High Temperature Oxidation Behaviour of D-gun Sprayed Cr_2O_3 -50% Al_2O_3 Coating on ASTM-SA213-T-22 Boiler Steel

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Abstract—*In the current investigation Cr_2O_3 -50% Al_2O_3 coating was deposited on ASTM-SA213-T-22 boiler steel by D-gun spray process. The high temperature oxidation performance of coated as well as bare alloy was evaluated in air at 900°C under cyclic conditions. The kinetics of the oxidation was approximated by the weight change measurements made after each cycle for a total period of 50 cycles. Each cycle consisted of 1 h heating in a tube furnace followed by 20 min cooling in ambient air. X-ray diffraction (XRD), scanning electron microscopy/energy dispersive X-ray analysis (SEM/EDAX) techniques were used to analyze the oxidized products. Both the bare alloy suffered intensive spallation in the form of removal of their oxide scales, which may be attributed to the formation of unprotective Fe_2O_3 dominated oxide scales. The Cr_2O_3 -50% Al_2O_3 coated alloy showed lesser weight gain and the oxide scales remained intact till the end of the experiment. The phases revealed in the oxide scales of the coated specimens were mainly oxides of chromium and aluminum which are reported to be protective against the hot corrosion.*

Keywords: *Oxidation; Scale; Detonation Gun Coating; Cr_2O_3 -50% Al_2O_3 Coating*

INTRODUCTION

Metals and alloys gets oxidized when exposed to elevated temperatures in air or highly oxidizing environments, such as combustion gas with excess of air or oxygen. They often rely on the oxidation reaction to develop a protective oxide scale to resist corrosion attack. Ferritic steels, containing chromium and molybdenum are well known for their excellent mechanical properties combining high temperature strength and creep resistance with high thermal fatigue life, as well as with good thermal conductivity, weldability, and resistance to corrosion and graphitisation. Because of these characteristics this type of steels have attracted special interest for application in industrial processes related to carbochemistry, oil refining, carbon gasification and energy generation in thermal power plants, where components like, heat exchangers, boilers and pipes operate at high temperatures and pressures for long periods of time [1, 2]. At high temperature exposure the interaction between a metal or an alloy and the surrounding gases and combustion products leads to corrosion, thus leading to failure for materials and structures [3-5]. Alloys that are developed for heat and oxidation resistance typically form a protective layer of chromia or alumina. The more rapidly this layer is established, the better protection is offered. As this layer grows or as it reforms over areas from which the original layer was removed, it must withdraw chromium or aluminium from the metal in order to provide for further scale growth [6]. Oxide scale is constituted by a layered structure with compositional and microstructural variations from the substrate to the outer interface [7–12]. On the other hand, depending on the oxidation temperature and the chemical composition of the steel, both, the mechanisms of formation and the microstructural characteristics of the oxide scale, along with the degree of protection it provides, are different [13]. Recent studies showed that the materials used for high temperature strength are highly susceptible to high temperature corrosion and the surface engineering plays a key role in effectively combating the high temperature corrosion problem [14]. One of the protective means to counteract the problem of hot corrosion is to coat the base material with a protective layer (coating) using various surface modification techniques. The protective coatings are being used widely now a days; on structural alloys in energy conversion and utilization systems to protect their surface from high temperature oxidation [15]. Among the various coating methods; detonation gun (D-gun) spray coating process (a thermal spray process) gives an extremely good adhesive strength, low porosity and coating surface with compressive residual stresses. The porosity values of D-gun sprayed coatings are very much lower (<0.8%) than that of Plasma or HVOF sprayed coating as reported in the literature [16–19]. Coatings are usually designed in such a way that on exposure to reactive environments, the selective oxidation of an element occurs to form a protective oxide scale such as Cr_2O_3, Al_2O_3 or SiO_2 [20].

There is no reported literature on high temperature oxidation behavior of detonation gun (D-gun) spray deposited Cr_2O_3 -50% Al_2O_3 coating on boiler steel substrates. Therefore, the present work has been focused to study the influence of D-gun sprayed Cr_2O_3 -50% Al_2O_3 coating on high temperature oxidation behavior of ASTM-SA213-T-22 boiler steel in air at 900°C under cyclic conditions. The kinetics of oxidation of D-gun sprayed Cr_2O_3 -50% Al_2O_3 coating and bare alloy substrate was investigated by thermogravimetry technique. X-ray diffraction (XRD), scanning electron microscopy/energy-dispersive analysis (SEM/EDAX) and X-ray mapping techniques have been used to characterize the oxidized products in order to render an insight in to the corrosion mechanisms.

EXPERIMENTAL PROCEDURE

Development of the Coatings

Substrate Material: The Fe-based substrate materials selected for this study, namely 2.25Cr-1Mo steel "ASTM-SA213-T-22 (Grade T-22)"in the tube form. The chemical composition of the base materials has been provided in Table 1 which presents the composition provided by supplier and the actual composition measured by optical spectroscopy.

Table 1: Chemical Composition (wt.%) of "ASTM-SA213-T-22 (Grade T-22) Boiler Steel

ALLOY GRADE ⇒	ASTM-SA213-T-22	
Elements ⇓	Nominal	Actual
C	0.15	0.15
Mn	0.3–0.6	0.45
Si	0.5	0.25
S	0.03	0.006
P	0.03	0.03
Cr	1.9–2.6	2.46
Mo	0.87–1.13	0.80
Ni	-	-
Ti	-	-
Al	-	-
Fe	Balance	Balance

Coating Powder: A commercially available Ni-20Cr (Praxair NI-105) metallic powder was used for bond coat and the Cr_2O_3 -50% Al_2O_3 powder for top coat was prepared in laboratory ball mill for 8 hrs to form a uniform mixture from two types of commercially available alloy powders namely Chromia (Cr_2O_3) with minimum assay 99.5% (AMPERIT® 704 H. C. Starck) and Alumina (Al_2O_3) with minimum assay 98.0% (AMPERIT® 740; H. C. Starck) and. The coating powders were made available by SVX POWDER M SURFACE ENGINEERING (PVT.) LIMITED, Greater Noida, (U.P.) India. A SEM (scanning electron microscope) micrograph of the Cr_2O_3 -50% Al_2O_3 powder has been shown in Fig. 1. It is observed from SEM micrograph that the powder particles have irregular morphology with larger particle 41.93μm and smaller one with 6.58μm measured by back scattered electron image (BSEI), which is consistent with the nominal size range provided by the manufacturer.

Coating Formulation: Specimens with dimensions of approximately 20mm×15mm×5mm were cut from the alloy sheets/tubes, polished using emery papers of 220, 400, 600 grit sizes and subsequently on 1/0, 2/0, 3/0 and 4/0 grades, and subsequently cleaned, degreased and shot blasted grit blasted with alumina powders (Grit 60) prior to the deposition of the coatings for developing better adhesion between the substrates and the coatings. The coatings were deposited on the substrates using Detonation gun (D-gun) Spray (a thermal spray process) apparatus. The coating work was carried out by a commercial firm namely SVX Powder M Surface Engineering Private Limited, Greater Noida (India). The process parameters for the D-gun spray process employed for applying the coatings are summarized in Table 2.

Characterization of the As-sprayed Coatings

The Field Emission Scanning Electron Microscope (FEI: CARL ZEISS EVO-18 Research; at Metallizing Equipment Co. PVT. LTD. Jodhpur & IIT Roorkee) fitted with an EDAX attachment (Oxford, UK) was used to characterize the surface morphology of the coatings. SEM micrographs along with EDS spectrum were taken with electron beam energy of 20 keV. The XRD analysis was carried out using a Bruker AXS D-8 Advance diffractometer (Germany) with Cu K_radiation. The specimens were scanned with a scanning speed of 2^o/min in 2θ range of 20^o to 120^o and the intensities were recorded. The diffractometer interfaced with the Bruker DIFFRAC Plus x-ray diffraction software that provides the d-values directly on the diffraction pattern.

High Temperature Oxidation Studies in Air

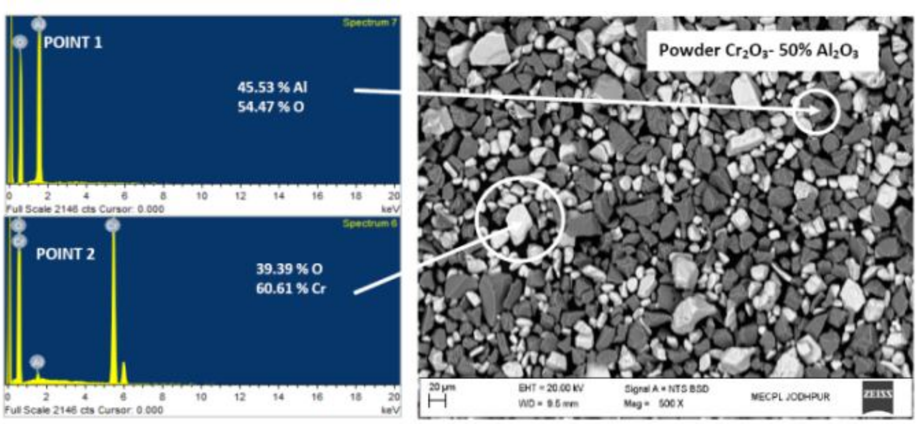

Fig. 1: SEM Micrograph of Cr_2O_3 -50% Al_2O_3 Coating Powder

All the specimens were polished down to 1 µm alumina wheel before being subjected to high temperature oxidation runs. The high temperature oxidation studies were performed under cyclic conditions for 50 cycles at 900°C. Each cycle consisted of 1 h of heating at 900°C in a silicon carbide tube furnace followed by 20 min of cooling at room temperature. The specimens were kept in alumina boats and inserted in the furnace. The cyclic study provides the most severe conditions for testing and represents the actual industrial environment, where breakdown and shutdown occur frequently.

Table 2: The Process Parameters Employed During D-gun Spray Process

Working Gases		Fuel Gas	Fuel Gas	Carrier Gas
		Oxygen	Acetylene	Nitrogen
Pressure of Working Gases (MPa)		0.2	0.14	0.4
Flow Rate of Working Gas (LPH)	For Bond Coat (Ni-20Cr)	2800	2240	720
	For Coating (Cr_2O_3-x Al_2O_3)	4800	1920	1020
Spraying Distance (mm)		For Bond Coat (Ni-20Cr)	For Coating ((Cr_2O_3-x Al_2O_3))	
		165	180	
Consumption of powder per shot (g/shot)		0.05.0.02		
Water Consumption Rate (Liters/min)		15–25		
Firing rate (Hz)		1–10		
Diameter of Accelerating Portion of Barrel		0.022 m		
Coating Thickness per shot (µm)		5–25		
Sound pressure level (dB)		150		
Relative Humidity of Air (% age)		0.50 %		
Coating Capacity at the Rate of 7 µm/shot (m^2/hr)		0.75		
Power Supply from Mains		Frequency	Voltage (Volts)	Power (VA)
		50–60	430	450

A cyclic study of 50 cycles had been performed as the study of 50 cycles is considered to be adequate for attaining the steady-state oxidation for the material [21–24]. The studies were performed for uncoated as well as coated specimens for the purpose of comparison. The weight change measurements were taken at the end of each cycle with the help of Electronic Balance Model 06120 (Contech) with a sensitivity of 1 mg. The spalled scale was also included at the time of measuring weight change to determine the total rate of corrosion. Weight change data was analyzed to approximate the kinetics of corrosion. After the exposure, the corroded samples were subjected to the XRD and FE-SEM/EDAX analyses for the surface as per the procedure mentioned characterization of coatings section.

RESULTS

XRD Analysis of the As-Sprayed Coatings

The XRD diffractrograms of the D-gun sprayed Cr_2O_3 -50% Al_2O_3 coating in as-sprayed conditions on ASTM-SA213-T-22 boiler steel are depicted in Fig. 2 on reduced scale. The analysis indicates Cr_2O_3 and Al_2O_3 as the principal phases for the Cr_2O_3 -50% Al_2O_3 coatings on both T22 boiler steel.

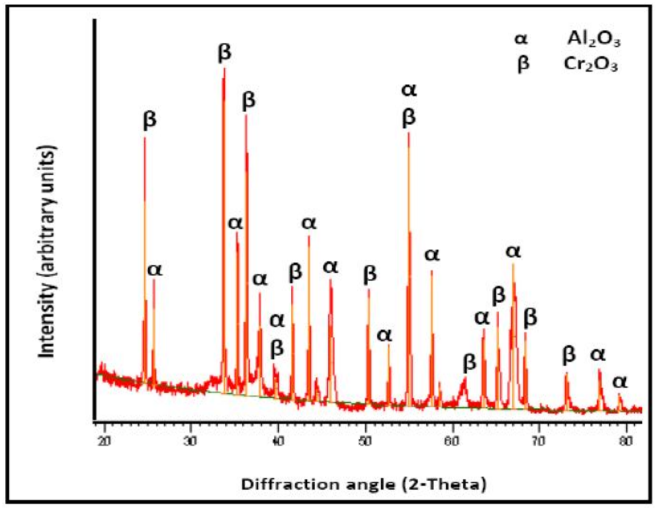

Fig. 2: X-ray Diffraction Pattern of D-gun Sprayed Cr_2O_3-50% Al_2O_3 Coating on ASTM-SA213-T-22 Boiler Steel

SEM/EDAX Analysis of the As-sprayed Coatings

The SEM micrographs along with EDS spectrum reveal the surface morphology of the as-sprayed Cr_2O_3 -50% Al_2O_3 coating on ASTM-SA213-T-22 boiler steel showing elemental composition (%) at selected points are shown in Fig. 3. The micro-structure consists of interlocked particles where most of the sprayed particles appear to be deformed significantly giving a flattened appearance. The deformed shapes of particles are due to impact of particles which occurs at higher velocities during the D-gun spray process. In general microscopic features indicate that the coatings are homogeneous and massive, free from cracks (Fig. 3). Presence of some oxide stringers as well as open pores has been noticed in general in the coatings. The dark regions in between are expected to be porosity. The EDAX analysis shows the domination of Cr and O in the light grey region (Point 1 of Fig. 3) with small traces of Al. Whereas the EDAX analysis of the dark grey region (Point 2 of Fig. 3) of the coating reveals the domination of O and Al with small traces of Cr. This composition is nearly approaching the composition of the sprayed powder.

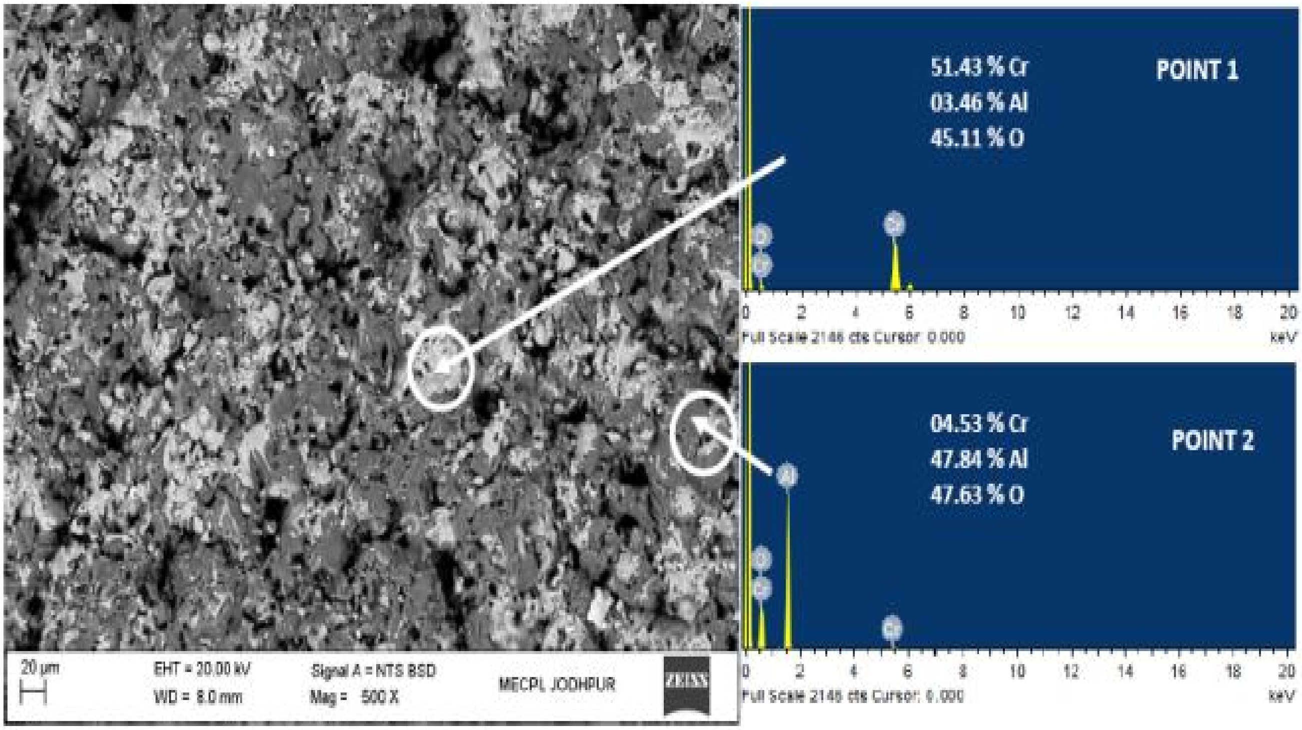

Fig. 3: Surface Scale Morphology and EDAX Analysis Showing Elemental Composition (wt%) at Selected Points of D-gun Sprayed Cr_2O_3 -50% Al_2O_3 Coating on ASTM-SA213-T-22 Boiler Steel

High Temperature Oxidation Studies in Air

Macrographs of the uncoated and coated samples subjected to high temperature oxidation in air at 900°C for 50 cycles have been represented in Fig. 4. In the case of the uncoated T22 boiler steel; a grey colored fragile scale appeared on the surface right from the 1st cycle. This bare steel showed spalling of scale just after the 6th cycle, which continued till the end of 50 cycles. At the end of cyclic study, irregular and fragile scale was observed with deep cracks and grey color surface appearance (Fig. 4. a). The specimen appeared to be swollen with cracks all over. The colour of the specimen changed to grey at the end of the second cycle for the Cr_2O_3 -50% Al_2O_3 coated ASTM-SA213-T-22 boiler steel (Fig. 4. b). The coating by and large, was found to be adherent to the substrate with no spallation tendency initially up to 15^{th} cycle. However, a marginal spallation was observed at one edge of the specimen at the end of the 11^{th} cycle. A small amount of powder was also found in the boat at the end of the 30^{th} cycle. By the end of the 50^{th} cycle the specimen was blackish grey in colour.

Weight change data measured during the high temperature oxidation testing has been compiled in Fig. 5. In the case of the Cr_2O_3 -50% Al_2O_3 coated specimen, it can be inferred from the plots (Fig. 5. a) that the necessary protection against high temperature oxidation has been provided by the Cr_2O_3 -50% Al_2O_3 coating as the weight gain value for the coated alloy is negligible as compared to the uncoated counterpart. The (weight gain/area)^2 versus number of cycles plot (Fig. 5. b.) is shown for all the samples to ascertain conformance with the parabolic rate law. The parabolic rate constant Kp were obtained from the slope of the linear regression fitted line (cumulative weight gain/area)^2 *vs*. number of cycles and are shown in Table 3. It is clear that in spite of some fluctuations in the data for the bare alloys; the data conforms to the parabolic rate law to an acceptable limit for the alloy. The coating also followed the parabolic rate law of oxidation for the entire 50 cycles of study, as can be inferred from the plots (Fig. 5. b). The parabolic rate constant (Kp) value for the coated substrate is negligible then the barecounterpart. The minimum value of parabolic rate constant (Kp) was observed in case of Cr_2O_3 -50% Al_2O_3 coated T-22 boiler steel i.e. 0.03 x 10^{-08} $gm^2cm^{-4}s^{-1}$ and maximum for uncoated T-22 boiler steel i.e. 192.19 x 10^{-08} $gm^2cm^{-4}s^{-1}$. Also the overall weight gain (Fig. 5.c) after 50 cycles of oxidation studies for bare T22 steel is 179.73 mg/cm^2 and for the Cr_2O_3 -50% Al_2O_3 coated specimen is 07.014 mg/cm^2. Thus it can be inferred from the weight change graphs that the weight gain in case of coated T22 steel is much lesser than the bare T22 steel. The plots for the uncoated sample show higher weight gain at initial cycles followed by gradual weight gain. In case of Cr_2O_3 -50% Al_2O_3 coated T22 steel; the weight change is almost negligible throughout the study.

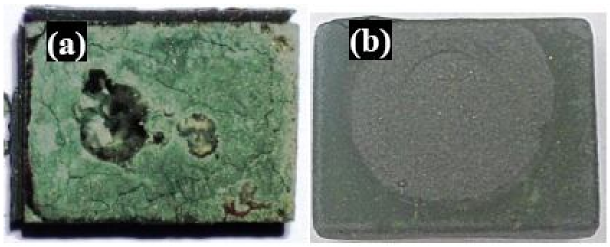

Fig. 4: Macrographs of the Uncoated and Coated Samples Subjected to High Temperature Oxidation in air at 900°C for 50 Cycles: (a) Uncoated T22 Steel; (b) Cr_2O_3 -50% Al_2O_3 Coated ASTM-SA213-T-22 Boiler Steel

Weight Change Kinetics for the Oxidation Studies

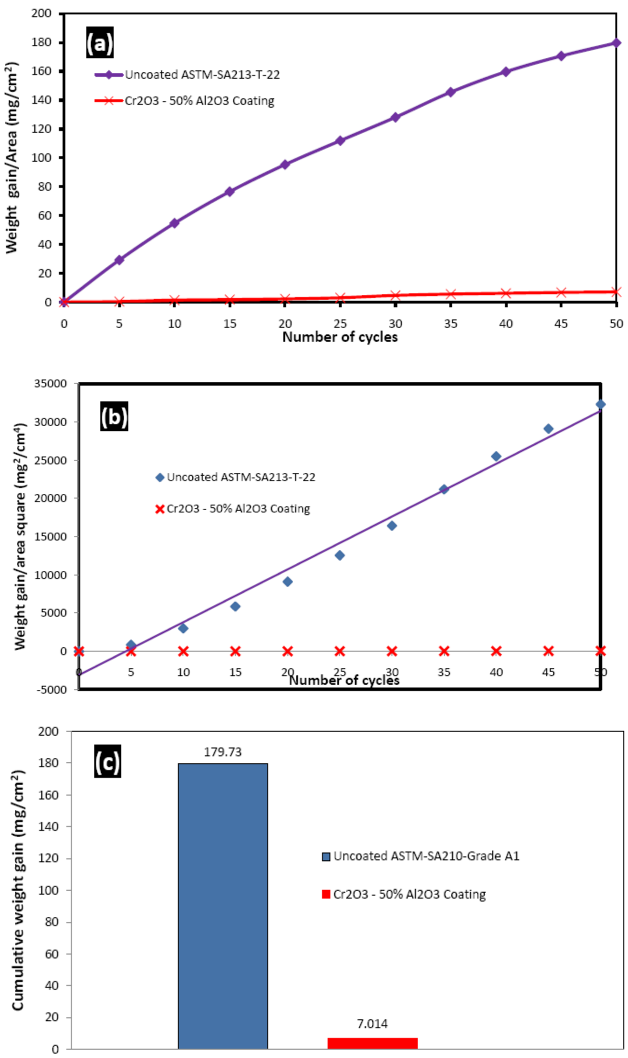

Fig. 5: (a) Weight Change/Area vs. Number of Cycles Plot; (b) (Weight Change/Area)^2 vs. Number of Cycles Plot (c) Cumulative Weight gain; for the Uncoated and D-gun Sprayed Cr_2O_3-50% Al_2O_3 Coating on ASTM-SA213-T-22 Boiler Steel Subjected to High Temperature Oxidation in Air at 900°C for 50 Cycles

Table 3: Parabolic Rate Constant 'Kp' Values of the Uncoated and Coated Samples Subjected to High Temperature Oxidation in Air at 900°C for 50 Cycles

Bare & coated Alloy	$K_p \times 10^{-08} gm^2\ cm^{-4}\ S^{-1}$
Bare T22 boiler steel	19.19
Cr_2O_3 -50% Al_2O_3 $_{Coated}$ T-22 boiler steel	00.03

X-ray Diffraction Analysis of the Scales

The XRD diffractograms (on reduced scale) of the oxide scale for the coated and bare alloy samples exposed to the high temperature oxidation at 900°C for 50 cycles are depicted in Fig. 6. The scale of uncoated T22 steel indicated mainly the presence of Fe_2O_3 and Cr_2O_3 phases (Fig. 6.a). Whereas in case of the Cr_2O_3 -50% Al_2O_3 coated alloy the top scale indicated the presence of Al_2O_3 and Cr_2O_3 phases mainly (Fig. 6. b).

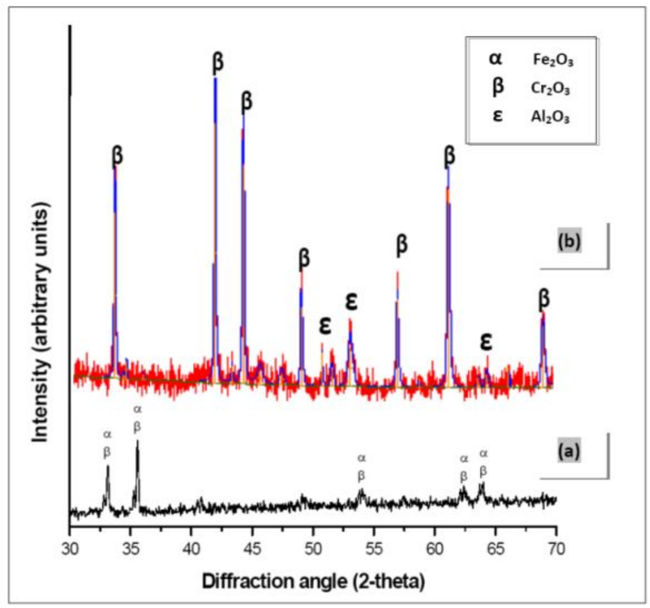

Fig. 6: X-ray Diffraction Pattern for the Bare and D-gun Sprayed Cr_2O_3 -50% Al_2O_3 Coated Samples Subjected to High Temperature Oxidation in Air at 900°C for 50 Cycles: (a) Bare T22 Steel; (b) Coated T-22 Specimen

SEM/EDAX Analysis of the Scales

The SEM micrographs indicating morphology of the bare and the Cr_2O_3 -50% Al_2O_3 coated specimens after being subjected to the high temperature oxidation in air have been shown in Fig. 7. In the case of bare T22 boiler steel (Fig. 7. a) the micrograph shows badly damaged oxide scale with significant spalling of its top layer. The surface scale shows distorted and spalled grains like microstructure. The exposed areas of the scale seem to be dense and presence of deep cracks is also being noticed. At some other locations, the scale has an amorphous appearance. The EDAX analysis reveals that the scale in general is found to be rich in Fe and O, which indicates the possibility of formation of Fe_2O_3

along with small amount of Mo (more at Point 1) and Cr. On the other hand in the case of the Cr_2O_3 -50% Al_2O_3 coated alloy reveals the formation of a homogeneous, massive and free from cracks structure (Fig. 7.b). The surface appearance at microscopic level is almost identical. The EDAX analysis shows the domination of Cr and O in the light grey region (Point 2 of Fig. 7.b.) with small or no traces of Al. Whereas the EDAX analysis of the dark grey region (Point 1 of Fig. 7.b.) of the coating reveals the domination of O and Al with small traces of Cr.

DISCUSSION

The D-gun spray process provides the possibility of deposition of Cr_2O_3 -50% Al_2O_3 coating on the Fe-based alloy i.e. T22 boiler steel; the coating has nearly uniform, adherent and dense microstructure. The microscopic features indicate that the coatings are homogeneous and massive, free from cracks for both of the substrates (Fig. 3). Cr_2O_3 and Al_2O_3 have been identified as the prominent phases by the XRD analysis (Fig. 2) for as-sprayed coating for the as sprayed Cr_2O_3 -50% Al_2O_3 coating on T22 boiler steel by D-gun process. This is further endorsed by the EDAX analysis which shows the dominance of Al, Cr and O in the coating (Fig. 3). There is a presence of some superficial pores in the micro-structure. The weight change plots (Fig. 5 a & b) for the uncoated and coated ASTM-SA213-T-22 boiler steel indicated that the oxidation behavior has shown conformance to parabolic rate law. The parabolic kinetic behavior is due to the diffusion controlled mechanism operating at 900 °C under cyclic conditions [25–30]. Small deviation from the parabolic rate law might be due to the cyclic scale growth. The higher weight gain during the first few cycles might be attributed to the rapid formation of oxides at the splat boundaries and within the open pores due to the penetration of the oxidizing species, further the subsequent increase in weight is gradual [31]. Also in case of coatings; once the oxides are formed at places of porosity and splat boundaries, the coating becomes dense and the diffusion of oxidizing species to the internal portions of the coatings gets slowed down and the growth of the oxides becomes limited mainly to the surface of the specimens. This, in turn, will make the weight gain and hence the oxidation rate steady with the further progress of exposure time [32]. Intense spalling, high corrosion rate, irregular and fragile scale with deep cracks and grey color surface appearance was observed for bare T22 alloy (Fig. 4. a.). The oxidation rate was higher in the case of bare T22 alloy. The severe spalling of the scale for similar type of steel i.e. T22 steel was also observed by Singh [32], Bala *et al.* [33–34] and Chawla *et al.* [25–26] during high temperature oxidation study at 900°C. The surface XRD analysis (Fig. 6.a) indicated the formation of Fe_2O_3 as the main constituent of the top scale in bare T22 alloy after the high temperature oxidation run in air at 900°C for 50 cycles. Similar results were reported by Tiwari and Prakash [35–37] and Singh *et al.* [32] during high temperature corrosion studies of iron-base superalloy at 900°C. The weak peaks of Cr_2O_3 along with major peaks of Fe_2O_3 in the case of bare T22 alloy may be due to the presence of Cr in the alloy steel. Similar results have been reported by Chawla *et al.* [25–28] and Singh [32]. The XRD results are further supported by the surface EDAX analysis (Fig. 7. a). The presence of Cr might have led to control the oxidation rate in the case of T22 alloy as chromium is present in the oxide scale along with oxygen (Fig. 7.a). Similar results were reported by Sididue *et al.* [38]. The authors have reported that Fe–Cr alloys in oxygen at higher temperature (950–1050°C) form spinel ($FeCr_2O_4$ and Cr_2O_3) on the inner side and Fe_2O_3 on the outerside of the scale. Both the uncoated and coated alloys showed near parabolic behavior with a transition in their Kp values (Table 3). The parabolic rate constant Kp were obtained from the slope of the linear regression fitted line (cumulative weight gain/area)^2 vs. number of cycles. It is clear that in spite of some fluctuations in the data for the uncoated alloy; the data conforms to the parabolic rate law to an acceptable limit for both the alloys. The maximum value of parabolic rate constant (Kp) was observed in case of uncoated T-22 boiler steel i.e. 19.19 x 10^{-08} $gm^2cm^{-4}s^{-1}$. The D-gun spray Cr_2O_3 -50% Al_2O_3 coated alloy has shown better corrosion resistance than its uncoated counterpart. The Cr_2O_3 -50% Al_2O_3 coating was successful to reduce the oxidation rate of the T22 steel by 96%, in terms of overall weight gains (Fig. 5.c.). In case of Cr_2O_3 -50% Al_2O_3 coated T22 alloy; the weight change was almost negligible throughout the study. The Cr_2O_3 and Al_2O_3 generally regarded as the best protective oxides, with relatively slow diffusion compared to other oxides [39]. As reported by Schutze *et al.* [40], a common feature of Al-based coatings is that they act as a reservoir phase for the formation of protective and slow growing Al-based oxide scales by reaction with the operation environment, thus providing an environment barrier against the ingress of more aggressive species down to the metal to be protected and slowing down metal consumption rates by the oxidation process itself. Furthermore, the coated steel followed the parabolic law, which indicates that the scales formed have shown the tendency to act as diffusion barrier to corrosive species. This shows the corrosion protective behavior of the Cr_2O_3 -50% Al_2O_3 coating. The minimum value of parabolic rate constant (Kp) was observed in case of Cr_2O_3 -50% Al_2O_3 coated T-22 boiler steel i.e. 0.03 x 10^{-08} $gm^2cm^{-4}s^{-1}$ and maximum for uncoated T-22 boiler steel i.e. 19.19 x 10^{-08} $gm^2cm^{-4}s^{-1}$.

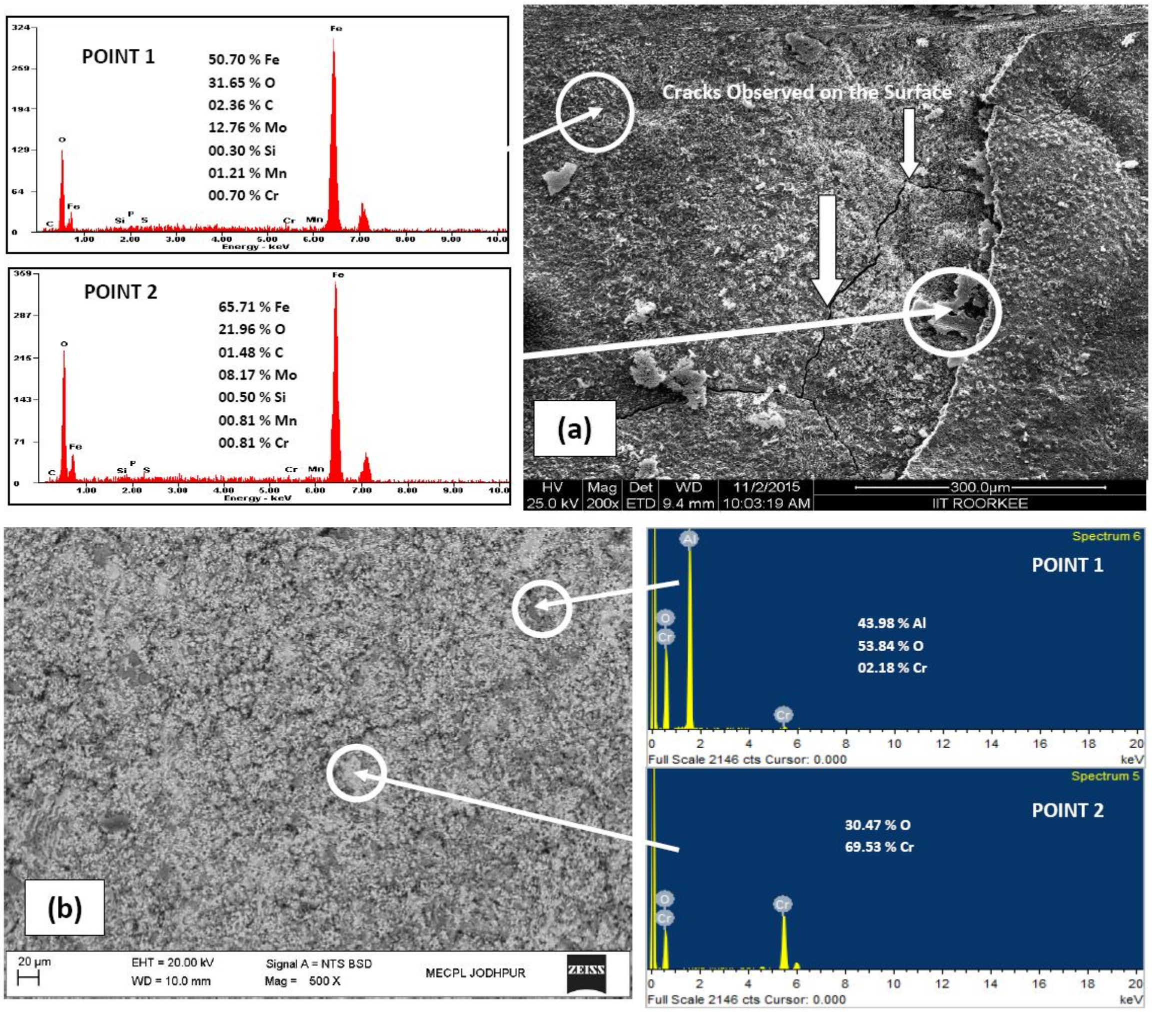

Fig. 7: Surface Scale Morphology and EDAX Analysis Showing Elemental Composition (wt%) at Selected Points for the Bare and D-gun Sprayed Cr_2O_3 -50% Al_2O_3 Coated Samples Subjected to High Temperature Oxidation in Air at 900°C for 50 Cycles: (a) Bare T22 Steel; (b) Coated T-22 Specimen

CONCLUSIONS

1. Cr_2O_3 -50% Al_2O_3 ceramic powders was successfully sprayed on Fe based alloys namely T-22 boiler steel by the D-gun spray process, which resulted in a coating which has nearly uniform, adherent and dense microstructure.
2. The bare T22 boiler steel showed enormous weight gain, high corrosion rate, irregular and fragile scale with deep cracks, grey color surface appearance and substantial spallation of their oxide scales during high temperature oxidation studies at 900°C. The D-gun sprayed Cr_2O_3 -50% Al_2O_3 coated T-22 substrate when subjected to high temperature oxidation at 900°C; was found to be successful in maintaining its adherence with the substrate steels. The oxide scales were also found to be intact and there was no indication of spalling in both the cases.
3. The Cr_2O_3 -50% Al_2O_3 coating was successful to reduce the corrosion rate of the T22 steel by 96%, in terms of overall weight gains. In case of Cr_2O_3 -50% Al_2O_3 coated T22 alloy; the weight change is almost negligible throughout the study than the bare counterpart.
4. The D-gun spray coated Cr_2O_3 -50% Al_2O_3 coating was found to be very useful in developing high temperature oxidation resistance in T22 alloys.

REFERENCES

[1] Wortel, J.C. Van, Etienne, C.F. and Arav, F. (1992), "Application of Modified 9chromium Steels in Power Generation Components, in: VDEh ECSC Information Day", *The Manufacture and Properties of Steel 91 for the Power Plant and Process Industries, Dusseldorf*, 5th November, paper 4.2.

[2] Fujita, T. (1992), "Current Progress in Advanced High Cr Steel for High Temperature Applications", *ISIJ Int*., Vol. 32(2), p. 175.

[3] Birchenall, G.E. (1981), "A Brief History of the Study of Oxidation of Metals and Alloys", in: *High Temperature Corrosion, Proceedings, NACE*, San Diego, CA, p. 3.

[4] Jones, D.A. (1996), *Principles and Prevention of Corrosion*, second ed., Prentice Hall, USA, 1996.

[5] Kofstad, P. (1988), "High-temperature Corrosion, Elsevier Applied Science", London, pp. 382–385 (Chapter 11).

[6] Link, R.J., Birks, N., Pettit, F.S. and Dethorey, F. (1998), "The Response of Alloys to Erosion–corrosion at High Temperatures", *Oxid. Met*., Vol. 49(3–4), pp. 213–236.

[7] Saeki, I., Saito, T., Furuichi, R. and Itoh, M. (1998), "Growth Process of Protective Oxides Formed on Type 304 and 430 Stainless Steels at 1273°K", *Corros. Sci*., Vol. 40(8), p. 1295.

[8] Jianian, S., Longjiang, Z. and Tiefan, L. (1997), "High Temperature Oxidation of Fe–Cr Alloys in Wet Oxygen", *Oxid. Met.*, Vol. 48(3, 4), p. 347.

[9] Tokei, Z., Viefhaus, H. and Grabke, H.J. (2000), "Initial Stages of Oxidation of a 9CrMoV Steel: Role of Segregation and Martensite Laths", *Appl. Surf. Sci.*, Vol. 165(1), p. 23.

[10] Greeff, A.P., Louw, C.W. and Swart, H.C. (2000), "The Oxidation of Industrial FeCrMo Steel", *Corros. Sci*., Vol. 42(10), p. 1725.

[11] Arztegui, A., Gomez-Acebo, T. and Castro, F. (2000), "Steam Oxidation of Ferritic Steels: Kinetics and Microstructure", *Bol. Soc. Esp. Ceram. Vidr*., Vol. 39(3), p. 305.

[12] Khanna, A.S., Rodriguez, P. and Gananamoorthy, J.B. (1986), "Oxidation Kinetics, Breakaway Oxidation and Inversion Phenomenon in 9Cr–1Mo Steels", *Oxid. Met*., Vol. 26(3,4), p. 171.

[13] Laverde, Dionisio, Gomez-Acebo, Tomas and Castro, Francisco (2003), "Continuous and Cyclic Oxidation of T-91 Ferritic Steel Under Steam", *Corrosion Science*, Vol. 46, 2 July 2003, pp. 613–631.

[14] Gurrappa, I. and Rao, A.S. (2006), "Thermal Barrier Coatings for Enhanced Efficiency of Gas Turbine Engines", *Surf Coat Tech*, Vol. 201, pp. 3016–3029.

[15] Sidhu, B.S. and Prakash, S. (2006), "Erosion-Corrosion of Plasma as Sprayed and Laser Remelted Setallit-6 Coatings in a Coal Fired Boiler", *Wear*, Vol. 260, pp. 1035–1044.

[16] Wang, B.Q. and Lee, S.W. (1997), "Elevated Temperature Erosion of Several Thermal Sprayed Coatings under the Simulated Erosion Conditions of in-bed Tubes in a Fluidized Bed Combustor", *Wear*, Vol. 203–204, pp. 580–587.

[17] Wang, B. and Lee, S.W. (2000), "Erosion-corrosion Behavior of HVOF NiAl-Al_2O_3 Intermetallic Ceramic Coating", *Wear*, Vol. 239(1), pp. 83–90.

[18] Wang, B.Q. (1996), "Effect of Alkali Chlorides on Erosion-corrosion of Cooled Mild Steel and Cr_3C_2-NiCr Coating", *Wear*, Vol. 199, pp. 268–274.

[19] Wang, B.Q. and Shui, Z.R. (2002), "The Hot Erosion Behavior of HVOF Chromium Carbide-metal Cermet Coatings Sprayed with Different Powders", *Wear*, Vol. 253, pp. 550–557.

[20] Rhys-Jones, T.N. and Swindells, N. (1985), "The High Temperature Corrosion of a Commercial Aluminide Coating on IN738-LC and MarMOO2 at 700°C and 830°C", *Corros. Sci.*, Vol. 25(7,) pp. 559–576.

[21] Bala, N., Singh, H. and Prakash, S. (2010), "High Temperature Corrosion Behavior of Cold Spray Ni-20Cr Coating on Boiler Steel in Molten Salt Environment at 900°C", *J. Thermal Spray Technol.*, Vol. 19(1-2), pp. 110–118.

[22] Ul-Hamid, A. (2003), "Diverse Scaling Behavior of the Ni-20Cr Alloy", *Mater. Chem. Phys.*, Vol. 80, pp. 135–142.

[23] Sidhu, B.S. and Prakash, S. (2003), "Evaluation of the Corrosion Behaviour of Plasma-Sprayed Ni3Al Coatings on Steel in Oxidation and Molten Salt Environments at 900°C", *Surf. Coat. Technol.*, Vol. 166, pp. 89–100.

[24] Singh, H., Puri, D. and Prakash, S. (2005), "Some Studies on Hot Corrosion Performance of Plasma Sprayed Coatings on a Fe-Based Superalloy", *Surf. Coat. Technol.*, Vol. 192, pp. 27–38.

[25] Chawla, V., Chawla, A., Sidhu, B.S., Prakash, S. and Puri, D. (2011), "Performance of Nanostructured Metal Nitride Coated T-22 Boiler Steel in Na_2SO_4–60% V_2O_5 Environment at 900°C under Cyclic Conditions", *J Minerals Mater. Character. Eng.*, Vol. 10(7), pp. 583–608.

[26] Chawla, V., Chawla, A., Sidhu, B.S., Prakash, S. and Puri, D. (2010), "Oxidation Behavior of Nanostructured TiAlN and AlCrN Thin Coatings on ASTM-SA213-T-22 Boiler Steel", *J Minerals Mater. Character. Eng.",* Vol. 9(11), pp. 1037–1057.

[27] Chawla, V., Puri, D., Prakash, S., Chawla, A. and Sidhu, B.S. (2009), "Characterization and Comparison of Corrosion behavior of Nanostructured TiAlN and AlCrN Coatings on Superfer 800H (INCOLOY 800H) Substrate", *J. Minerals Mater. Character. Eng.*, Vol. 8(9), pp. 715–727.

[28] Chawla, V., Prakash, S., Puri, D.D. and Singh, B. (2008), "Performance of Plasma Sprayed Nanostructured and Conventional Coatings", *J. Aus. Ceramic Soc.*, Vol. 44(2), pp. 56–62.

[29] Singh, H., Prakash, S. and Puri, D. (2007), "Some Observations on the High Temperature Oxidation Behaviour of Plasma Sprayed Ni_3Al Coatings", *Mater. Sci. Engg. A.*, Vol. 444, pp. 242–250.

[30] Mahesh, R.A., Jayaganthan, R. and Prakash, S. (2009), "Microstructural Characteristics and Mechanical Properties of HVOF Sprayed NiCrAl Coating on Superalloys", *J. Alloys and Compounds*, Vol. 468, pp. 392–405.

[31] Singh, H., Puri, D. and Prakash, S. (2005), "Corrosion Behaviour of Plasma Sprayed Coatings on a Ni-base Superalloy in Na_2SO_4-60%V_2O_5 Environment at 900°C", *Metall. Mater. Trans. A.*, Vol. 36(4), pp. 1007–1015.

[32] Singh, H., Prakash, S. and Puri, D. (2007), "Some Observations on the High Temperature Oxidation Behaviour of Plasma Sprayed Ni_3Al Coatings", *Mater. Sci. Engg. A.*, Vol. 444, pp. 242–250.

[33] Singh, B. (2003), "Studies on the Role of Coatings in Improving Resistance to Hot Corrosion and Degradation", *Ph.D. Thesis*, IITR, Roorkee, India; 2003.

[34] Bala, N., Singh, H. and Prakash, S. (2010), "Accelerated Hot Corrosion Studies of Cold Spray Ni–50Cr Coating on Boiler Steels", *Mater. Design*, Vol. 31, pp. 244–253.

[35] Tiwari, S.N. and Prakash, S. (1996), "Hot Corrosion Behaviour of an Iron-Base Superalloy in Salt Environment at Elevated Temperatures", *Proc. of Sympos. Metals and Materials Research,* Indian Institute of Technology Madras, Madras, 4–5th July, pp. 107–117.

[36] Tiwari, S.N. and Prakash, S. (1997), "Studies on the Hot Corrosion Behaviour of Some Superalloys in Na_2SO_4-V_2O_5", *Proc. of SOLCEC*, Kalpakkam, India, 22-24th Jan., Paper C33.

[37] Tiwari, S.N. and Prakash, S. (1998), "Literature Review-Magnesium Oxide as Inhibitor of Hot Oil Ash Corrosion", *Mater. Sci. Technol.*, Vol. 14, pp. 467–172.

[38] Sadique, S.E., Mollah, A.H., Islam, M.S., Ali, M.M., Megat, M.H.H. and Basri, S. (2000), "High Temperature Oxidation behavior of Iron–chromium–aluminum Alloys", *Oxid. Met.*, Vol. 54(5–6), pp. 385–400.

[39] Roure, S., Czerwinski, F. and Petric, A. (1994), "Influence of CeO_2-coating on High Temperature Oxidation of Chromium", *Oxid. Metals*, Vol. 42(1), pp. 75–102.

[40] Schutze, M., Malessa, M., Rohr, V. and Weber, T. (2006), "Development of Coatings for Protection in Specific High Temperature Environments", *Surf. Coat. Technol.*, Vol. 201, pp. 3872–3879.

[41] Kamal, S., Jayaganthan, R., Prakash, S. and Kumar, S. (2008), "Hot Corrosion behavior of Detonation Gun Sprayed Cr_3C_2–NiCr Coatings on Ni and Fe-based Superalloys in Na_2SO_4–60% V_2O_5 Environment at 900°C", *J Alloys Compd*., Vol. 463(1), pp. 358–372.

[42] Stott, F.H. (1998), "Principles of Growth and Adhesion of Oxide Scales", In: Lang E, editor. *The Role of Active Elements in the Oxidation Behaviour of High Temperature Metals and Alloys"*, London: Elsevier Applied Science.

[43] Li, L., Zhu, R. and Gesmundo, F. (1996), "Hot Corrosion of Iron in the Presence of Salt Mixture Deposit containing NaCl and V_2O_5 at 600^0C", *J. Mater. Sci. Technol.*, Vol. 12(6), pp. 445–451.

[44] Sundararajan, S., Kuroda, F. and Abe (2004), "Behaviour of Mn and Si in the Spray Powders During Steam Oxidation of Ni-Cr Thermal Spray Coatings", *ISIJ Int.*, Vol. 44, pp. 139–144.