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Effect of Ultrasonic Nanocrystal Surface Modification on residual stress, microstructure and fatigue behavior of ATI 718Plus alloy

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ABSTRACT

Ultrasonic Nanocrystal Surface Modification (UNSM) is a mechanical surface treatment that induces large compressive residual stresses and near-surface microstructural changes in the material using repetitive impacts at ultrasonic frequencies with a WC tip. In this study, we investigate the use of UNSM to improve the fatigue life of ATI 718 Plus (718Plus). UNSM induced severe surface plastic deformation in 718Plus, which led to nano-sized crystallites, twins, and high dislocation density in the near surface regions, coupled with an increase in surface hardness by 2.3 GPa and high magnitude of compressive residual stresses. These changes increased the endurance limit by ~ 13% (~ 100 MPa) in room temperature fatigue tests. This improvement in fatigue life was attributed to near-surface microstructural changes, material hardening and high compressive residual stress induced by UNSM. The crack propagation rates were 66% lower for UNSM-treated 718Plus as compared with untreated material. The residual stress relaxation after cyclic loading indicates the effectiveness of UNSM in improving the fatigue life of 718Plus.

1. Introduction

There is a continuing demand to develop new nickel-based superalloys that can provide for improved strength, creep, fatigue, environmental resistance and reliability to meet the increasing performance requirements even at elevated temperatures. ATI 718 Plus (718Plus) is a nickel-based superalloy that has a maximum usage temperature of 650 °C which is 50 °C improvement over the traditionally used Inconel 718 (IN718) [1]. 718Plus is able to retain strength up to 704 °C and this is due to the high temperature stability of its γ' phase [2]. By contrast, the transformation of metastable γ'' into its stable δ phase causes a drop in mechanical properties of IN718 at 650 °C and limits the temperature for its application to around 600 °C. In addition, it has superior processing and welding characteristics over Waspaloy or Udimet720Li. It also has good low cycle fatigue (LCF) properties and low crack propagation rates [1]. The tensile properties of IN718 and 718Plus are comparable at room temperature, but are higher for 718Plus at 649 °C and 704 °C [3]. Thus, 718Plus is starting to replace IN718 that is currently widely used for aerospace applications.

While there is little fatigue life data reported on 718Plus alloy in the open literature, a few studies on fatigue crack growth showed that crack growth rates for 718Plus alloy were lower than that for either IN718 or Waspaloy [4–8]. Fatigue begins with micro-crack initiation at a region of high stress intensity, i.e. a structurally weak spot or a region of tensile stress, followed by crack growth leading to final failure when the material cross section can no longer bear the load [9]. The origin of fatigue cracking often lies in the Bauschinger effect and the formation of extrusions and intrusions by a dislocation based mechanism. Early work of Mughrabi and Laird successfully identified the formation of persistent slip bands (PSB) by dislocations during fatigue loading, to be the basis of intrusions and extrusions formation [10]. Crack propagation with each cycle leaves a microscopic fingerprint of fatigue crack growth in the form of striations on the fracture surface indicating the advance of the crack with each cycle [11].

Mechanical surface treatments like shot-peening, deep-rolling, roller-burnishing, laser shock peening in addition to Ultrasonic Nanocrystal Surface Modification (UNSM) have been used to increase resistance to early fatigue crack initiation and growth, and to improve the fatigue life. These surface treatments introduce compressive residual stresses that improve fatigue resistance by delaying crack initiation and lowering growth rates. Several researchers compared the effect of these different techniques on fatigue life of different materials [12–15].

UNSM is an advanced mechanical surface treatment technique that

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imparts ultrasonic energy [16,17] through a tungsten carbide tool tip on the surface of the material. The UNSM device includes an ultrasonic transducer that emits ultrasonic waves at 20 kHz. The high frequency ultrasonic vibrations generated by the transducer are amplified by a booster. The booster is followed by a horn and an impacting tungsten carbide tool tip, which is in contact with the work piece. Thus, the tip delivers static and dynamic forces to the work piece, which induces severe plastic deformation and nanostructure formation in near-surface region, in addition to high compressive residual stresses, and near-surface hardening. The mechanism and the device has been described in more detail in literature [18]. A study of the effects of UNSM on residual stress, hardness, roughness, and microstructure of IN718 (SPF) has been reported [19]. This technique has been used to improve fatigue life in several materials [20–22], including improvement in rotary bending fatigue of IN718 [23,24].

The purpose of this study was to evaluate and understand the improvement in strength and fatigue behavior of 718Plus alloy due to heat treatment and UNSM treatment at room temperature. The effect of these treatments on near-surface and through-the-depth hardness and residual stresses were characterized using nanoindentation and X-ray diffraction (XRD), respectively. Optical interferometry was used to characterize surface roughness and the condition of the surface before and after UNSM treatment. Corresponding uniaxial tension tests and uniaxial tension-tension fatigue tests were conducted at room temperature to produce stress-strain and stress-life (S-N) curves to evaluate the effect of the treatments on strength and fatigue behavior. The compressive residual stress relaxation with the cycles at different stress levels was investigated. In addition, changes in the microstructure after UNSM and fatigue testing were characterized using Scanning Electron Microscopy (SEM), Electron Back-Scatter Diffraction (EBSD)/ Orientation Imaging Microscopy (OIM), energy dispersive x-ray spectroscopy (EDS) and Transmission Electron Microscopy (TEM). Fracture modes, mechanisms, and crack propagation rates were also characterized by SEM to explain the improvement in fatigue life due to UNSM treatment.

2. Experimental details

2.1. ATI 718Plus

The 718Plus used in this study was obtained from ATI as plates 30 cm × 30 cm and thickness 12.7 mm. The nominal composition of the Alloy 718Plus compared to IN718 is given in Table 1. The as-received (AR) material was hot-rolled and solution treated at temperature 954–982 °C for an hour then air-cooled by ATI. ATI recommends a heat treatment and aging process that was conducted in a vacuum furnace at 788 °C for 8 h, furnace cooled at 38 °C per hour to 704 °C, held at 704 °C for 8 h, then air cooled to produce heat-treated (HT) material [25]. The aim of the heat treatment is formation and growth of γ' precipitates for strengthening of the material. ATI recommends using of 718Plus in its HT form, thus UNSM treatment was done on the HT material to produce the UNSM-treated (UNSM) samples.

2.2. Test coupons and samples

Coupons of dimensions 30 mm × 12.5 mm × 2 mm thick were fabricated for the hardness, and residual stress measurements. Rectangular cross section samples with continuous radius between ends according to ASTM E466-07 [26] (Conducting Force Controlled Constant Amplitude Axial Fatigue Tests of Metallic Materials) of dimensions 90 mm long × 3 mm wide in the center × 2 mm thickness and radius 30 mm were prepared using electrical discharge machining (EDM), and is displayed in Fig. 1(a). These samples were used for uniaxial tension and tension-tension fatigue tests.

2.3. Ultrasonic Nano-Crystal Surface Modification (UNSM)

A patch of 10 mm × 10 mm was UNSM-treated in the center of the HT coupons, whereas for the tensile and fatigue test samples, a patch of 30 mm × 10 mm was UNSM-treated in the center of the HT metallic strip to cover the gauge area of the sample then the sample was cut out as shown in Fig. 1(b). Several UNSM process conditions were initially investigated but only two conditions shown in Table 2 were carried out for the full study of the hardness, residual stress measurements, and optical profiling. From the latter, the process condition that gave better combination of results for near-surface residual stress, hardness, and especially surface finish was selected to treat the material that the UNSM-treated samples were cut out from before testing. The static load is the dead weight that is applied, the amplitude is the dynamic load (amplitude of the strikes) which is a percentage of 40 µm, the scanning speed is the speed at which the table holding the sample is moving, and the spacing interval is the distance between two adjacent UNSM traverses. The tip used is Tungsten Carbide (WC) ball with Ti alloy ball gripper of diameter 2.38 mm and roughness Ra = 0.1 µm.

2.4. Hardness

Nanoindentation tests were performed directly on the coupons using a CSM Nano/Micro indentation system in accordance with ASTM E2546-15 [27] (Standard Practice for Instrumented Indentation Testing) to determine the surface hardness measurements before and after each treatment. The conditions for the indentations are load control with maximum load of 100 mN held for 2 s and loading/unloading rates of 600 mN/min. A square matrix of 3 × 3 indents was made at the surface where each of the points was separated from the adjacent point by 30 µm. This measurement was performed three times for each sample in different areas and average value with the standard deviation reported. A cross-sectioned piece from various coupons was mounted in a conductive epoxy and polished to mirror finish to perform through-the-depth hardness measurements. Measurements in the form of rectangular matrix of 21 × 3 indents were made on the polished cross sections going from the peened edge towards the center of the coupon. This rectangular matrix has a 50 µm spacing between the 21 indents through the depth and 30 µm spacing between the three indents that are at each depth to get a good statistical study. The average value with the standard deviation was reported at each depth. A distance of at least 30 µm was kept between indents to ensure that the adjacent measurements were not affected by each other.

2.5. Residual stress and FWHM

Residual stresses were analyzed in two orthogonal directions using conventional X-ray diffraction $\sin^2\Psi$ technique with a Proto LXRD instrument (single axis goniometer using Ω geometry, Mn Kalpha x-rays) and electrolytic layer removal. The two directions will be denoted as X and Y for simplicity in presenting the data. Alignment of instruments

Table 1
Nominal composition of 718Plus compared with IN718.

Element	Ni	Cr	Co	Mo	Al	Ti	Nb	Fe	W	P	C	B
IN718	Bal	17.9	0.16	2.86	0.49	1.01	5.22	18.08	0.03	0.008	0.025	0.004
718Plus	Bal	17.42	9.13	2.72	1.46	0.71	5.48	9.66	1.04	0.013	0.028	0.005