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Effect of hot corrosion on low cycle fatigue behavior of superalloy IN718

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ABSTRACTS

Low cycle fatigue behavior of the superalloy IN718 was studied with Type-A ($\text{Na}_2\text{SO}_4 + \text{NaCl}$) and Type-B ($\text{Na}_2\text{SO}_4 + \text{NaCl} + \text{V}_2\text{O}_5$) salt coatings, at 650 °C in total strain controlled mode. Fatigue life of the salt coated specimens was found to be drastically reduced at all the total strain amplitudes. In general there was cyclic softening both in the bare as well as salt coated specimens. Variation of fatigue life with plastic strain amplitude followed Coffin–Manson relationship. Reduction in fatigue life from salt coating was found to be associated with early crack initiation from the roots of corrosion pits on the surface and faster crack propagation.

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1. Introduction

The problem of accelerated corrosion of high temperature marine gas turbine components arises from the presence of salts like NaCl, Na_2SO_4 and V_2O_5 in the combustion chamber. Tiny particles of sodium chloride in the marine atmosphere get ingested with combustion air. Oxidation of sulfur as impurity in the fuel and its subsequent reaction with NaCl results in formation of Na_2SO_4 . Residual vanadium in the fuel is oxidized to V_2O_5 . These compounds deposit on surface of engine components and induce accelerated attack known as hot corrosion [1–7]. Surface degradation of marine gas turbine components occurs mainly from three distinctly different modes of attack; high temperature oxidation, high temperature hot corrosion (HTHC > 700 °C), and low temperature hot corrosion (LTHC 550–700 °C) [8]. All these temperature dependent processes become aggressive particularly in marine environment and could be performance limiting especially for those engine components having close life-time tolerances by design. The most damaging salt in HTHC is Na_2SO_4 because of its high thermodynamic stability. LTHC occurs well below the melting point of pure Na_2SO_4 . Formation of low melting eutectics like Na_2SO_4 – NiSO_4 with melting points of 575 °C causes typical LTHC pitting in nickel-based superalloys. LTHC process becomes less effective above 700 °C and HTHC becomes the dominant mode of attack. Most of the researches and nearly all the manufacturer's information on mechanical properties of metals and alloys have been

based on the tests conducted in air or in vacuum including low cycle fatigue (LCF) [9–15]. Studies on the effect of salt coatings on LCF behavior of superalloys are quite limited. Nazmy [16] observed that high temperature fatigue life of the superalloy IN738, exposed to synthetic ash and SO_2/SO_3 containing air at 850 °C for 1000 h, was lower than that of the standard unexposed material. Effect of sulfur containing environment on corrosion behavior of nickel-based alloys depends on alloy composition, duration and temperature of exposure. The fall in LCF life of the exposed specimens was attributed to effect of sulfidation on the process of crack initiation. Jianting et al. [17] studied LCF behavior of as heat treated IN-738LC in air and in hot corrosive environment of $\text{NaCl} + \text{Na}_2\text{SO}_4$ (25/75 wt%) at 900 °C at two different strain rates and noted that under cyclic plastic deformation protective films were hard to reform at an exposed crack tip because of the combined mechanical action of stress and chemical action of NaCl on the scales. Cracks were observed to initiate always at hot corroded grain boundaries near the surface or generally at oxide spikes in surface-connected grain boundaries. Crack propagation from these nucleation sites was largely transgranular for both air as well as the hot corrosive environment. Whitlow et al. [18] studied the effect of salt mixture of $\text{Na}_2\text{SO}_4 + \text{MgSO}_4$ (60/40 mol%) at 730 °C on LCF life and fracture morphology of Udimet 720 and effectiveness of a protective coating in minimizing life degradation. Presence of corrosive salt environment was found to cause severe degradation in fatigue life by more than one order of magnitude. Both in air as well as in salt initially the fracture was transgranular but in salt it quickly changed to an intergranular mode particularly at cyclic strains above 0.65%. Our earlier study on the effect of coatings of NaCl and salt mixtures

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of NaCl + Na₂SO₄, and NaCl + Na₂SO₄ + V₂O₅ on LCF behavior of the alloy IN718 at room temperature showed severe degradation in fatigue life from NaCl coating and subsequent exposure of the coated sample at 550 °C for 25 h. However, pre-exposure of the samples coated with two salt mixtures, referred to above, even at 650 °C, was found to be less detrimental [19]. Bagui et al. [20] have studied the effect of Na₂SO₄ + NaCl salt mixture on creep rupture properties of the Nimonic-263 alloy at 800 and 850 °C. They found that rupture life was not much affected by corrosive action of the salt mixture for short duration tests at both the temperatures however degradation of creep rupture properties was observed during the long term creep tests. Sahu et al. [21] observed that there was drastic loss in LCF life of the nickel base superalloy SU 263 at 800 °C from Na₂SO₄ + NaCl salt mixture due to severe grain boundary oxidation and grain boundary cracking.

Some of the critical parts of marine gas turbine engines like shafts, discs, turbine casing and stator blades are made of superalloy IN718 and these are used without any protective coating over the operating temperature range from 250 °C to 650 °C. Alloy IN718 is one of the important nickel–iron based superalloy designed for such applications up to the temperature of 650 °C. LCF data on superalloy IN718 under hot corrosive environment are not available in literature. Therefore, it was considered essential to study the behavior of this material under such operating conditions. The present investigation was undertaken to examine the effect of salt coatings of Type-A (Na₂SO₄ + NaCl, 75/25 wt%) and Type-B (Na₂SO₄ + NaCl + V₂O₅, 90/5/5 wt%) on LCF behavior of the alloy IN718 at 650 °C. It was observed that hot corrosion by salt coatings accelerated the process of fatigue crack initiation as well as propagation and caused drastic reduction in fatigue life especially at the lower strain amplitude.

2. Experimental

2.1. Material

Superalloy IN718 contained (by wt%): Ni-53.50, Cr-17.91, Nb-5.22, Mo-3.01, Ti-1.02, Al-0.54, and Fe-balance. It was procured from M/s MIDHANI (India) in the form of rods of 15 mm diameter in solution annealed (980 °C–1½ h) and air cooled condition. Solution treated blanks of appropriate size were subjected to double-aging heat treatment (720 ± 5 °C–8 h, furnace cooling @55 °C/h to 620 °C, holding at 620 ± 5 °C–8 h, and forced air cooling to room temperature).

2.2. Salt coating on LCF specimens

Coatings of salt mixtures Type-A and Type-B were used to simulate hot corrosive environment encountered in marine gas turbine engine components. Salt solutions were prepared by dissolving the respective salt mixtures in distilled water. Since the solubility of V₂O₅ in water is very limited, 7.5 wt% of a soluble salt (NaVO₃) was used for 5 wt% equivalent of V₂O₅. Salt solutions were uniformly sprayed over gauge section of the specimens, using an air brush kit coupled with an automated compressor, traditionally used for tattoo making, with a nozzle diameter of 0.2 mm. Volume capacity of reservoir of the original air brush was increased by connecting a syringe of 25 mm diameter and 100 mm length to ensure adequate quantity of salt solutions during the process of coating. A salt coating device, comprising of salt solution sprayer, a resistance heating furnace with open top, and a stainless steel plate above it was designed and developed for uniform and controlled heating of specimen gauge section during the process of salt coating. Specimens were cleaned with acetone, weighed and preheated to temperature of 120–150 °C by holding the sample horizontally at a height of ~20–30 mm above the hot plate. It was necessary

to evaporate water from the salt solution for better adherence of salt coating on the specimen surface. Salt spraying was carried out continuously until salt coating of desired weight per unit area was achieved. For uniformity in salt coating thickness over the gauge section the specimens were rotated at 5 rpm, connecting one side of the threaded end to a motorized device. Several trials were made to obtain uniform and reproducible salt coatings on gauge section of the LCF test specimens. Salt deposit between 2.5 and 5 mg/cm² was found to form a uniform and intact salt layer in gauge section of the LCF specimen. Salt deposition of less than 2.5 mg/cm² was observed to form a non-uniform and less corrosive layer and that of more than 5 mg/cm² was found to spall during thermal exposure. Bagui et al. [20] and Sahu et al. [21] have also made similar observations. In order to avoid damage of the internally threaded grips during high temperature fatigue test from residual salts in threaded regions of the specimen two internally threaded cylindrical caps of commercial purity aluminum were used to cover the threaded ends of LCF specimen from both sides, during the process of salt coating. It was found to completely eliminate the process of post cleaning of threaded ends of LCF specimens. Use of the hot plate eliminated the likely problem arising from humidity during the process of coating. Adherent salt coatings were achieved by standardizing the salt coating parameters and examining the coatings interrupting LCF tests at elevated temperatures. The adherence of salt coating, prior to LCF test was checked on dummy specimens by scratching the coatings with sharp pointed end of smaller length of a L-shaped rod of mild steel of ~5 mm diameter, holding the longer length in tool post of a lathe machine, and applying a load of 10 gm on the vertical short length. In order to avoid moisture absorption in dry coatings the salt coated LCF specimens were kept in an oven at 110 °C till before the LCF tests.

2.3. LCF test procedure and microscopic examination

Cylindrical LCF specimens with threaded ends of 30 mm length and 12 mm diameter, gauge section of 14 mm length and 4.5 mm diameter, and shoulder radii of 17 mm, were machined from the heat-treated blanks. LCF tests were performed on a completely computer-controlled Servo Hydraulic MTS Testing Machine (Model-810) of 50 kN capacity with FlexTest40 digital controller interface equipped with a split electric resistance heating furnace (model-652.01D, Sr. No. 0114704) with temperature control of ±2 °C accuracy. Fully reversed ($R = -1$) LCF tests were carried out in air under total axial strain control with and without salt coatings. Tests were carried out at 650 °C, at four different total strain amplitudes of ±0.40%, ±0.60, ±0.80 and ±1.00% at a constant frequency of 0.3 Hz. Strain control was accomplished by means of a high temperature MTS extensometer (Model 632.53F-14) mounting in gauge section of the specimen. Fracture surface, cylindrical surface of gauge section and longitudinal section of the LCF tested specimens were examined under scanning electron microscope (SEM) and optical microscope. Salts on the fracture surface as well as in the surface cracks in gauge section were analyzed using Energy Dispersive Spectroscopy (EDS).

3. Results

A typical SEM micrograph of the superalloy IN718 in the peak aged condition is shown in Fig. 1 with precipitates of orthorhombic (Ni₃Nb) δ-phase along the grain boundaries. The mean intercept length of the grains was found to be ~10 μm. Digital photograph of salt coated specimen, prior to LCF testing is shown in Fig. 2a. Salt coating on the specimen surface was found to be intact during LCF testing. Fusion points of Type-A and Type B coatings are known to be below 650 °C [22,23]. Thus at 650 °C these salt mixtures were in

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