

## Comparison on cyclic air oxidation and synthetic molten salt corrosion for bimetallic compound employed in power plant environment

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**Abstract:** The cyclic high temperature corrosion studies on bimetallic compound of Inconel 625 and stainless steel 316L were investigated in the present study. Investigations have been carried out by subjecting this bimetallic compound under air oxidation and  $K_2SO_4 + 60\% NaCl$  aggressive environmental conditions at 650 °C. The corrosion kinetics has been established by thermo-gravimetric technique. In this work, Scanning Electron Microscopy/Energy-Dispersive X-ray Spectroscopy analysis (SEM/EDS) was used to characterise the hot corroded samples. The results showed that the corrosion resistance of bimetal interface was found to be less, in molten salt environment. In addition, the SEM/EDS results witnessed changes in reaction rate associated with formation of a laminated and inner-oxide layer which contains both fine and coarse grain spinel oxide.

**Keywords:** Hot corrosion; Air oxidation; synthetic molten salt; Bimetallic compound.

### 1. Introduction

Low-grade fuels with high concentrations of sulphur, vanadium and sodium are often used for firing industrial processes which results in severe corrosion attack by oxidation, sulfidation and chloridation<sup>1</sup>. The industries at off-shore rigs undergo hot corrosion when the sodium chloride from the ocean breeze mixes with sulphates from the fuel and deposits on hot-section of the components. This leads to accelerated attack on the components. The hot corrosion often increases the corrosion loss of heat resisting components by over hundred times<sup>2</sup>. The gas turbines operating in a marine environment, NaCl is injected into the turbines predominantly as an aerosol of sea salt together with the intake air. Thus, hot corrosion induced by NaCl seems to be a very important problem when the components exposed in these aggressive environments<sup>3</sup>.

Studies of hot corrosion induced by mixtures of NaCl/ $K_2SO_4$  have generally focused on Ni- and Co-base super alloys and Ni-Cr alloys used in turbine engines or gas turbines<sup>4,5</sup>. Arivazhagan et al.<sup>6</sup> reported that the most severe hot corrosion attack is observed on bimetal interface even at 600 °C in air as well as molten salt environment. Arivarasu et al.<sup>7</sup> studied the high temperature corrosive behaviour of gas tungsten arc welded AISI 4140 and AISI 304 in air-oxidation, molten salt environment of  $Na_2SO_4$ -60%  $V_2O_5$  and  $Na_2SO_4$ -60% NaCl at 650°C under cyclic condition. The investigations on the performance of GTA welded dissimilar AISI 304 and AISI 310S subjected to cyclic hot corrosion was reported by Devendranath Ramkumar et al.<sup>8</sup>.

Bimetallic component fabricated by Inconel 625 and austenitic stainless steels were employed by NASA for the construction of sub-scale boilers. These boilers were tested to investigate the boiling stability after being operated with boiling NaK for 791.4 hr at temperatures from 700 to 750 °C. Further, Johnson et al.<sup>9</sup> and Bourshis et al.<sup>10</sup> reported that these combinations could be employed in oil-refinery converters where the temperature can reach to 1050 °C and the atmosphere is highly carburizing and oxidizing.

As evident from the open literatures, the scope and application for these bimetallic joints requires thorough analysis in terms of their high temperature corrosion resistance in aggressive chemical and power plant environments. The present study features on the bimetallic joint of Inconel 625 and stainless steel 316L employing by ER2209 filler in air oxidation and molten salt environment at cyclic condition.

The performance of individual alloys in these combinations in oxidizing environments is well established, but its bimetallic compound behaviour in corrosive environments, particularly under eutectic mixture of NaCl(60%) and K<sub>2</sub>SO<sub>4</sub>(40%) is not focused. Both kinetics evolution and morphological development are investigated by means of thermal gravimetric analyses, measurements of corrosion attack, metallographic examination and the identification of the corrosion products. The relationship between the corrosion morphology and composition of deposited salt layers is also explored.

## 2. Experimental procedure

### 2.1. Cyclic hot corrosion studies

The chemical composition of the individual materials employing in the bimetallic compound is represented in Table 1. Cyclic hot corrosion studies were performed at the various zones of the bimetallic compound by exposing them in air and molten salt environment containing K<sub>2</sub>SO<sub>4</sub> + 60% NaCl for about 50 cycles. Each cycle constitutes 1 h heating followed by 20 min of cooling to room temperature.

A coating of uniform thickness with 3–5 mg/cm<sup>2</sup> of K<sub>2</sub>SO<sub>4</sub> + 60% NaCl was applied using a fine camel hair-brush on the individual coupons before corrosion cycles. The salt coated samples were initially heated and dried at 200 °C in the oven. The weight changes were measured at the end of every cycle using electronic weighing balance with a sensitivity of 0.1 mg. The weight gain or loss of the spalled scale was also included at the time of measurement to determine the rate of corrosion. The corroded samples were characterized for SEM/EDAX analysis to establish the hot corrosion mechanism.

## 3. Results and discussion

### 3.1. Physical observations

The physical observation of hot corroded samples after 50 cycle exposure in air and molten salt environment is represented in Fig 1 (a-f). It clearly envisaged the more corrosion attack in the interface of bimetallic joint when exposed in molten salt environment at the end of 50 cycle (Fig 1(e)). However, the effect of air oxidation is less prone to corrosion. In addition, there is less significant corrosion attack is witnessed in the parent metals.

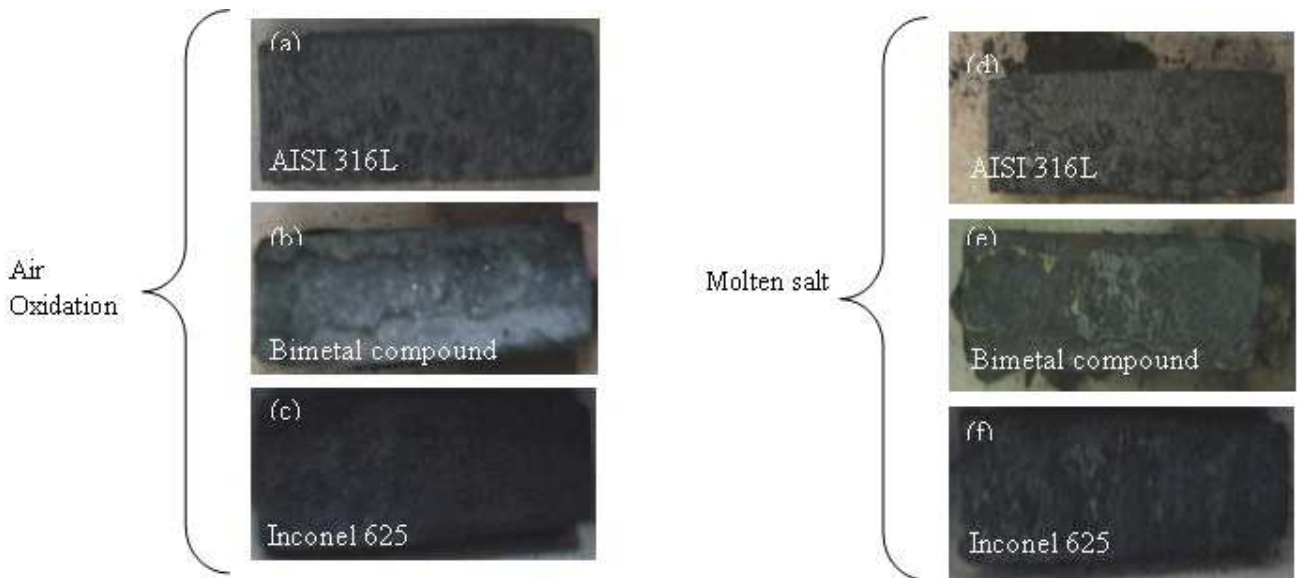
### 3.2. Thermo gravimetric analysis

The corrosion kinetics of parent and bimetallic joint exposed in air and molten salt environment is represented in Fig 2 as a plot of weight gain per unit area vs. function of time (number of cycles). In general, the corrosion kinetics for both environments witnessed a steady-state parabolic rate law. The weight gain square (mg<sup>2</sup>/cm<sup>4</sup>) vs time (number of cycles) plots are shown in Fig 3 to establish the corrosion rate. The parabolic rate constant, K<sub>p</sub>, was calculated by a linear least-square algorithm to a function in the form of  $(W/A)^2 = K_p t$ , where W/A is the weight gain per unit surface area (mg/cm<sup>2</sup>) and t indicates the number of cycles representing the time of exposure and is shown in Table 2.

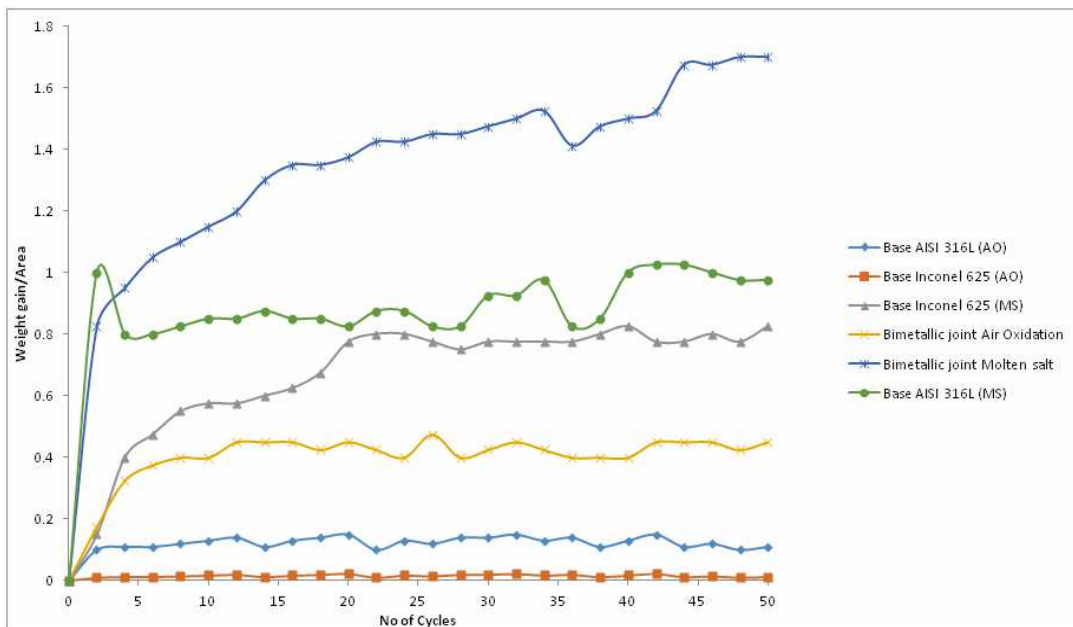
It is observed from the thermo gravimetric data that the weight changes are found to be more in the bimetallic compound exposed under molten salt environment (0.0428 mg<sup>2</sup>/cm<sup>4</sup>/h) as compared to other zones of the weldments which is represented in Table 2. In general, both parent metals in air oxidation exhibited less weight gain. Whereas the weight gain corrosion under mixed salt environment is found to be pronounced effect. In which the initial corrosion rate was found to be higher which slowly reduced and showing parabolic behaviour. Based on the magnitude of weight gain, bimetallic compound is found to undergo accelerated corrosion in molten salt environment, which was also optioned by Arivrasu *et al.*<sup>7</sup> and Devendranath *et al.*<sup>8</sup>. Further, it was also witnessed from photographs which depicted more degradation near the interface of bimetallic compound with the grains fully degraded (Fig 1 b, e).

**Table 1.** The chemical composition of taken materials.

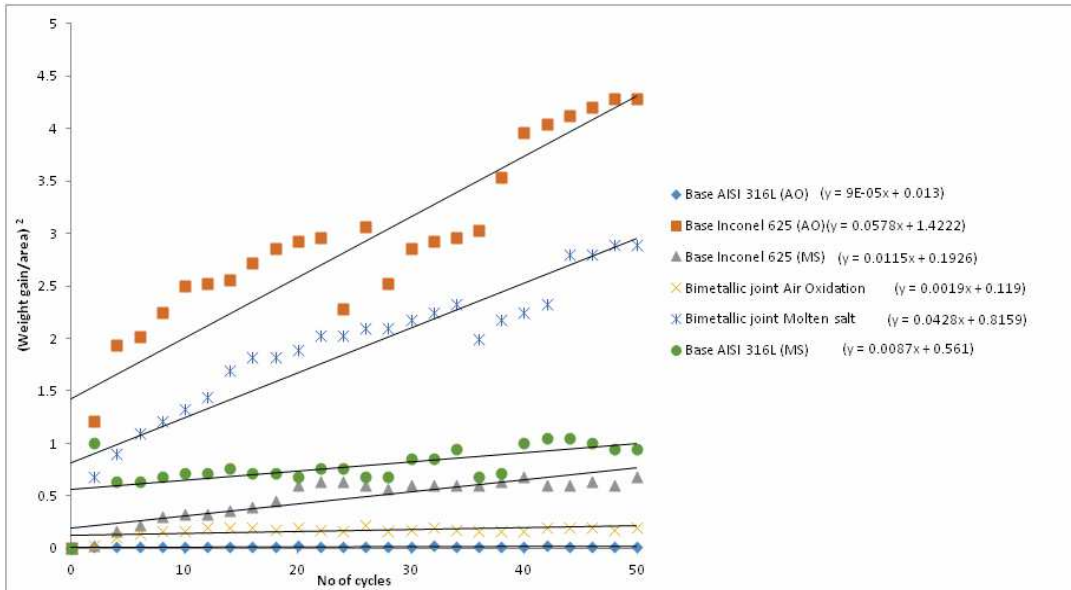
	Ni	Cr	Mo	Fe	Nb+Ta	C	Mn	Si	P	S
Inconel 625	58.0	20.0	8.0	5.0	4.15	0.10	0.50	0.50	0.015	0.015
AISI 316L	12.0	16.00	2.00	62.00		0.03	2	0.75	0.045	0.03
ER2209	8.5	23	3.1	--	--	0.02	1.6	0.5	--	--



**Fig 1.** Macrograph of hot corroded samples (a-c) Air oxidation; (d-f) molten salt environment



**Fig 2.** Thermo gravimetric graph for hot corroded bimetallic compound in air oxidation and molten salt environment at 650 °C



**Fig 3.** The rate of corrosion for hot corroded bimetallic compound in air oxidation and molten salt environment at 650 °C

**Table 2.** The corrosion rate for base and bimetallic joint after exposed in air and molten salt environment after 50 numbers of cycles.

Environments	Test coupon	$K_p=(\Delta W/A)^2$ (mg <sup>2</sup> .cm <sup>-4</sup> /h)
Air oxidation	Base Inconel 625	0.0578
	Base stainless steel 316L	0.00009
	Bimetallic compound	0.0019
Molten salt	Base Inconel 625	0.0115
	Base stainless steel 316L	0.0087
	Bimetallic compound	0.0428

### 3.3 SEM/EDS analysis

SEM/EDS analysis on the bimetallic compound after corrosion cycle in air oxidation environment is represented in Fig 4. It is evident that the scale on the inconel 625 contains the continuous oxide layer of Cr and Ni which enhanced the corrosion resistance. In contrast stainless steel 316L is porous in nature which leads to less corrosion resistance.

The SEM/EDS results of bimetallic compound exposed in molten salt environment is shown in Fig 5. It is witnessed that the oxide of Cr, Ni and Fe is found to be less in weld zone. It ensures that the protective oxide layer allowed the oxygen which enhanced the corrosion rate. On the other hand, the oxide of Cr is predominated in the interface after exposed in air oxidation which influenced the reduction of corrosion rate.

In general, the EDS results witnessed the formation of scale that is continuous and protective in nature in the parent metal when exposed in both environment which has been successful in reducing the overall corrosion rate as compared to bimetallic compound. On the other hand, spallation of protection oxide in the bimetallic compound due to variation in thermal coefficient expansion of parent metals and scale enhanced their corrosion rate. It is also widely agreed that the corrosion rate will be more when the temperature is higher than the melting point of salt deposits.



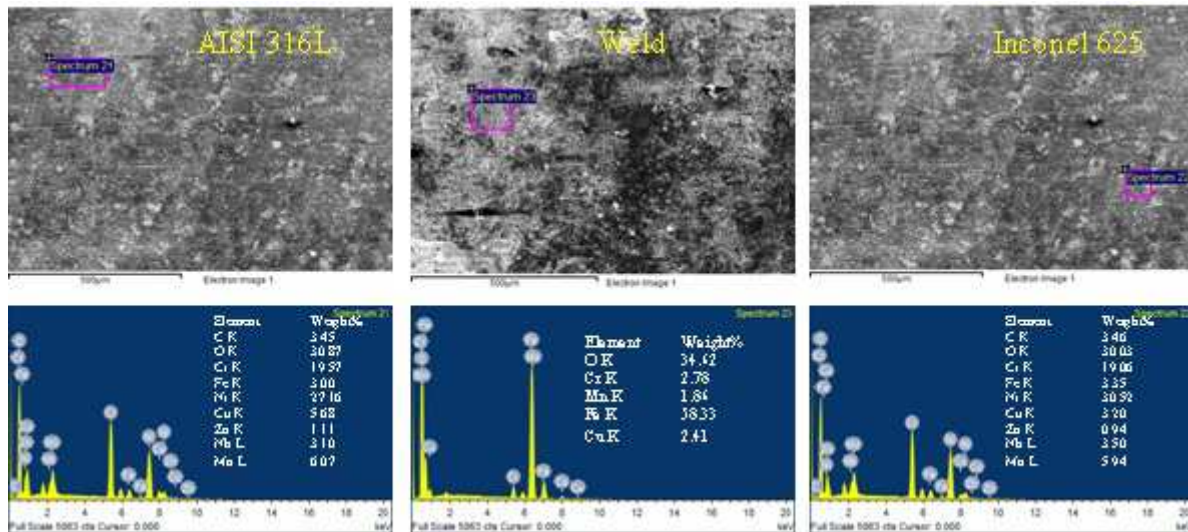


Fig.4. SEM/EDS point analysis on the hot corroded bimetallic joint subjected to air oxidation at 650°C

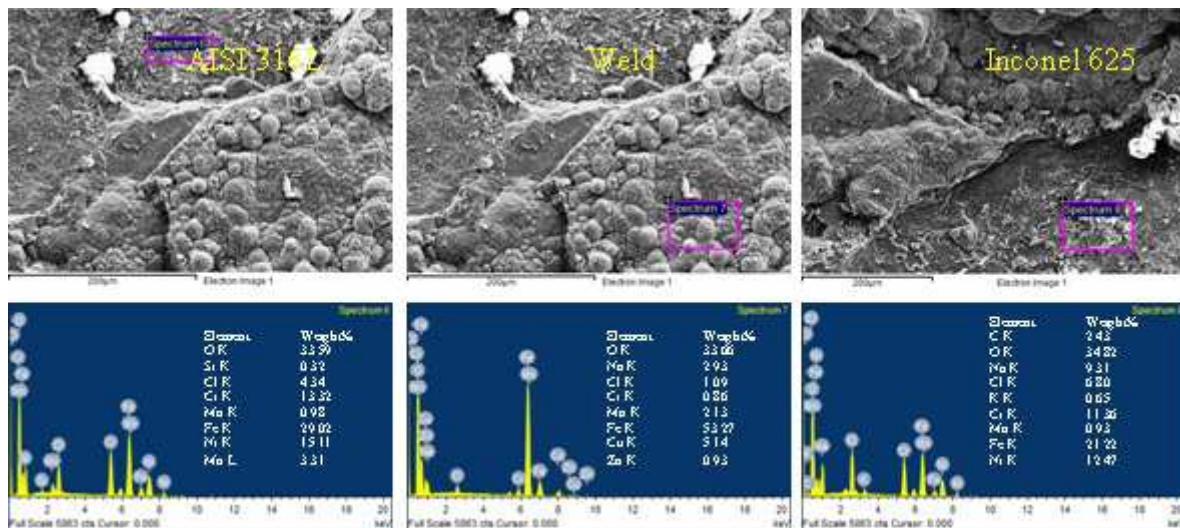


Fig.5. SEM/EDS point analysis on the hot corroded bimetallic joint subjected to molten salt environment containing  $K_2SO_4+60\% NaCl$  at 650°C

#### 4. Conclusion

- The composition variation in the bimetallic interface plays a major role on the high temperature corrosion resistance.
- EDS results showed that the scale predominated with continuous oxide of Cr in the parent metals could be influenced by the higher corrosion resistance.
- The corrosion rate of bimetallic interface is found to be higher (20 times) when exposing in mixed salt environment as compared to air oxidation.
- The accelerated corrosion trend is observed in the bimetallic joint in molten salt environment due to the galvanic type of corrosion arising out of heterogeneity in composition.
- The hot corrosion in air and molten salt mixture of  $K_2SO_4 - 60\%NaCl$  environment follows parabolic rate constant.

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