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Hot Corrosion Behaviour of Inconel 617 in Mixed Salt Environment at 900 and 1000 °C for Gas Turbine Applications

Abstract: An attempt is made to study the hot corrosion behaviour of Inconel 617 under mixed salt environment (Na_2SO_4, NaCl and/or V_2O_5) at 900 and 1000 °C. The results were analysed and discussed with respect to mass change, XRD, optical image and SEM/EDAX. The oxide scales are enriched with Ni, Cr, Mo and Co at elevated temperatures. The presence of V_2O_5 in the salt mixture is found to be the most influencing corrosion species for hot corrosion.

Keywords: hot corrosion, superalloy, oxides, SEM/EDAX, XRD

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1 Introduction

Engines for aviation applications in marine environments are generally considered to be highly reliable at high operating temperatures. Carter [1] made an effort to explain the common failures of modern aviation gas turbine engines. Both compressor and turbine blades are exposed to aggressive corrosive environment containing sodium chloride, in the form of salt from sea water or marine environment. Most of the gas turbine components are susceptible to hot corrosion due to many factors, which include temperature, cyclic loading conditions, alloying elements, impurities like sulphur, sodium, vanadium, potassium, lead and molybdenum from the fuel, and various halides from seawater are ingested into turbine engine during combustion [2–8]. The sulphur and other impurities from the aviation fuel get deposited in the form of Na_2SO_4 and or V_2O_5 on the hot section of turbine components working at elevated temperatures along with the sodium chloride coming from seawater [9, 10].

In this paper, the hot corrosion behaviour of Inconel 617 was studied to simulate the gas turbine environment at 900 and 1000 °C.

2 Experimental procedure

2.1 Material and method

The Inconel 617 with a chemical composition given in Table 1 is considered as a candidate for hot corrosion studies simulating gas turbine environment. The samples were sliced and polished with SiC papers down to 1000 grit, cleaned sequentially in acetone and then dried in hot air.

Samples after preparation were exposed to corrosive environment and evaluated as per the ASTM G111-97. The salt mixtures are prepared with Na_2SO_4, NaCl and/or V_2O_5 (75+25; 75+22+3 and 75+20+5) in respective three proportions. The salt mixtures are applied in a concentration of 3–5 mg/cm^2 on the calculated surface area. The samples were then kept on the ceramic boats and preheated (upto 250 °C) in a tubular furnace to eliminate the moisture content in the salt. After preheating, the samples were weighed along with the boats and then placed in the furnace at 900 and 1000 °C respectively for an interval of two hours each. After a soaking time of two hours, the samples were air cooled and measured for mass change considering the spalling of oxide scale also. The same procedure was repeated for 25 cycles of two hours each completing 50 hours.

2.2 Testing and evaluation

The samples exposed to corrosive environment were removed from the furnace and cooled at room temperature

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Table 1: The chemical composition of Inconel 617

Inconel 617	Ni	Cr	Co	Mo	Fe	Al	Mn	C	Si, Ti, Cu & B
Element wt%	54.50	21.25	12.20	7.82	1.90	1.05	0.08	0.06	Traces

to measure the mass change for predetermined hours. After mass change measurements, the microstructural features like oxide scale, micro cracks/pores, etc. were examined using optical and scanning electron microscope. EDAX and XRD analyses were also carried out to determine the element and oxides enriched on the surface of the exposed samples.

3 Results and discussion

3.1 Mass change

The mass change plot for the substrate with respect to the time is shown in Figure 1. In the presence of V_2O_5 the rapid increase in mass change was observed and in the absence of V_2O_5 gradual increase in mass change at both the temperatures. The vanadate in combination with sulphur and chlorides accelerated the corrosion rate by forming eutectic mixture above 650 °C. Initially, the surface exposed to corrosive environment starts to oxidize and oxide layers are formed with micro pores/cracks. This can be explained as follows: molten vanadates during oxidation, deposited on the metal surface can flux oxide scales and passive layers at higher temperature. At the elevated temperature, vanadate accelerates the diffusion of oxygen through fused salt on the metal surface [11]. The oxide scales start to spall on prolonged exposure and the corroding species start to attack the adjacent layer of the metal surface to continue the same. The cumulative mass change in the presence of vanadate is twofold at both the temperatures than in Na_2SO_4 and NaCl. The experimental results obtained are thoroughly studied and explained through SEM, XRD and EDAX in the following sections.

3.2 Surface morphology

The surface morphology of the oxide scale on the samples exposed to corrosive environment at elevated tempera-

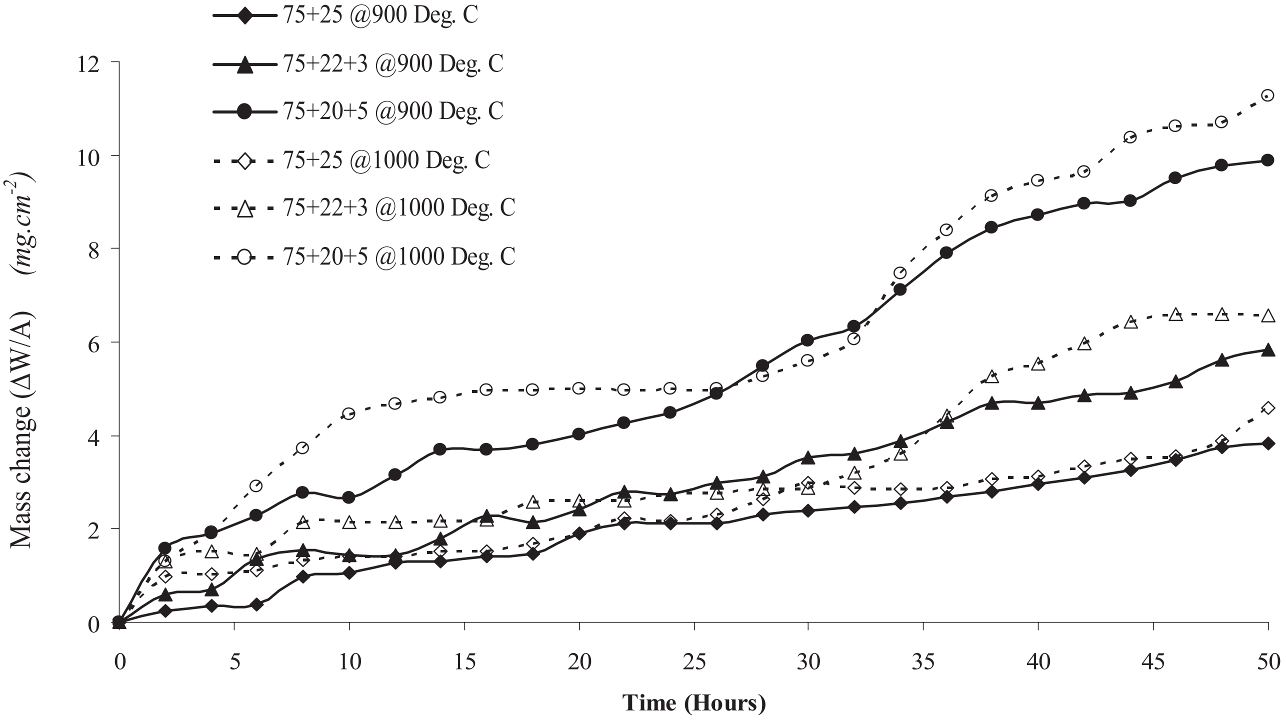
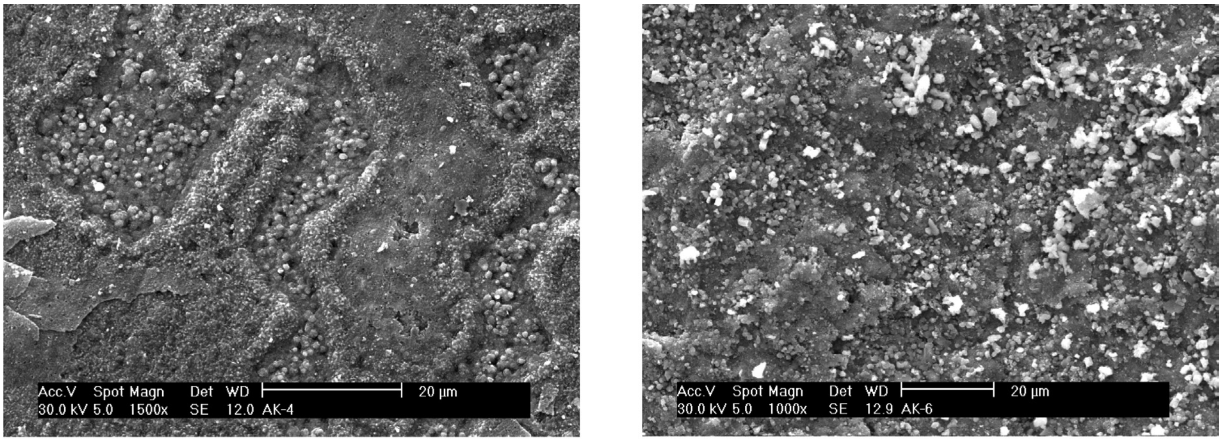


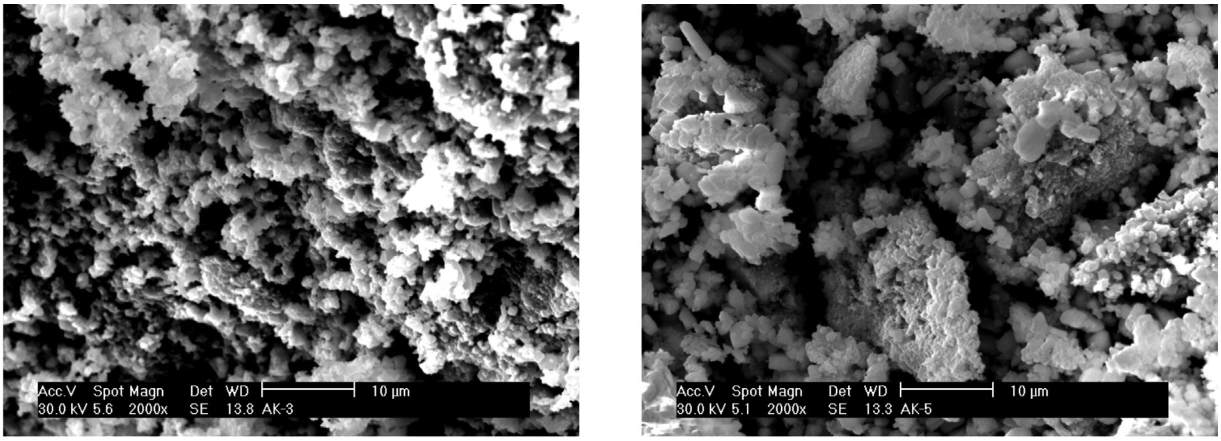
Fig. 1: Mass change in cyclic hot corrosion with respect to exposed time (hours).



(a)

(b)

Fig. 2: (a) Wrinkling and spalling of oxide scale at 900 °C without V_2O_5 in salt mixture. (b) Oxides scale with micro pores on the surface of the samples with V_2O_5 in salt mixture



(a)

(b)

Fig. 3: Samples exposed to corrosive environment at 1000 °C (a) without V_2O_5 in salt mixture and (b) with V_2O_5 in salt mixture

tures is evaluated with the scanning electron microscope (SEM) images. Figure 2 shows the SEM images of oxide scales of sample exposed at 900 °C. It is clearly observed that the oxide formed has nodular structure. Wrinkling and spalling of oxides were observed on the surface of the samples (Figure 2a). Scale wrinkling and spalling of oxides are due to the lateral oxide growth within the scale due to the compressive force [11]. Sample with the presence of vanadium in the salt mixture shows more uniform oxide formation on the surface (Figure 2b) than that of the sample without vanadium on the salt mixture. Porous oxides were also observed on the surface of samples exposed at corrosive environment. As the oxidation proceeds at high temperature, the surface breeds nodular oxides and covers the whole surface of the samples. The formed oxides develop a non-uniform stratifying layer, which increases the rate of spalling with wrinkles on the outer scale in the temperature range of 900–1000 °C.

Figure 3 shows the SEM image of samples exposed to corrosive environment at 1000 °C with and without V_2O_5 in salt mixture. And under higher magnification, the well structured oxide morphology is observed (Figure 4). At higher temperature, the quantity of ridges reduces and the tendency of spalling increases. This leads to the inference that corrosion attack is severe, notable and the spalling of oxides on the surface occurred followed by deep long cracks in the oxide scale. Cracks and spallation further enhance the corrosion attack and hence the mass change. It is evident from the corrosion kinetics that the sudden or rapid increase in mass change can be attributed to non-protective scales. Figure 5 shows the cross-section image of multilayer oxide growth over the alloy 617. The scale

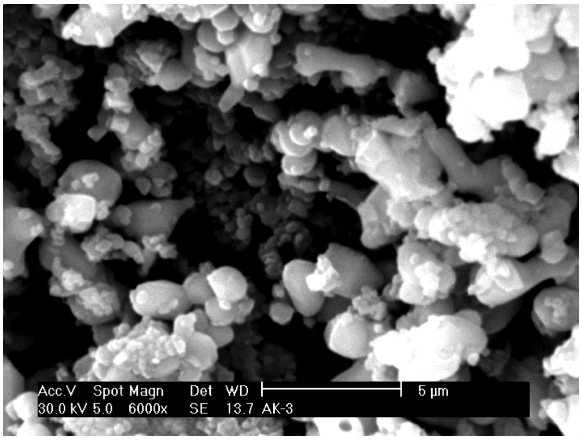


Fig. 4: Typical scale morphology on the surface of Inconel 617 at 1000 °C

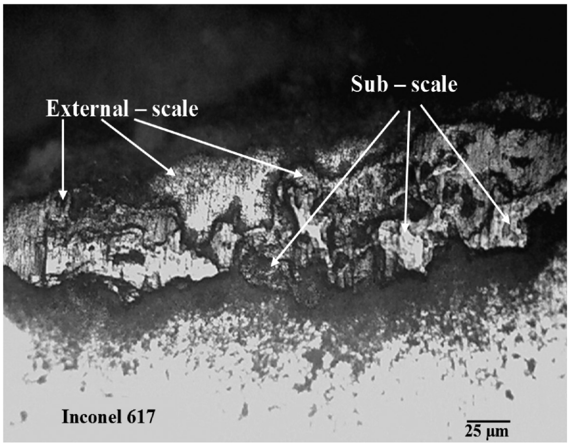


Fig. 5: Optical image of the oxide layer on the surface of Inconel 617 with external-scale and sub-scale

indicates that the mechanism of oxide growth is due to the formation of multilayer oxide.

3.3 EDAX and XRD analysis

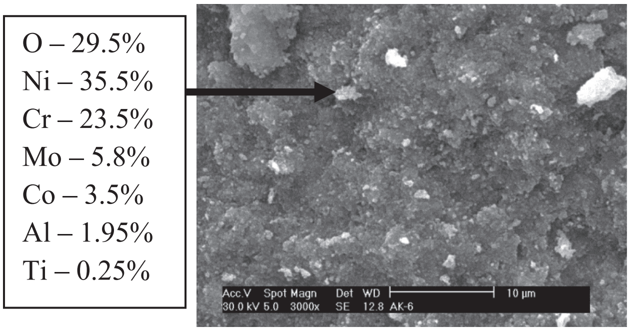


Fig. 6: EDAX results confirming presence of oxide of Ni and Cr on the sample exposed at 900 °C in mixed salt environment

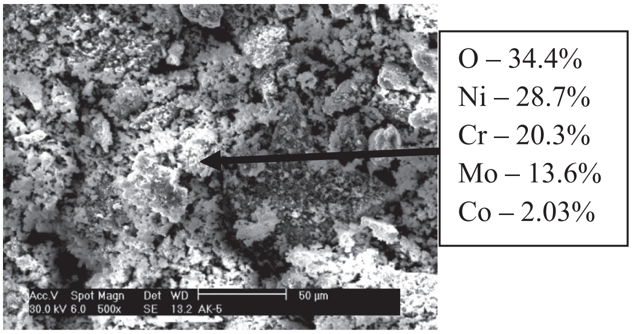


Fig. 7: EDAX results indicating presence of Mo and Co along with Ni and Cr oxides exposed at 1000 °C in mixed salt environment.

To identify and analyse the corrosion products, oxide scales, energy dispersive X-ray (EDAX) analysis and X-ray diffraction (XRD) analysis were performed. Figures 6 and 7 show the EDAX analysis of oxides formed on the surface of the sample exposed to salt environment at 900 and 1000 °C. SEM images reveal that these oxides were nodular and hemispherical in shape in the size range of 2 to 10 microns. Also the oxides were found to be in the combination of agglomerates of Cr, Ni, Al, Mo and Co. Oxides rich in Cr and Ni, namely Cr_2O_3 and NiO, are observed on the surface of the exposed samples at 900 °C, whereas Ni, Cr, Mo and Co are predominantly observed over the surface exposed at 1000 °C. It is clearly observed that molybdenum and chromium have continuous distribution along with nickel on the oxides other than aluminium, iron and cobalt. The chromia (Cr_2O_3) combines with the NiO to nucleate and form $NiCr_2O_4$ which acts as a protective layer at elevated temperatures. Similar behaviour is also reported by Kamal et al. [11]. The presence of NiO, Cr_2O_3, Fe_2O_3, Al_2O_3 and $NiCr_2O_4$ were confirmed in the XRD analysis shown in Figures 8a and 8b. The inherent presence of Al_2O_3 in the oxide scale also acts as a good oxygen barrier protecting the alloy along with Cr_2O_3.

4 Conclusion

- The severity of corrosion attack increased substantially after the eutectic melting salt mixture allowed the diffusion of V_2O_5 above 800 °C to penetrate through cracks in the oxide layer and react with the substrate.
- After 34 hours of exposure, the rich chromia oxides on the surface no longer adhere to the surface and start to spall off.

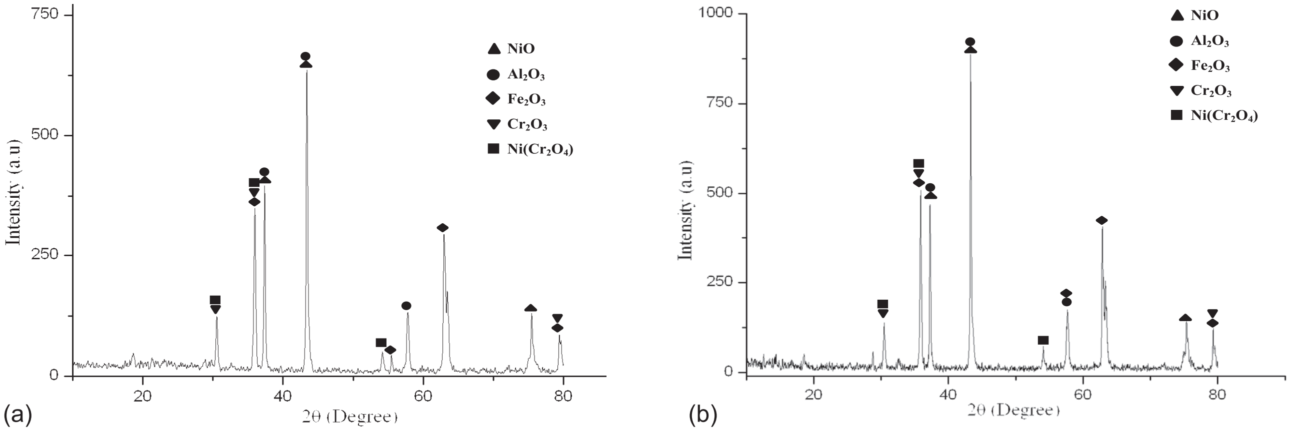


Fig. 8: XRD pattern for Inconel 617 exposed to corrosive environment at (a) 900 °C and (b) 1000 °C

- An increase in vanadium percentage up to a level of 5 wt% is found to influence threefold the enhancement of hot corrosion kinetics value.
- Formation of $NiCr_2O_4$ oxide contributes to greater corrosion resistance.

The alloying elements present in the Inconel 617 do not seem to contribute much for the corrosion attack at elevated temperatures. The presence of V_2O_5 in the salt mixture is found to be the most influencing species for accelerating hot corrosion.

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