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HIGH FREQUENCY FATIGUE TEST OF IN 718 ALLOY – MICROSTRUCTURE AND FRACTOGRAPHY EVALUATION

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INCONEL alloy 718 is a high-strength; corrosion-resistant nickel chromium material used at -253 °C to 705 °C for production of heat resistant parts of aero jet engine mostly. The fatigue test provided on this kind materials were done via low frequency loading up to this time. Nowadays, needs of results at higher volume of loading cycles leads to high frequency loading with aim to shorten testing time. Fatigue test of experimental material was carried out at frequency 20 kHz with stress ration R = - 1 (push – pull) at room temperature. It was found that this superalloy can still fracture after exceeding 10^8 cycles. Besides fatigue test were microstructural characterisation and scanning electron microscopy (SEM) fractography evaluation done.

Key words: Ni – base superalloy, high frequency fatigue testing, microstructure, SEM fractography.

INTRODUCTION

The strength of the alloy 718 comes from coherent solid-state precipitates, which are for a small part γ′-Ni_3Al but mostly γ″-Ni_3Nb precipitates [1–6]. The major strengthening phases in the alloy 718 are the γ″ and γ′ phases which produce coherency strains in the γ matrix. The γ″ phase is considered to be the main strengthening phase and has a DO_{22} BCT crystal structure while the γ′ is a FCC ordered phase with a Ll_2 crystal structure.

The γ″ and γ′ phases have unique morphologies which sometimes helps to identify the phases. The γ′ phase precipitates as a round particles which size can be less than 200 Å and continues to be round in shape when it coalesces at higher temperature. The γ″ phase has more of a disk shape nature whose length is 5 to 6 times its thickness; however, when the γ″ precipitate at very low temperatures, a TEM is necessary to resolve its shape. The γ″ phase continues to grow in the disk shape at higher heat treatment temperatures or exposures. Some studies [7] have indicated that the γ″ and γ′ phases grow in a sandwich-like morphology indicating a co-precipitation of the phases.

The delta phase found in alloy 718 is incoherent with the γ and has an orthorhombic crystal structure. The delta phase is found mostly as plates growing on the (111) planes or nucleating on the grain boundaries and is associated with loss of strength in this alloy. The delta phase in the grain boundaries is used to control grain size in wrought materials and seems to be also important for notch ductility [7].

MATERIAL AND EXPERIMENTAL METHODS

A typical microstructure of wrought alloy 718 is on Figure 1. The microstructure consist of light gray blocks of carbides and fine lenticular and lamellar particles of delta phase (Ni_3Nb) distributed in the FCC matrix, with grain size approximately 10 μm and a few deformation twins.

Carbides also are an important constituent of superalloys. They are particularly essential in the grain boundaries of cast polycrystalline alloys for production of desired strength and ductility characteristics [8]. Carbide levels in wrought alloys always have been below those in cast alloys, but some carbide has been deemed desirable for achieving optimal strength properties. Carbides may provide some degree of matrix strength-

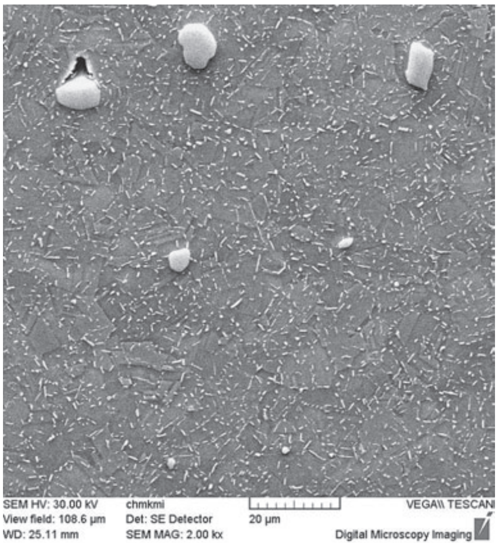

Figure 1 The typical microstructure of wrought INCONEL alloy 718, SEM, etch. Kallings

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ening, and are necessary for grain-size control in some wrought alloys. Various types of carbides are possible depending on alloy composition and processing. Some of the important types are MC, M_6C, $M_{23}C_6$, and M_7C_3, where M stands for one or more types of metal atom.

Important carbide-forming elements are chromium ($M_{23}C_6$, M_7C_3); titanium, tantalum, niobium, and hafnium (MC); and molybdenum and tungsten (M_6C).

During the past few decades, extensive investigations have been made on the low cycle fatigue (LCF) and high cycle fatigue (HCF) properties of IN718, such as the effect of temperature on the cyclic stress-strain response and LCF life associated with the deformation microstructures [9-11], the factors (temperature, environment, and loading parameters, etc.) influencing fatigue crack growth [12-14], the creep-fatigue oxidation interactions [15], the mechanism-based modelling of fatigue life prediction [16], and so on.

However, another study [17], under ultrasonic frequency, revealed that fatigue fracture of IN718 occurred between 10^7 and 10^8 cycles. Furthermore, it is known that the fatigue crack initiation process becomes increasingly important with the extension of fatigue life.

In this study, the high cycle fatigue (HCF) and very high cycle fatigue (VHCF) properties of IN718 superalloy were investigated under push-pull high frequency fatigue test at room temperature. With the help of scanning electron microscope (SEM), fractographic analyses were performed to disclose the fracture features of specimens in different life ranges.

The material bars used in this study is a Ni – based superalloy INCONEL 718 with a chemical composition in wt.%: C – 0,026; Si – 0,09; Mn – 0,07; P – 0,008; S <0,001; Al – 0,57; B – 0,004; Bi (ppm) <0,1; Co – 0,14; Cr – 19,31; Cu – 0,03; Mo – 2,99; Nb – 5,30; Ni – 53,32; Pb (ppm) – 0,1; Se (ppm) < 3; Ta <0,01; Ti – 0,96; Ni + Co – 53,46; Nb + Ta – 5,31; and Fe – balance.

The material was heat treated, according to suppliers BIBUS Ltd. (CZ) material sheet, 980 °C / 1 hrs. AC + heating at 720 °C / 8 hrs. followed FC (50 °C per hour) to temp. 620 °C holding time 8 hrs. and air cooled. Achieved mechanical properties of material with grain size ASTM 12 are in Table 1.

Table 1 **Mechanical properties of IN 718**

	Temperature / °C	
	20	649
Rp 0.2 / MPa	1 213	986
Rm / MPa	1 549	1 123
A / %	21,3	22,6
Z / %	33,3	68,0
HB 10/3000	429	-
$\sigma_{T/649}$ / MPa	-	689
Rupture life / hrs.	-	26,8
A / % creep	-	45,7

Carbide size were evaluated with NIS Elements software on non etched specimens. Microstructure evaluation at starting stage and fractography of specimens' fracture surface after fatigue testing were provided on SEM.

The high frequency fatigue experiments were performed by ultrasonic push-pull method and appropriate cooling was used to avoid the temperature rise. Experimental fatigue machine KAUP – ŽU with loading frequency 20 kHz was developed by Department of Material Scicence, Faculty of Mechanical Engineering, University of Žilina in Slovak Republic. Stress ratio of R = -1 was used for experiments.

RESULTS AND DISCUSSION

Both low and high cycle fatigue cracking have been observed to initiate at large (length greater than 50 μm) carbides present in these alloys. From this point of view is carbide size evaluation important. Carbides of MC form are presented in microstructure of INCONEL 718, as shown in Figure 2, that are mostly formed by Ti and Nb. Average size of these carbides vary from 4,01μm to 11,79 μm with area ratio 0,53 % on evaluated specimen view, Figure 3.

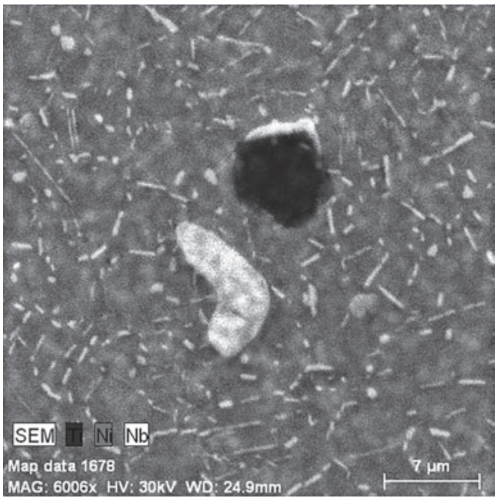

Figure 2 The MC carbides in INCONEL alloy 718 + SEM mapping, SEM, etch. Kallings

According to carbide size evaluation there is no reason to be afraid of affecting fatigue life at any, low or high cycle fatigue cracking.

Superalloy consists of the austenitic fcc matrix phase γ (solid solution of such elements as Cr, Fe, and Co in Ni) plus a variety of secondary phases. Secondary phases of value in controlling properties are the fcc carbides MC, $M_{23}C_6$, M_6C, and M_7C_3 (rare) in virtually all superalloy types; gamma prime (γ′) fcc ordered $Ni_3(Al,Ti)$; gamma double prime (γ″) bct ordered Ni_3Nb; and the delta (δ) orthorhombic Ni_3Nb intermetallic compounds in iron-nickel-base superalloys. The γ′, γ″, and η phases also are known as geometrically close-packed (gcp) phases.

The microstructure of tested alloy, Figure 4, consist of very fine grains size according ASTM = 12 (length of grains around 10 μm) and various forms of segregated δ

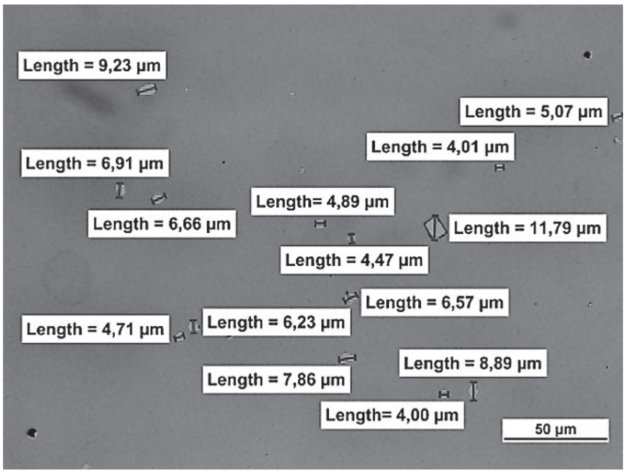

Figure 3 Carbide size evaluation, non etched specimen

phase (light gray particles). The δ phase is presented mainly at grain boundary in needle like shape and in form of fine blocks inside of grain. However, needle like morphology of δ phase can be found also inside of grains. Presence of γ″ or γ′ was hard to prove and observe due to low temperature (phases γ″ and γ′ became more obvious after exposing at higher temperatures – because of its growing) and insufficient magnification of SEM observing.

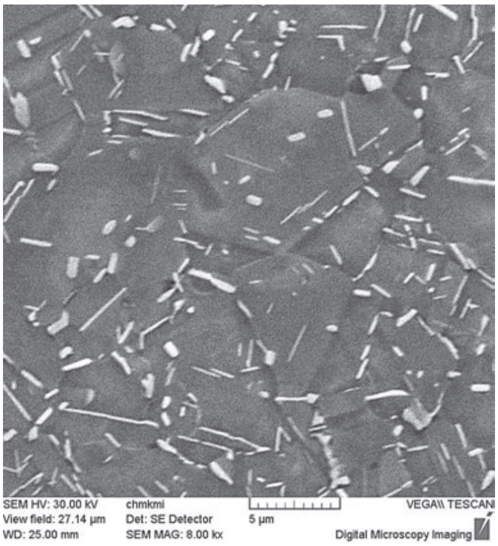

Figure 4 Microstructure of wrought INCONEL alloy 718 as seen in SEM, etched Kallings

For high frequency fatigue testing were used specimens with hourglass shape. Figure 5 shows the *S-N* curve of IN718 obtained from the ultrasonic push-pull fatigue tests at room temperature with frequency 20 kHz under the load ratio of *R* = −1. Obtained results were approximated with equation (1) what is a Basquin formula for S-N presentation and approximation. This approach was also used at different material [18].

$$\sigma_a = 1\,470 \times N_f^{-0.0795} \qquad (1)$$

where $\sigma_f' = 1\,470$ is a coefficient of fatigue strength and - 0,0795 = b is lifetime curve exponent.

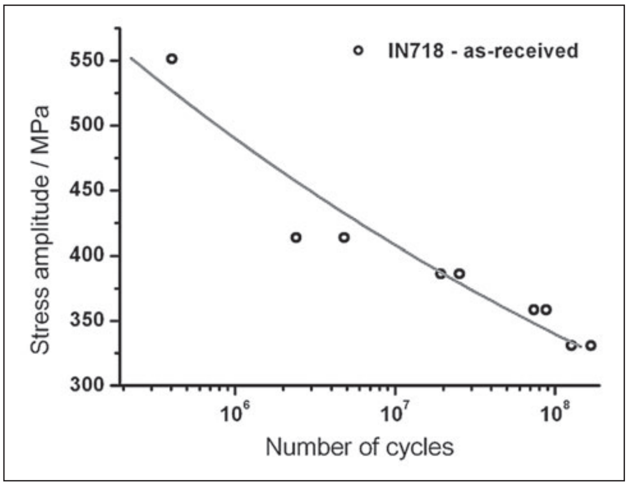

Figure 5 Fatigue test S-N curve of INCONEL alloy 718 at f ≈ 20kHz, room temperature, and stress ratio R = -1

From measured S-N curve is clearly seen that the fatigue life increases with decreasing stress amplitude and the *S-N* curve appears to continuously decline as the life extends.

Note that fatigue failure of this superalloy continues to occur after exceeding 10^7 cycles what is value considered as a fatigue limit for most of steels and hard materials. The longest fatigue life of the fractured specimens is $1{,}679 \times 10^8$ cycles, which takes 2 hours and 19 minutes of fatigue testing at frequency of 20, 13 kHz. The test result can be regarded as the direct evidence of fact that IN718 may still fracture in the VHCF regime at room temperature.

Overall view of the fracture surfaces at different stress level can be seen on Figure 6. Initiation sites are marked by arrow. As a confirmation of fact published in [19] at high stress levels as shown in Figure 6a, fatigue crack initiated from multiple initiation sites and resulted into a very small tensile final fracture area. With decreasing stress level, the number of initiation sites decreases, Figure 6b, controlled by crystallographic slip at surface grains and static tensile final fracture area increases. Fracture due to a single fatigue crack occurs for specimens with longer fatigue life (> 2, 4139 x 10^6 cycles, e. g. Figure 6b). In this case fatigue crack takes place at the specimen surface where can be seen a massive initiation point, probably oxide, resulting into a significant crack as seen in Figure 6c. After initiation fatigue crack propagates with transcrystalline mechanism with typical striations, indicates the stable crack propagation as reported in Figures 6d and 6e.

At higher stress level, Figure 6e, a few secondary cracks have appears whose are perpendicular to main fatigue crack propagation and probably are situated at grain boundaries.

In Figure 6f is reported a change in micro-mechanism of fracture, very sharp border with secondary crack, between typical fatigue crack propagation and classical transcrystalline ductile dimpled fracture mechanism in the tensile final fatigue region.

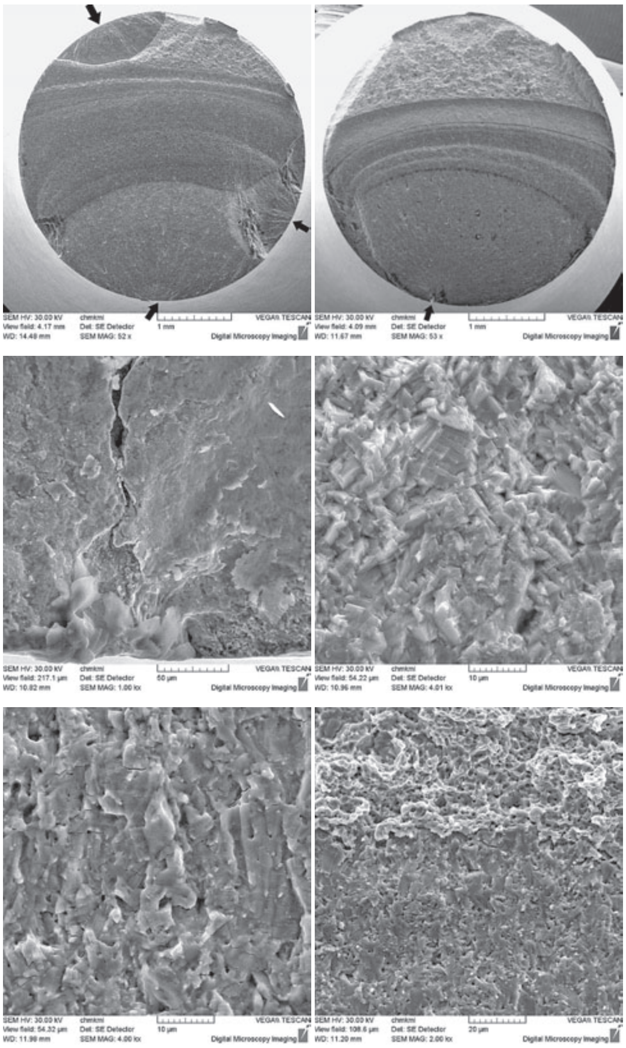

Figure 6 Overview of the typical surfaces in HFF regime, SEM. a) σ_a= 827,3 MPa, N_f = 1,58 x 10^5 cycles; b) σ_a= 413,65 MPa, N_f = 2,4139 x 10^6 cycles; c) and d) σ_a= 386,07 MPa, N_f = 1,9299 x 10^7 cycles – very fine striations; e) σ_a= 413,65 MPa, N_f = 2,4139 x 10^6 cycles – very fine striations; and f) σ_a= 386,07 MPa, N_f = 1,9299 x 10^7 cycles

CONCLUSIONS

Nickel-based superalloy INCONEL 718 was subjected to high frequency push-pull fatigue test up to ≈ 10^8 cycles at room temperature. Conclusions are as follows:

- Microstructure of alloy consist of lenticular and needle like particles of stable δ (Ni_3Nb) orthorhombic phase and light gray blocks of mostly primary carbides MC created by Ti and Nb; growing mechanism of major strengthening phases γ'' and γ' was hard to observe due to low temperature of testing as well as insufficient SEM magnification – better to use TEM.
- Carbide size evaluation proves that its size (average size was up to 11,79 μm) is not acting as a fatigue crack initiators.
- S-N curve in VHCF of alloy 718 has been measured. Also was proved that alloy is still fracture even after reaching 1,679 x 10^8 – fatigue limit was not observed. Even after reaching value 10^8 cycles was not observed run-out of specimens.
- Fractography analysis shows that at higher stress level fatigue crack initiates from a multiple sites and with decreasing of stress amplitude crack initiation sites are reduced into a single one controlled by crystallographic slip at surface grains or massively oxidized areas. After initiation the crack is propagated by typical transcrystalline mechanism.

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