LINKAGE BETWEEN DUCTILE FRACTURE AND EXTREMELY LOW CYCLE FATIGUE OF INCONEL 718 UNDER MULTIAXIAL LOADING CONDITIONS

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Abstract

Ductile fracture and extremely low cycle fatigue (ELCF) [1] are two common failure modes in aircraft engines and turbomachinery designs [2]; however, the linkage between these two failure modes under multi-axial loading conditions has never been systematically studied. Inconel 718 (IN718) is one type of high temperature alloys widely used in turbomachines. Specially designed specimens and tests were used to achieve desired multi-axial loading conditions. Two groups of tests were conducted: (a) round bar specimens with different notches; (b) plane strain specimens. Similar types of tests were conducted for IN718 under both types of failure modes (ductile fracture and ELCF). It is found that the ductile fracture of IN718 under multi-axial loading conditions is strongly dependent on stress triaxiality, but weakly dependent on the Lode angle parameter [3]. A 3D fracture locus was calibrated using modified Mohr-Coulomb (MMC) criterion proposed by Bai and Wierzbicki [4]. It is found that the same phenomenon of stress state dependency exists in the ELCF, which need to be addressed. The mechanism linkage between these two failure modes was explored.

Introduction

Ductile fracture is an important failure mode for many materials and structures including turbomachines. For example, the foreign object damage (FOD) on the blade and casing is a design factor in aircraft engines and turbomachinery under extreme loading conditions [2], Here are two examples of FOD on turbomachines. The first one is bird/ice/hail strike on aircraft engines fan blades and further ingestion into the engine hot sections, which may cause blade out and further damage on engine casing. Each year, bird and other wildlife strikes to aircraft (including engines and fuselage) cause more than $600 million in damage to U.S. civil and military aviation [5]. The second one is the bolts and nuts (or other hard bodies) passing screen and ingestion into gas/steam turbines, which may cause damage on high speed rotating blades [3]. One critical technique here is the accurate prediction of ductile fracture under complex loading conditions. Extremely low cycle fatigue (ELCF) is another critical failure mode for turbomachinery. For example, the damage caused by frequently turning on and off in gas turbines. It is also one of important failure mechanisms of aircraft engine casings under blade out events, which can be caused by, for instance, foreign object impacts as described above.

Fatigue crack growth and life prediction of Inconel 718 was studied by Chen et al. [7] at different temperatures. They discovered that the fatigue strength is considerably lesser at room temperature than at elevated temperature. A recent published paper by Shamsaei et al. [8] studied the fatigue life estimation of Inconel 718 when subjected to multiaxial loading based on their basic tensile properties and the without using any fatigue data. It was found that fatigue life could be estimated using simple tensile properties and suitable damage models. Lately, Ince & Glinka [9] proposed a generalized fatigue damage parameter for multiaxial fatigue life prediction. This new parameter was examined using steel and Inconel 718 superalloy. Their numerical results show good agreement with the experimental data. Generally, low cycle fatigue under multiaxial loading damage models (strain-based models) has shown great results and correlations. Strain based damage models implicitly incorporates the significance of the plastic deformation [10-14].

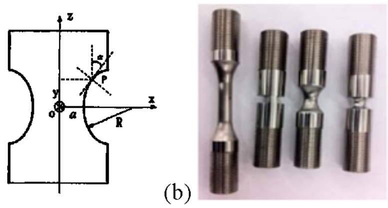
The common thing between these two failure modes is that notable plastic deformation is involved before material failure. Material fatigue failure can be divided into three groups: high cycle fatigue, low cycle fatigue and extremely low cycle fatigue. The ductile fracture can be treated as an extreme case of ELCF with only 1/4 cycle. The ELCF is the bridge to link the fatigue and fracture mechanics. Study on ductile fracture and ELCF of Inconel 718 (IN718) under multiple axial loading conditions and failure mechanism/linkage of these two failure modes is the main subject of this paper. The chemical composition of IN718 studied by the authors is listed in Table 1.

Table 1: Material composition of the used Inconel 718

Element	Content wt%	Element	Content wt%
Ni	52.90	Al	0.58
Cr	18.41	Co	0.19
Mo	2.89	C	0.04
Cb+Ta	5.17	S	0.0005
N	0.0078	Mn	0.09
Si	0.08	B	0.004
Cu	0.06	P	0.007
Fe	Bal.		

Multiaxial Ductile Fracture

Multiaxial ductile fracture under monotonic loading condition is the baseline for studying ELCF. Four types of specimens (Fig. 1) are designed and tested: smooth round bars (denoted by type R0), round bar with notch ratio 1 ($\frac{a}{R}=\frac{0.125''}{0.375''}=\frac{1}{3}$ where a is the minimal cross-section radius, and R is the notch radius, denoted by type R1), round bar with notch ratio 2 ($\frac{a}{R}=\frac{0.125''}{0.125''}=1$, type R2), and plane strain tension (denoted by type PE). The dimensions of all four different specimens shape are clearly shown in Fig. 2, and all units declared are mm in the drawings.



(a) (b)

Figure 1: (a) Symbol notation of the cross section of a notched specimen (b) Four different shapes of the specimens before fracture.

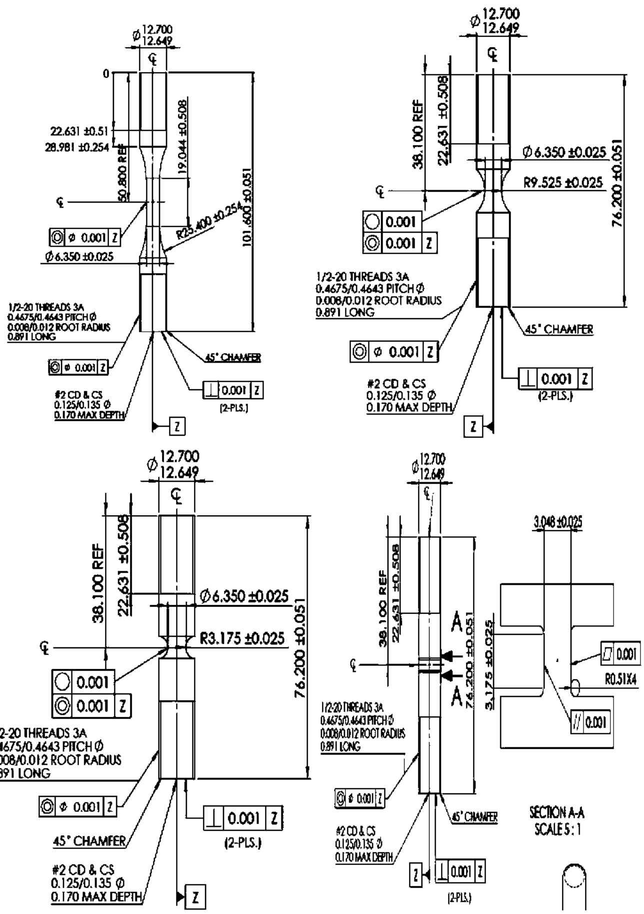
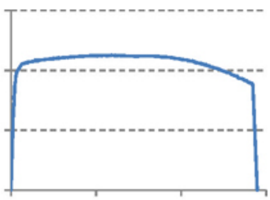
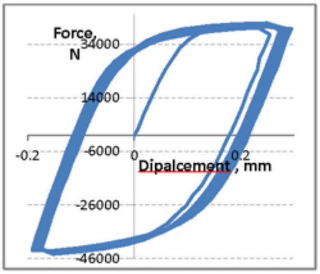


Figure 2: Drawings show different dimensions of four types of specimens. The specimens notation used are R0, R1, R2, and PE (from left to right)

All the tests were conducted at room temperature and quasi-static loading conditions at a MTS servo-hydraulic testing machine. The used MTS hydraulic machine has a capacity of 100kN. A collection of one of each specimen before testing is shown in Fig. 1(a). The fractured surfaces of specimens are shown in Fig. 4. Cup-cone failure modes and slant fracture surface indicate that the fracture is shear dominated. The material initial yield stress is about 1050MPa, and the engineering stress-strain curve is shown in Fig. 3(a). The material strain hardening can be described by the following power hardening law, $\bar{\sigma} = 1480.3\bar{\varepsilon}^{\,0.0813}$.



(a)



(b)

Figure 3: (a) Engineering stress vs. strain hardening curve obtained from smooth round bar specimen (R0). (b) One example of the displacement controlled extremely low cycle fatigue test for R1 notched specimen.

(a)

(b)

Figure 4: (a)The specimens were spray painted in black and white before the ELCF test for optical measurement and digital imaging correlation. From left to right are R0, R1, R2, and PE, respectively. (b) Fractured specimens after ELCF tests of R1(a/R=1/3, left) and R2(a/R=1, right)

The classical Mohr-Coulomb criterion was extended by Bai and Wierzbicki [4] to describe ductile fracture under multi-axial loading conditions. This model is referred as the modified Mohr-Coulomb (MMC) model. The equivalent plastic strains to fracture of all tests are directly measured by area reduction or thickness reduction. The stress triaxiality and Lode angel parameter are calculated using derived analytical solutions [6]. For round specimens (R0, R1, & R2), the Lode angle parameter is $\bar{\theta} = 1$, and the stress triaxiality η can be estimated using the Bridgman equation (Eq. 1.a).

$$\eta = \frac{1}{3} + \ln\left(1 + \frac{a}{2R}\right) \qquad (1.a)$$

For plane strain specimens (PE), the Lode angle parameter is $\bar{\theta} = 0$, and the following equation (1.b) is used for stress triaxiality [6].

$$\eta = \frac{\sqrt{3}}{3}\left[1 + 2\ln\left(1 + \frac{a}{2R}\right)\right] \qquad (1.b)$$

The calibrated 2D and 3D fracture locus using MMC model are shown in Fig. 5. Note that the stress triaxiality and Lode angle parameter are used to describe different stress states under multi-axial loading conditions. Experiment results show that the fracture limits of IN718 are strongly dependent on the stress triaxiality and weak dependent on the Lode angle parameter.

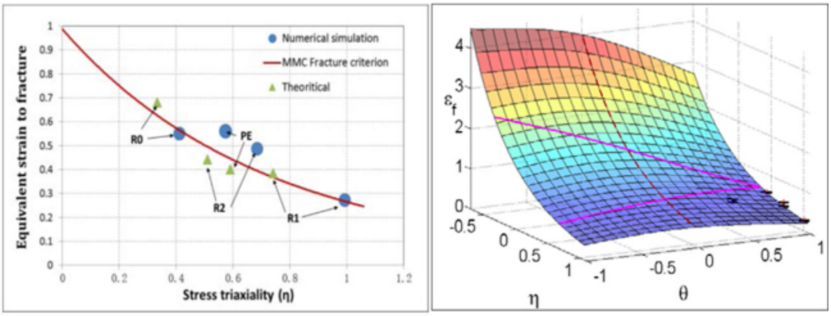


Figure 5: (a) Calibrated ductile 2D fracture locus of IN718 and a generic 3D fracture surface with the Lode angle dependency. (b) 3D fracture locus of IN718. Stress triaxiality is denoted by η, Lode angle parameter θ, and equivalent strain to fracture ε_f

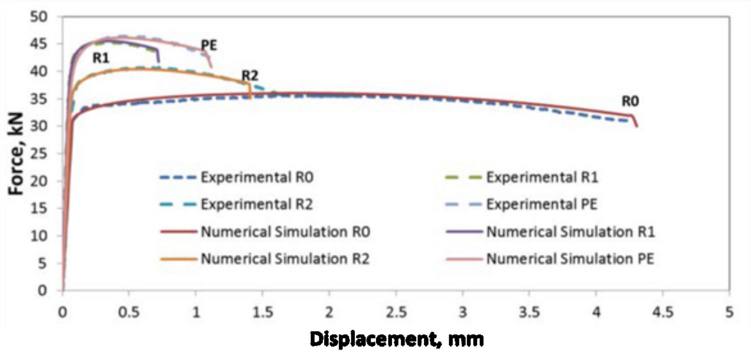


Figure 6: The applied modified Mohr-Coulomb failure criterion in Finite Elements simulations shows good agreement with the experimental results in monotonic ductile fracture tests.

Extremely Low Cycle Fatigue

Fully reversed displacement controlled fatigue tests were conducted on the same type of specimens as ductile fracture tests to calibrate the ELCF properties of IN718. The test had a total number of 16 specimens with 4 pieces for each shape. Before testing, the estimated numbers of cycles to failure range from 5 to 100 cycles. Note that the real cycles to failure were different. Real failure cycles are used when the data are presented in strain life diagram. Digital Imaging Correlation (DIC) was utilized to capture the full field strain and determine strain amplitude during tests. The force – displacement hysteresis loops were observed and recorded by the help of the DIC. It is noticeably observed in Fig. 3.b that the plasticity of Inconel 718 should be described using a combined hardening law (isotropic and kinematic hardening). The tests were run until total failure and the numbers of cycles were counted.

The measured strain results are divided into two parts: elastic strain amplitude and plastic strain amplitude for ELCF (see Equ. 2. a).

Using the equations in (2.b & 2.c) and with accurate measurements of the changes in the diameters and axial displacement during the ELCF tests by the help of DIC, we can measure the changes of the total strain in each cycle during tests. Equ. (2.b) is used for R0, R1, and R2 while Equ. (2.c) is only applied for plane strain PE. The strain in each cycle for specimen R1 is presented in Fig. 7.

$$\bar{\varepsilon} = \bar{\varepsilon}_e + \bar{\varepsilon}_p \qquad (2.a)$$

$$\bar{\varepsilon} = 2\ln\left(\frac{D_0}{D}\right) \qquad (2.b)$$

$$\bar{\varepsilon} = \frac{\sqrt{3}}{2}\ln\left(\frac{L}{L_0}\right) \qquad (2.c)$$

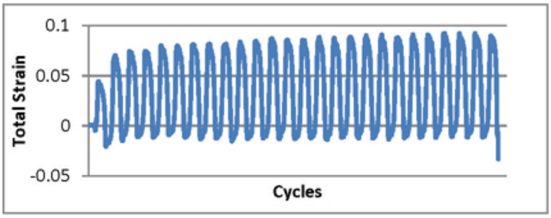


Figure 7: Total Strain vs. cycles for specimen R1.

These results are illustrated in the strain life curve, as shown in Fig. 8. The fractured specimens of two ELCF tests are shown in Fig. 8.

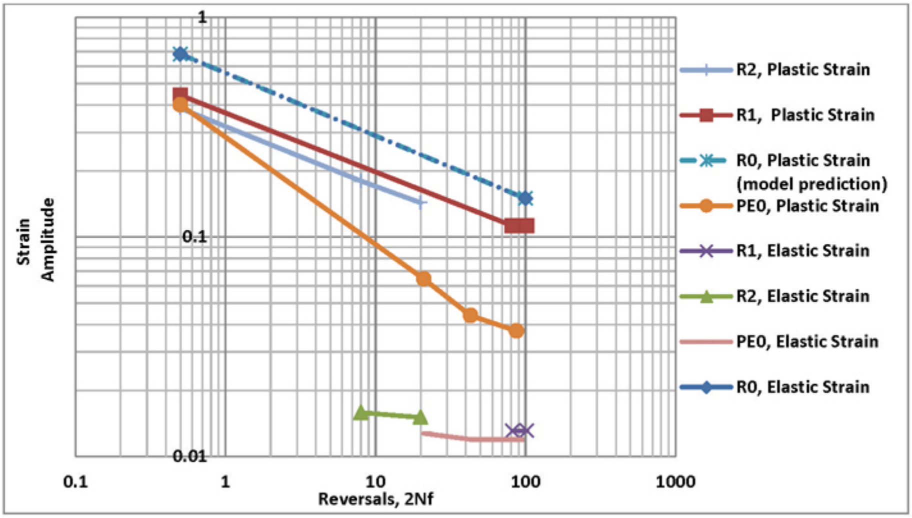


Figure 8: Dependence of fatigue life on plastic strain and different stress states (each cycle has two strain reversals)

The results shown in Fig. 8 can tell us that fracture strain's strongly dependency on stress states (due to the difference of stress triaxiality and Lode angle parameter) give different starting points at 1/4 to failure in strain-life plot. These differences have propagated to the region of ELCF. It should be noted that the data point of smooth round specimen (R0) at 100-cycle ELCF is from model estimation because significant buckling was found in the compression loading and tests were stopped.

Conclusion and Discussion

This paper presents results on ductile fracture of IN718 under multi-axial loading conditions, which is achieved by novel design of specimen geometry. Four types of specimens are used to calibrate the fracture of IN718. It is found that ductile fracture strain of IN718 is strongly dependent on the stress states, especially the stress triaxiality. This phenomenon is usually contributed to the effect of hydrostatic pressure on the micro void growth and nucleation rate. The ELCF tests on IN718 on the same group of specimens indicate that the similar pressure dependent mechanism applies to ELCF, which was seldom addressed in the literatures. This paper presents a novel method using stress triaxiality to describe the notch effect on material fatigue.

The current tests were conducted under room temperature, quasi-static loading and fully reverse loading conditions. The effect of frequency, temperature, and loading history effects will be needed to investigate as well, and the coupling effects of these parameters should also be studied in the future.

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