EFFECT OF PLASMA SPRAYED ALSI COATING ON LOW CYCLE FATIGUE PROPERTIES OF CAST SUPERALLOY INCONEL 738LC

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Abstract

Air plasma spraying was applied to obtain AlSi protective surface coating on cylindrical specimens of cast polycrystalline superalloy Inconel 738LC. Chemical composition of the surface treated layer was studied and the hardness depth profile was measured. Surface treated and untreated specimens were cyclically strained under total strain control at 800 \degree C in air. Cyclic stress-strain response and fatigue life of both materials were obtained. The coating results in a slight decrease of cyclic stress-strain curve. A detrimental effect of the surface treatment on derived Wöhler curve is documented while Manson-Coffin curves of both materials are almost identical. Specimen section observations and fracture surface examinations help to discuss fatigue behaviour of both materials.

Keywords:
High temperature fatigue, Inconel 738LC, fatigue life curves, cyclic stress-strain curve, AlSi plasma coating.

1. INTRODUCTION

Nickel-base superalloys were developed for the critical parts of gas turbines in aerospace and marine propulsion and land based power generation. They are exposed to complex cyclic and sustained loading during operation under extreme environmental conditions including erosion. Since their excellent mechanical properties are attained to some extent at the expense of environmental resistance, a suitable surface protection against oxidation and hot corrosion can improve the performance of structural parts [1-3].

Polycrystalline cast Inconel 738LC is a precipitation strengthened nickel base superalloy that is used to produce blades and discs of gas turbine engines. Its fatigue behaviour at high temperature has been reported previously [4-9]. It has been published recently that fatigue crack paths of a cast superalloy can be influenced by its heterogeneous dendritic structure [10,11].

The effect of surface treatment on low cycle fatigue properties of Inconel 738LC at high temperature is ambiguous [5,6,12,13]. An Al-Si diffusion coating had a slight beneficial effect on the fatigue life of Inconel 738LC in the low amplitude domain [5]. A vacuum plasma sprayed NiCoCrAlY coating [14] did not change the fatigue life of Inconel 738LC while a Pt modified Al diffusion coating resulted in the fatigue life decrease [12]. Itoh at al. [13] have reported an inferior fatigue life under push-pull load control tests of CoCrAlY and CoNiCrAlY vacuum plasma coated Inconel 738LC when compared with the uncoated material.

The aim of the present paper is to study the effect of an AlSi air plasma spraying on the low cycle fatigue behaviour of Inconel 738LC at 800 \degree C in air. Special attention is devoted to coating characterization and to fatigue damage of the coating-substrate composite. This work is a part of an extensive research on the influence of surface treatment on the high temperature fatigue properties of cast polycrystalline nickel based superalloys [14-18].
2. EXPERIMENTAL DETAILS

Conventionally cast polycrystalline superalloy Inconel 738LC was provided in the form of casting rods in fully heat treated condition, i.e. after 1120 °C / 4 h / air cooling (AC) + 845 °C / 24 h / AC. Chemical composition of the material is 15.86 Cr, 8.26 Co, 3.27 Ti, 3.31 Al, 2.54 W, 1.74 Mo, 0.15 Fe, 0.88 Nb, 1.65 Ta, 0.11 C, <0.05 Si, <0.05 Mn, 0.03 Zr, 0.008 B, <0.004 P, 0.004 S, the rest Ni (all in wt. %). Polished section of the material revealed coarse grains with dendrites, carbides and shrinkage pores. The microstructure consists of γ’ precipitates embedded in γ matrix and is characterized by dendritic segregation of elements. An example of coarse dendritic structure is shown in the optical micrograph of the section parallel to the rod axis in Fig. 1. The average grain size, found using the linear intercept method, was 3.6 mm.

Fatigue tests were performed on button-end specimens having gauge length and diameter of 15 mm and 6 mm, respectively. Specimens were machined parallel to the rod axis and their gauge length was mechanically ground [19]. Five specimens were surface-treated by air plasma spraying (APS) using SNECMA equipment of PLASMA – TECHNIK with a gun power of 35 kW. The coating material was Al and Si powder (50/50 wt. %). Besides, flat specimens with a thickness of 10 mm and diameter of 20 mm were surface treated to study coating properties. Surface treated specimens were annealed in the protective Ar atmosphere at 950 °C for 5 hours followed by slow cooling. Then the fatigue specimen gauge length was finely ground to a diameter of 6.2 mm. The mean thickness of their resulting surface layer was 380 μm. The mean coating thickness of flat specimens was 187 μm.

Surface treated and untreated specimens were fatigue in a closed-loop electro-hydraulic testing system at total strain rate of 2x10^{-3} s^{-1} with fully reversed total strain cycle (Rε = -1) at 800 °C in air. Heating was provided by a three-zone resistance furnace and the temperature was monitored by three thermocouples. Strain was measured and controlled using a MTS extensometer 632.53F-14 with 12 mm base. Hysteresis loops for selected numbers of cycles were recorded in disk memory. Plastic strain amplitude derived from the half of the loop width and stress amplitude at half-life were evaluated.

Optical microscopy (OM) and scanning electron microscopy (SEM) Philips XL30 were used to study surface relief, fracture surfaces and polished sections of the gauge segments in both treated and untreated specimens. The micro-hardness was measured in LECO 400M-PC2 indentation tester equipped with the Knoop indenter using a load of 0.025 kgf (0.245 N). The chemical analysis of the diffusion coating was investigated with energy dispersion X-ray spectrometer EDAX built in SEM using spot and plane analysis.

![Fig. 1. Dendritic structure of Inconel 738LC (OM).](image1)

![Fig. 2. Microstructure of a coated flat specimen in the section perpendicular to the surface (OM).](image2)
3. RESULTS AND DISCUSSION

3.1 Characterization of coating

Fig. 2 shows an OM image of a section perpendicular to the surface of a coated and annealed flat specimen. The thickness of the coating ranges in the interval of 149 to 218 μm and 352 to 411 μm for flat and cylindrical fatigued specimens, respectively. Cracks were not identified at the interface between the coating and substrate.

The concentration profiles of major elements in the coating on a flat specimen measured by plane analysis are shown in Fig. 3. Individual phases in the coating were obtained through EDAX spot analysis. The matrix of the coating is formed by the β NiAl phase with a number of small particles of Si-Cr and complex carbides based on Mo, W, Ta, Nb whose distribution and shape depend on a distance from the surface.

Fig. 4 shows the micro-hardness depth profile measured in three different locations on the section perpendicular to the flat specimen surface. A sharp decrease of the Knoop hardness is apparent in the vicinity of the interface between the coating and the substrate. Within a 10 μm interval the hardness value is reduced by a factor of 2.2 – see Fig. 4. The average Knoop hardness \( H_K \) 0.025 of all coating values and of all substrate values shown in Fig. 4 is 1126 and 478, respectively. It can be concluded that the high gradient of mechanical properties between the coating and substrate can support crack initiation close to the interface.

3.2 Cyclic stress-strain response and fatigue life

Fig. 5 shows the stress amplitude \( \sigma_a \) as a function of the number of cycles \( N \) obtained for both coated and uncoated specimens cycled with different total strain amplitudes. The stable stress response is typical for low amplitudes while the initial hardening followed by saturation and softening is observed in the high amplitude domain in the uncoated material (see Fig. 5a). Fig. 5b shows the gradual slow softening for all strain amplitudes in the coated superalloy.

Fatigue life curves are shown in Fig. 6 both for the uncoated and coated Inconel 738LC. Fig. 6a shows the plastic strain amplitude \( \varepsilon_{ap} \) at half-life vs. the number of cycles to fracture \( N \). Experimental data for the uncoated superalloy were approximated by the Manson-Coffin law and parameters obtained using the regression analysis were published elsewhere [5]. It can be seen from Fig. 6a that within experimental

![Fig. 3. Concentration profiles of major elements in the coating layer of a flat specimen.](image1)

![Fig. 4. Hardness depth profile of a coated flat specimen measured in three different locations.](image2)
scatter the experimental data for the surface treated and untreated material are almost identical. Fatigue life curves in the representation of the stress amplitude $\sigma_a$ at half-life vs. the number of cycles to fracture $N_f$ (derived Wöhler curves) are shown in Fig. 6b. The Baquin law was fitted to the data for the uncoated material and parameters were published elsewhere [5] (see a dashed line in Fig. 6b). The plasma AlSi coating results in a fatigue life decrease in the low amplitude domain.

The cyclic stress-strain curve both for the uncoated and coated material is shown in Fig. 7. The stress amplitude $\sigma_a$ is plotted vs. the plastic strain amplitude $\varepsilon_{ap}$ at half-life. The power law was fitted to experimental data for the treated material (see a dashed line in Fig. 7). Fig. 7 shows that the surface treatment results in a small decrease of the stress-strain response particularly for low amplitudes.

### 3.3 Observations of specimen sections and fractography

Fig. 8 shows an optical micrograph of the section parallel to the loading axis of a plasma coated specimen cycled to fracture with low strain amplitude ($\varepsilon_a = 0.24\%$, $N_f = 2447$ cycles). Four cracks can be seen in Fig. 12. The crack in the left goes through the coating and terminates in the substrate. Three other cracks...
star at the specimen surface and stop at the coating-substrate interface. Rarely, cracks were observed to begin at the specimen surface and terminate within the coating or to extend from the coating-substrate interface and stop in the coating without reaching the specimen surface. The density of surface cracks in coated specimens is several times higher than that in uncoated specimens. Therefore, surface crack initiation is more homogeneous in the coated material. Fracture surface observation of the plasma coated superalloy reveals that casting defects present close to the surface play an important role in the fatigue crack initiation.

Low cycle fatigue tests at 800 °C show that the fatigue life in the Basquin plot of AlSi plasma coated Inconel 738LC is reduced in comparison with the untreated material – see Fig. 6b. Numerous crack initiate in the comparatively brittle coating during the fatigue lifetime – see Fig. 8. Stress concentration ahead of the surface cracks results in the accelerated fatigue crack growth into the substrate. Therefore, the effect of plasma coating on the fatigue life is detrimental in the representation of the stress amplitude versus the number of cycles to fracture.

4. CONCLUSIONS

The present study on the effect of the AlSi plasma coating on the low cycle fatigue behaviour at 800 °C under constant total strain amplitude can be concluded as below.

1) The plasma coated specimens are characterized by the high hardness gradient in the vicinity of the coating-substrate interface.
2) The surface treatment of Inconel 738LC results in changes of its fatigue behaviour.
3) The plasma coating has detrimental effect on the fatigue life. The Basquin curve of the coated material is shifted to lower fatigue lives in comparison with the untreated material.
4) Surface crack initiation is more homogeneous and therefore plastic strain is less localized in the coated superalloy.

ACKNOWLEDGEMENTS

The assistance of Ing. Peter Petrik, SAV Bratislava in sample preparation is gratefully acknowledged. The research was financially supported by the grants Nos. P107/11/2065 and P107/12/1922 of the Czech Science Foundation.
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