials, Ni–20Cr coating exhibited maximum E–C, oxidation and wear resistance [28]. However, from the literature survey, it is noticed that various authors have used Ni–20Cr coating on boiler steels (T–22 and SA516) using distinct thermal spray techniques. But a very few studies are available on Ni–20Cr coating using wire arc spray technique. Although, some authors have used wire arc sprayed Fe based coating on steel in a distinct environment under cyclic conditions to resist corrosion [16–22].

Hence, the objective of the current study is to examine the high temperature erosion corrosion and air oxidation behavior of Ni–20Cr coatings on T–22 and SA516 steels in the laboratory and actual boiler environment for 50 cycles by adopting wire arc spray process. The coating properties such as micro-hardness, porosity and roughness were evaluated. In addition, the probable erosion corrosion mechanism of Ni–20Cr coated SA516 steels after subjected to an actual boiler environment is also briefly described. The current investigation indicates the valuable role of Ni–20Cr coatings in protecting the boiler tube steels.
2. Experimental descriptions

2.1. Substrates material

In this experimental work, iron-based boiler steels (SA516 and T-22) were used as the base material. The chemical composition of used substrate material (T-22 steel) in terms of weight %age was C: 0.15%, Si: 0.5%, Mn: 0.3%–0.6%, S: 0.03%, P: 0.03%, Mo: 0.87%–1.13%, Cr: 1.9%–2.6% and Fe: balance. However, SA516 steel contains: C: 0.27%, Si: 0.1%, Mn: 0.93%, S: 0.06%, P: 0.05% and Fe: balance [29].

Both the steels (T-22 and SA516) were taken from the Cheema Boilers Limited, Kurali, Punjab. Then, both steels were cut to prepare the samples having dimension of 20 mm × 15 mm × 5 mm. Subsequently, emery paper and cloth wheel polishing m/c was utilized for finishing and polishing the test samples.

2.2. Coating deposition

Firstly, the samples were washed with acetone (C₃H₆O) and grit blasted by silicon carbide particles and then Ni-20Cr coating was deposited on the substrates at Metallizing Equipment Co. Pvt. Ltd Jodhpur, Rajasthan. The variables used during the deposition of coating are represented in table 1. The uniform coatings were sprayed on six sides of test samples up to 200–300 μm thickness.

2.3. Characterization of wire arc sprayed coatings

XRD analysis was done on the coated samples using an XRD machine (PANalytical, X’pertPro and Netherlands). The high precision diamond cutter at low speed was used to cut the samples for cross sectional analysis. Further, SEM + EDS analysis of the samples was done after polishing the samples as per standard procedure. The digital micro hardness tester at 100 g load and dwell time of 10 s. was used to measure the mean micro hardness. The porosity was measured as per the ASTM B 276 standard [30]. The porosity of the polished cross-sectional area of the coated samples was measured by an optical microscope connected with metallurgical software. In this analysis, the image was captured by optical microscopy which were selected for porosity (pores) measurement. Firstly, a square area on the cross-section of the polished coated samples was selected and then the image was examined. The same steps were used at 5 distinct random locations to determine the mean %age volume of porosity.

Then stylus type surface roughness tester was used to determine the roughness of the as sprayed samples. The calculated value of average surface roughness, micro-hardness & porosity are given in table 2.

2.4. Air oxidation analysis

The cyclic isothermal air oxidation test was conducted in a silicon carbide (SiC) tube furnace at 900 °C for fifty cycles. Before oxidation study, the samples were measured using digital Vernier caliper. Then, washing and drying of the samples was done using acetone and air drier. Subsequently, alumina boat was preheated for 4 h at 250 °C in oven and then cooling in air for 20 min. The Al₂O₃ boats were one more time heated for 2 h at 900 °C.

### Table 1. Wire arc spray parameter.

| Variables                  | Values                          |
|----------------------------|---------------------------------|
| Source of Heat             | Electric Arc                    |
| Temp. of Particles         | Up to 5000 °C                   |
| Velocity of Powder Particles | 150 m s⁻¹                        |
| Arc Temp.                  | ~4000 °C                        |
| Dia. of feed-stock Wire    | 2 mm                            |
| Air Flow Rate              | Up to 60 m³ hr⁻¹                |
| Spary Rate                 | 16 Kg hr⁻¹                      |
| Spray Performance          | 15 to 3,300 g min⁻¹             |
| Spray Distance             | 15 to 25 cm                     |
| Input Power                | 6 to 80 KW                      |
| Pressure                   | 4 to 6 bar                       |

### Table 2. Average values of coating parameters.

| Coating material | Substrate | Microhardness | Porosity | Surface roughness |
|------------------|-----------|---------------|----------|------------------|
| Ni-20Cr          | SA516     | 379.8 Hv      | 1.54%    | 2.799 μm         |
| Ni-20Cr          | T-22      | 273.5 Hv      | 1.53%    | 3.04 μm          |
in SiC furnace to eliminate the humidity. Further, the samples were kept in the boat and preheated at 150 °C in oven for 2 h and then the initial weight of the samples were noted. Subsequently, an isothermal air oxidation study was started in SiC furnace. Then, after each cycle, weight change along with visual examination i.e. physical changes (color, lustre and spallation) were noted. Further, XRD, SEM + EDS was utilized to analyze the x-sectional and surface structure. The oxidation study was done for 50 cycles, as the time period is sufficient to acquire the oxidation steady condition [31–33].

2.5. Erosion corrosion analysis
For erosion corrosion study, a hole of 3 mm diameter was drilled in each sample to hang in the boiler using kanthal wire. Then the samples were hanged in stage 3 of boiler −1 at GGSS Thermal Power Plant, Ghanauli, Ropar. All the test samples were hung in the super heater zone of the boiler at 42 m height at 740 ± 10 °C for 15 cycles. The volumetric flow of the flue gases (3% O2 and 16% CO2 by volume) in the boiler was approximately 700 tonnes per hour and average velocity of gas stream was approximately 13 m s⁻¹ [34].

The camel hair brush and acetone (C₃H₆O) was used to clean and remove the deposited ash particles from the eroded samples to some extent. The electronic balance machine (Kern: AB100–5M, having 0.01 mg sensitivity) was utilized to calculate the weight change of each corroded samples. Although, the weight change value alone was not sufficient to judge the E-C performance of the samples, due to ash deposition of the test samples. Thus, the degree of degradation of the samples was evaluated by measuring thickness loss in mill per year (mpy) and extent of the internal corrosion attack in terms of depth. Visual examinations were also made to examine the change in color, spallation, adherence, lustre, and other aspects of the coating/scale. After the cyclic E-C analysis, the surface and x-sectional study of the samples was done using XRD and SEM/EDS analysis.

3. Results

3.1. Microstructural description of coating

3.1.1. XRD Study
The XRD profile of Ni-20Cr coated T-22 and SA516 steel is illustrated in figures 1(a) and (b).

XRD investigation represents the development of nickel as the major phase and nickel oxide as the minor phase for coated steels. This means that a very less oxidation of feedstock wire has occurred during the deposition of coating.

3.1.2. SEM and EDS study
The SEM analysis of the coated T-22 and SA516 steel is illustrated in figures 2(a) and (b).

The Ni-20Cr on T-22 and SA516 steel shows rock-like structure with an irregular surface. The EDS study at particular points represents the existence of nickel and chromium as the major phase along with a very small amount of oxygen. In addition, a few numbers of micro pores were also observed in the coating microstructure which is accountable for the porosity.

3.1.3. Cross-section analysis
From FE-SEM backscattered micrographs the mean coating thickness of both coated samples varies between 200–300 µm as represented in figures 3(a), (b).
The variation in x-sectional micro hardness with respect to distance from the substrate to coating interface is shown in figure 4 for both the coatings. The mean value of micro-hardness for coated SA516 and T-22 steel were observed to be 379.8 Hv and 273.5 Hv, whereas for bare SA516 and T-22 steel were 229 Hv and 171 Hv respectively.

3.2. Cyclic air oxidation study

After oxidation analysis, the micrograph of exposed steel samples is displayed in figures 5(a) to (d).

During study the bare SA516 steel experience excessive spalling along with sputtering. The rapid weight gain during the initial hour of study may be due to sudden O2 take up by the dispersion of oxygen [35]. The metal initiate removing from the upper surface of the metal at the end of 12th cycles. Then, the spallation along with change in color (dark gray to dark black) take place during the subsequent cycles. After 36th cycles, material from the top surface of the sample start removing in layer form. But, no spallation takes place, for coated SA516 steel, only a change in color (black color changes to brownish) takes place along with reduction in weight gain by 99% than uncoated steel. This shows that Ni-20Cr coatings have shown an excellent resistance to the oxidizing species.

Similarly, for uncoated T-22 steel suffers huge cracking, spalling and sputtering of its oxide scale. Initially color changes take place (grey color to dark black). Then, the material starts removing in the form of micro flakes and scars after 10th cycle. Subsequently, the crack propagation takes place after 38th cycles and remain continue till 50th cycles. However, no spallation and cracking was seen in coated T-22 steel. The weight change value is utilized to establish the kinetics of the oxidation process. Since the oxidation rate is directly proportional to weight gain. Hence, on the basis of weight change data, the rate of oxidation for the uncoated and coated samples can be compared. The significance of the oxidation kinetic is examined by determining the parabolic rate constant (Kp).

Mathematically, \( K_p = \frac{(\Delta W/A)^2}{t} \), Here (\( \Delta W/A \)) is the weight change per unit surface and t is the time period [36, 37].
The deviation of weight w.r.t. no. of the cycles for fifty cycles at 900 °C is represented in figure 6. The similar weight change graph (mg cm\(^{-2}\)) w.r.t. no. of cycles has been plotted by various researchers to study the oxidation behavior of coated and uncoated boiler steel samples [32, 38–42].

The total weight gain for bare T-22 & SA516 steel was 104 mg cm\(^{-2}\) and 129 mg cm\(^{-2}\), whereas it was 11.70 mg cm\(^{-2}\) and 1.65 mg cm\(^{-2}\) for Ni-20Cr-coated T-22 and SA516 steel respectively. Thus, the coated

![Figure 4](image1.png)

**Figure 4.** X-sectional micro-hardness chart of Ni-20Cr coating on T-22 and SA516 steels.

![Figure 5](image2.png)

**Figure 5.** Macrograph of the coated and bare samples after 50 cycles of air oxidation at 900 °C: (a) bare SA516 (b) Ni-20Cr coated SA516 (c) uncoated T-22 (d) Ni-20Cr coated T-22.
SA516 steel has been found to be more effective to increase resistance against oxidation of SA516 tube steel, which is a +ve aspect [40]. The graph b/w (weight change/area)^2 versus number of cycles for test samples is depicted in figure 7.

### 3.2.1. XRD analysis
The XRD image of samples (bare and coated) after exposing to air oxidation at 900 °C is shown in figure 8.

From figures 8(a) and (c), it is clear that the uncoated steels have Fe_2O_3 as the primary phase. However, for coated samples, there is the presence of NiO, NiCr_2O_4 and Cr_2O_3 as shown in figures 8(b) and (d).
3.3. SEM/EDS analysis

3.3.1. Surface structure of the scales

SEM and EDS study of the samples (bare and coated) after subjected to oxidation environment for fifty cycles at 900 °C is depicted in figure 9.

The SEM analysis of the bare steels illustrates the presence of a coarse grained scale as indicated in figures 9(a), (c) whereas, EDS examination shows that the scale is max. in Fe and O₂. This indicates the formation of Fe₂O₃. However, SEM + EDS image of Ni-20Cr coated T-22 and SA516 after fifty cycles of air oxidation analysis is shown in figures 9(b), (d) which describes a scale with fine grain having crystalline structure. The scale

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**Figure 8.** XRD profile of steel samples exposed to oxidation at 900 °C for fifty cycles (a) bare SA516 steel (b) Ni 20Cr coated SA516 steel (c) uncoated T-22 (d) Ni-20Cr coated T-22 steel.

**Figure 9.** Surface SEM/EDS image for uncoated and coated steels exposed to cyclic air oxidation for 50 cycles at 900 °C. (a) uncoated T-22 (b) Ni-20Cr T-22 (c) uncoated SA516 (d) Ni-20Cr coated SA516 steel.
contains higher amount of chromium and nickel, which forecast the possibilities of formation of Cr₂O₃, NiO on the surface which further resist the oxidation [41].

3.3.2. X-ray mappings

X-ray mapping of uncoated SA516 steel and Ni-20Cr coated SA516 steel after exposure of fifty cycles at 900 °C in SiC furnace is illustrated in figures 10 and 11 respectively.

The composition image indicates that the uncoated steel shows the growth of (Fe₂O₃) in the scale. The scale interface in figure 11 is seen free from any destruction than the uncoated SA516 steel. The Ni, Cr, Fe and O as proved by the x-ray mapping for coated steel. However, in the upper layer, the existence of O₂ verifies Ni and Cr oxides. This indicates the formation of Cr₂O₃, which helps to combat hot corrosion.

4. E-C examination in a coal-fired boiler

The image of samples after exposing to the super heater region of the boiler for 15 cycles at 750 °C is represented in figures 12(a) to (d).

During the erosion corrosion analysis, it was noticed that uncoated T-22 steel experience cracking along with spalling and sputtering of its oxide scale. The T-22 steel form oxide scale and silver gray color start changing to a dark gray color during the initial cycles. After the end of 10th cycle, material appears removing in the shape of scars along with some redness on the corner of the sample. The redness shows the formation of Fe₂O₃ scale. The sputtering and spallation of bare T-22 steel still remain continue up to 15th cycle. However, no such phenomenon (spalling/sputtering) was noticed for coated T-22 steel during 15 cycles. Only a change in color (dark gray to darkest gray color and then red gray) takes place during erosion corrosion study.

Similarly, the bare SA516 steel underwent spallation and silver gray color changed to dark gray color during initial cycles. Subsequently, after tenth cycle a light red color oxide formed on the edge of the sample and material start removing in the form of microchip. Afterwards, red color oxide grows towards the center of the
substrate material till the fifteenth cycle. However, no such phenomena take place in coated SA516 steel, only a change in color from light black to light gray occur. The weight change per area versus no. of cycles (15 cycles) for coated and bare samples exposed to live boiler condition at 750 °C is shown in figure 13. The similar weight change graph (mg/cm²) w.r.t. no. of cycles has been plotted by various researchers to study the erosion-corrosion behavior of coated and uncoated boiler steel samples [43–46].

Figure 13 gives an understanding of the degradation of the uncoated and coated steel. It is clear from the weight change plot that uncoated steels show more erosion-corrosion than coated steel. The overall weight gain for bare T-22 and SA516 steel has been found to be 1.599 mg cm⁻² and 4.32 mg cm⁻² respectively. Although, the weight loss for coated T-22 and SA516 steel was observed to be 1.47 mg cm⁻² and 4.25 mg cm⁻². In addition, the thickness loss of uncoated T-22 and SA516 steel after 15 cycles was measured to be 0.51 mm and 0.41 mm respectively, whereas it was 0.06 mm and 0.008 mm for Ni-20Cr coated T-22 and SA516 steel.
Then, based upon thickness loss data the corrosion rate (mpy) has been calculated for 1500 h by using the relation \(1\text{mpy} = t \times 39.37 \times \frac{8760}{1500}\). Here, \(t\) = thickness loss in mm during 1500 h, 1 mm = 39.37mils and 1 year = 8760 h. For bare T-22 and SA516 steel, corrosion rate was calculated to be 117.25 and 94.26 mpy.

Figure 14. XRD profile of uncoated and coated samples after subjected to live boiler condition for 1500 h at 740 ± 10°C. (a) Bare SA516 (b) Bare T-22 (c) Ni-20Cr coated SA516 (d) Ni-20Cr coated T-22 steel.
respectively. The corrosion rate for Ni-20Cr coated T-22 and SA516 steel was 13.79 mpy and 1.83 mpy respectively. Hence, based upon thickness loss data Ni-20Cr coating on SA516 is more effective to reduce maximum erosion corrosion (98.04%) than the bare steel.

4.1. XRD study
XRD study of the samples exposed to live boiler condition for 15 cycles at 740 ± 10 °C is represented in figures 14 (a) to (d).

The bare SA516 steel indicates the presence of Fe$_2$O$_3$, Fe$_3$O$_4$ and Al$_2$O$_3$ phase as depicted in figure 14(a). However, figure 14(b) indicates that the oxide scale of T-22 steel has Fe$_2$O$_3$ and Fe$_3$O$_4$ as the primary phase along with Al$_2$O$_3$ and Cr$_2$O$_3$ as a secondary phase. The presence of Ni, NiO, and Cr$_2$O$_3$, along with Fe$_2$O$_3$, Al$_2$O$_3$ and SiO$_2$ were seen in Ni-20Cr coated samples as depicted in figures 14(c) and (d). The presence of Al$_2$O$_3$ is due to ash particles, whereas Cr$_2$O$_3$ is due to oxidation of chromium particles present in the coated samples. As chromium form more stable oxide, since it has more affinity for O$_2$ as compared to nickel and thus block the diffusion of reacting species resulting in higher resistance to oxidation of the substrate material [47, 48].
4.2. SEM/EDS result

4.2.1. Surface SEM morphology

SEM/EDS study of the samples exposed to live boiler condition for 15 cycles at 740 ± 10 °C is depicted in figure 15.

The surface morphology of the bare T-22 shows micro flakes and spallation with a top layer that shows the salt deposits as represented in figure 15(a). The EDS result shows that the scale has a high amount of oxygen and iron and form Fe₂O₃ and Fe₃O₄. In addition, minor composition of other elements like aluminium and chromium was also observed in the oxide scale, resulting from existence of fly ash particles and its basic element of base steel. The uncoated SA516 steel shows the scales of tiny flakes on the top surface having amorphous appearance, cracks, crater and spallation as shown in figure 15(c). However, coated T-22 shows the crystalline dense structure which is a nickel oxide scale with white coloured ash particles as shown in figures 15(b) and (d). The EDS result of coated SA516 steel indicates a major amount of Ni, Cr, Fe with small amount of Ti, Cu, O and Si, which forms Cr and Ni oxides. The presence of oxygen in the scale reveals the growth of the oxides of these elements. The coated T-22 boiler steel has Ni, O and Cr in large concentration with small concentration of Fe, Al, Ti and Si.

Figure 15. (Continued.)
5. Discussion

5.1. E-C studies

The wire arc spray process gives the possibility of deposition of Ni-20Cr coating on T-22 and SA516 boiler steel up to 200 $\mu$m to 300 $\mu$m. The average porosity of Ni-20Cr coatings was exhibited to be $<2\%$ as shown in table 2, which results in better corrosion resistance. The mean value of micro hardness for coated T-22 and SA516 steel was 59.90 and 65.86 percent higher than the bare steels, which is due to the high kinetic energy of nickel and chromium powder grain on the base material resulting in improved cohesion strength. Although, the different value of micro-hardness for the same coating on distinct substrate was observed. Since, coating properties is also depends upon the type of substrate material. Thus, the higher value of coating micro hardness offered high erosion corrosion resistance according to the tribological theory [49]. The average value of roughness, micro-hardness & porosity of Ni-20Cr coated T-22 and SA516 steel is shown in table 2.

After the exposure of the live boiler environment, the bare T-22 and SA516 steel indicates an enormous spallation and higher weight gain in comparison with coated boiler steel samples. This is due to the growth of Fe$_2$O$_3$ in their oxide scales as it decreases the cohesion strength and provides less corrosion resistance [50, 51]. Despite, the growth of Fe$_2$O$_3$, Fe$_3$O$_4$, Al$_2$O$_3$ and SiO$_2$ for bare steels (T-22 and SA516) is well shown by SEM/EDS and XRD analysis. However, the development of aluminum oxide (Al$_2$O$_3$) may be due to the accumulation of ash particles on the exposed samples.

In the live boiler environment, the uncoated samples indicated an overall weight gain, whereas both the coated samples showed an overall weight loss as represented in figure 13. This higher weight gain may be attributed to the development of oxides of iron (Fe$_2$O$_3$ and Fe$_3$O$_4$) [52]. The development of Cr$_2$O$_3$, NiO, AlO, NiCr$_2$O$_4$, and Al$_2$O$_3$ phases reduced E-C rate. However, the formation of Al$_2$O$_3$ and Fe$_2$O$_3$ in the coated samples was due to the ash deposition. Although, coated SA516 was beneficial to decrease the maximum E-C rate by 98.04%. This might be attributed to the existence of NiCr$_2$O$_4$ phase and more amount of chromium along with oxygen because the spinel of NiCr$_2$O$_4$ phase generally has less diffusion coefficient of the cations and anions than their parent’s oxides [53].

The probable mode of erosion corrosion for coated SA516 steel after given to live boiler condition for fifteen cycles at 750 $^\circ$C is represented in figure 16.

A similar probable E-C mechanism of cold sprayed Ni-20Cr-TiC-Re coating on SA516 steel exposed to live boiler condition for 1500 h at 700 $^\circ$C is also shown by Bala et al [54].

A various authors [29, 52,55–62] used distinct coating material on T-22 and SA516 steel using different thermal spray processes to combat erosion corrosion in the actual boiler environment. The comparison of weight change data of present investigation has been compared with the results of the various researchers who
have already applied different thermal sprayed coatings on boiler steels (SA516 and T-22) is shown graphically in figure 17.

From the graph (figure 17), it is clear that wire arc spray is a better choice to reduce E-C of boiler steel due to its economic benefits, simplicity and portability.

5.2. Air oxidation studies

During air oxidation studies at 900 °C, the bare T-22 and SA516 steel, experienced huge spallation and crack with scale of tiny flake. However, dense scale with no spallation and lower weight gain was observed for coated samples. Since the oxides of Ni, Cr (NiO, Cr2O3, and NiCr2O4) has a slow growth rate, which result in high cohesion strength. The other reason for high oxidation resistance of coating is the formation of Cr2O3 [63, 64]. The Ni-20Cr coated SA516 steel proved better than on T-22 steel in a laboratory environment. This may be due to the development of Cr2O3, NiCr2O4 and NiO in the oxide [65, 66].

Thus, the results indicate that wire arc spray is a better choice to combat oxidation and E-C of boiler tubes.

6. Conclusions

1. By adopting wire arc spray process Ni-20Cr coating on T-22 and SA516 boiler steel have been successfully deposited up to 200 μm to 300 μm thickness, which is useful for boiler applications.

2. The Ni-20Cr coated T-22 and SA516 steels reduced the E-C rate by 88.23% and 98.04% than the base steels, respectively in the actual boiler environment. Similarly, Ni-20Cr coating on T-22 and SA516 steels reduced the weight gain by 90% and 99% than base steels respectively. Thus Ni-20Cr coating on SA516 steel offered excellent E-C than T-22 steel.

3. The mean micro hardness value of Ni-20Cr coated T-22 and SA516 steel was 59.90% and 65.86% higher than base steel. This higher micro hardness results in higher E-C resistance.

4. The formations of the protective phase like Cr2O3, NiO along with NiCr2O4 in the oxide scale, less porosity and higher microhardness of the coating are responsible for providing a resistance against erosion corrosion and high temperature oxidation.
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ORCID iDs

Manoj Kumar @ https://orcid.org/0000-0002-1805-5072
Amit Handa @ https://orcid.org/0000-0002-0626-1602

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