

Mean stress effects on Low-Cycle Fatigue behaviour of Inconel 718 alloy

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Abstract. Uniaxial and biaxial fatigue test results related to Inconel 718 specimens are analysed by using the critical plane-based multiaxial fatigue criterion by Carpinteri et al., formulated in terms of strain, in conjunction with a model similar to that by Smith-Watson-Topper (SWT). More precisely, both smooth solid specimens and thin-walled tubular specimens subjected to proportional and non-proportional loading consisting of tension, torsion, and combined tension and torsion loading under strain control are examined, for strain ratio equal to 0 or -1. Fatigue life is then analytically computed through the above procedure and compared with the experimental one, in terms of number of loading cycles needed to form a surface crack whose length is equal to 1 mm.

1. Introduction

Under static loading, fracture in metals can be classified as either ductile or brittle, depending whether or not material plastic deformation develops before failure. Ductile fracture is characterized by tearing of metal and significant plastic deformation. Brittle fracture is characterized by either transgranular (cleavage) or intergranular fracture, and little or no plastic deformation. Therefore, brittle fractures are invariably stress-controlled since they involve breaking of atomic bonds, while ductile fractures are invariably strain-controlled since they involve slip mechanisms.

Under time-varying loading, crack propagation in metals can be classified as either ductile-like or brittle-like, depending whether or not large amount of plastic deformation around the crack tip occurs.

Ductile-like crack propagation is produced by loading a specimen up to strain level beyond the elastic limit, testing being conducted in strain control (low-cycle fatigue, LCF, testing). Brittle-like crack propagation is produced by loading a specimen up to strain level below the elastic limit, testing being conducted in stress control (high-cycle fatigue, HCF, testing).

By focusing the attention on LCF testing, strain hardening, strain softening and mean stress relaxation can take place, until a stable state is achieved (steady state condition), depending on the mode of the controlled variable (that is, fully reversed or pulsating loading). More precisely: under fully reversed testing, material hardens (that is, the uncontrolled stress increases) or softens (that is, the uncontrolled stress decreases) depending on the value of the strain range, whereas the presence of a prescribed mean

strain superimposed to a constant amplitude strain produces a mean stress relaxation. In such cases, fatigue damage models have to be developed considering the tensile stress effect.

For uniaxial fatigue loading, several models are available in the literature in order to take into account the above tensile stress effect [1-3]. The problem is more complex in the case of multiaxial fatigue loading. A new methodology is presented here for the latter case of loading, employing the critical plane-based criterion by Carpinteri et al. [4, 5] in conjunction with a model similar to that by Smith-Watson-Topper (SWT) [3]. Note that the maximum value of the applied axial stress in SWT equation is here proposed to be replaced with the amplitude of an equivalent stress related to the critical plane.

The effectiveness of the proposed methodology is evaluated through comparison with experimental data related to 17 specimens made of Inconel 718, under uniaxial and biaxial fatigue strain-controlled loading [6].

2. Fatigue tests on Inconel 718

The specimens here examined, tested during an experimental campaign [6], are made of nickel-based super alloy Inconel 718. Uniaxial fatigue tests under tension and torsion were performed on solid smooth specimens, and the nominal strain amplitudes, $\epsilon_{z,a}$ and $\gamma_{zt,a}$, applied to such specimens are listed in Table 1 (see tests from T1 to T6). Biaxial fatigue tests under combined tension and torsion were performed on tubular specimens, and the nominal strain amplitudes and corresponding mean values, $\epsilon_{z,m}$ and $\gamma_{z,m}$, are listed in Table 1 (see tests from T7 to T17).

Table 1. Biaxial fatigue data. The phase shift, β , is expressed in degrees and stresses in MPa.

No.	$\epsilon_{z,a}$	$\epsilon_{z,m}$	$\gamma_{zt,a}$	$\gamma_{zt,m}$	β	$\sigma_{z,a}$	$\sigma_{z,m}$	$\tau_{zt,a}$	$\tau_{zt,m}$
T1	0.010	0	0	0	-	1095	-26.5	0	0
T2	0.005	0	0	0	-	927.5	-24.5	0	0
T3	0	0	0.0176	0	-	0	0	600.5	2.5
T4	0	0	0.0087	0	-	0	0	536.5	-5.5
T5	0	0	0.0054	0	-	0	0	415	-5
T6	0	0	0.0043	0	-	0	0	304.5	-29
T7	0.0071	0	0.0123	0	0	755	-27.5	431	15.5
T8	0.0035	0	0.0061	0	0	633	-56.5	388	16
T9	0.0015	0	0.0027	0	0	326	-1	200.5	-5.5
T10	0.0035	0	0.0062	0	45	515	-19	495.5	28
T11	0.0071	0	0.0123	0	90	999	-30.5	559.5	-3.5
T12	0.0035	0	0.0062	0	90	758	-26.5	463	-5.5
T13	0.0035	0	0.0063	0.0063	180	634	90.5	393.5	123
T14	0.0071	0.0071	0.0123	0.0123	0	751	119	419	-71
T15	0.0035	0.0035	0.0063	0.0063	0	646	170	396	52
T16	0.0015	0.0015	0.0026	0.0026	0	311	327	190	198
T17	0.0035	-0.0035	0.0063	-0.0063	0	596	-201.5	378	-36

All tests were conducted by using an MTS Model 809 axial-torsion test system, in strain control and LCF regime. Stress-strain loop data were registered. Both uniaxial and biaxial tests with strain ratio equal to -1 showed strain softening, whereas mean stress relaxation was observed for all tests with strain ratio equal to 0. Measured stress amplitudes and corresponding mean values, listed in Table 1, are related to a number of loading cycles corresponding to half fatigue life.

During testing, crack growth was monitored by using replica technique. Cracks always initiated on the outside surface of the specimen. The specimen life to 1mm of crack length was determined by exploiting such a technique. Failure was defined at specimen separation or at 10% drop in tensile load carrying capacity of the specimen.

3. The proposed procedure to fatigue life estimation

Generally, fatigue analysis is performed at point P of the specimen being examined, located on the specimen surface (Figure 1). Under biaxial fatigue loading, conducted in strain control, consisting in synchronous constant-amplitude cyclic tension and torsion:

$$\varepsilon_z(t) = \varepsilon_{z,a} \sin\left(\frac{2\pi t}{T}\right) + \varepsilon_{z,m} \tag{1}$$

$$\gamma_{zt}(t) = \gamma_{zt,a} \sin\left(\frac{2\pi t}{T}\right) + \gamma_{zt,m} \tag{2}$$

the strain tensor at point P , with respect to the fixed frame $Prtz$ shown in Fig.1, is represented by:

$$\boldsymbol{\varepsilon} = \begin{bmatrix} -\nu_{eff} \varepsilon_z & 0 & 0 \\ 0 & -\nu_{eff} \varepsilon_z & \frac{1}{2} \gamma_{zt} \\ 0 & \frac{1}{2} \gamma_{zt} & \varepsilon_z \end{bmatrix} \tag{3}$$

where ν_{eff} is the effective Poisson ratio.

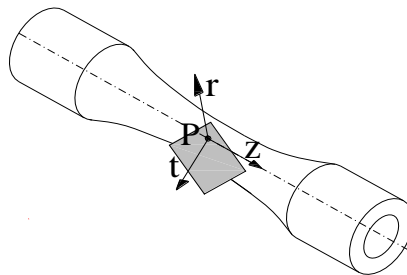


Fig. 1. Specimen being examined: fixed frame $Prtz$.

According to the Carpinteri et al. criterion formulated in terms of strain [4,5], firstly the critical plane, which is assumed to be correlated to an averaged maximum principal strain direction, has to be determined.

At a generic time instant t , the principal strains at point P ($\varepsilon_1 \geq \varepsilon_2 \geq \varepsilon_3$) can be computed from the strain tensor $\boldsymbol{\varepsilon}$, and the corresponding principal strain directions $1, 2, 3$ can be identified by exploiting the principal Euler angles ϕ, θ, ψ . The time varying frame $P123$ corresponding to the time instant when ε_1 attains its maximum value, over a loading cycle, is assumed as the averaged principal strain frame, $P\hat{1}\hat{2}\hat{3}$.

The orientation of the critical plane is here defined by assuming that the normal \mathbf{w} to such a plane and the direction $\hat{1}$ form an angle equal to 45° , being the rotation of the $\hat{1}$ -axis towards \mathbf{w} clockwise and around the $\hat{2}$ direction. The underlying physical reasoning is to assume, in the case of LCF, the critical plane as coincident with the plane of maximum shear deformation, which is typically regarded as the initiation crack plane.

Let us consider a local frame $Puvw$, where the u -axis is defined as the intersection line between the critical plane and the plane containing the \mathbf{w} vector and z -axis, and v -axis forms a right-handed frame together with u and z .

The displacement vector $\boldsymbol{\eta}$ at point P , related to the critical plane, can be computed from the strain tensor determined with respect to $Puvw$. Such a vector may be decomposed in:

(i) a normal vector $\boldsymbol{\eta}_N$:

$$\boldsymbol{\eta}_N(t) = \varepsilon_w(t) \mathbf{w} \tag{4}$$

whose direction is fixed with respect to time. Therefore, its amplitude $\eta_{N,a}$ is given by:

$$\eta_{N,a} = \max_{0 \leq t < T} |\boldsymbol{\eta}_N(t)| - \min_{0 \leq t < T} |\boldsymbol{\eta}_N(t)| \tag{5}$$

(ii) a tangential vector $\boldsymbol{\eta}_C$:

$$\boldsymbol{\eta}_C(t) = \frac{1}{2} \gamma_{uw}(t) \mathbf{u} + \frac{1}{2} \gamma_{vw}(t) \mathbf{v} \tag{6}$$

and the tip of such a vector describes, during the period T , a closed curve Σ on the critical plane. Therefore, its amplitude $\eta_{C,a}$ is computed by applying the minimum bounding circle method by Papadopoulos [7].

Firstly, the centre of the minimum circumscribed circle to the curve Σ is determined:

$$\boldsymbol{\eta}_{C,m} = \min_{\boldsymbol{\eta}'} \left\{ \max_{0 \leq t < T} \|\boldsymbol{\eta}_C(t) - \boldsymbol{\eta}'\| \right\} \tag{7}$$

where $\boldsymbol{\eta}'$ is a vector on the critical plane, identifying an arbitrary centre. Once $\boldsymbol{\eta}_{C,m}$ is found, the amplitude $\eta_{C,a}$ is obtained as follows:

$$\eta_{C,a} = \max_{0 \leq t < T} \|\boldsymbol{\eta}_C(t) - \boldsymbol{\eta}_{C,m}\| \tag{8}$$

An equivalent normal strain amplitude $\varepsilon_{eq,a}$, connected to the critical plane, is taken into account to perform the fatigue assessment:

$$\varepsilon_{eq,a} = \sqrt{\eta_{N,a} + 3\eta_{C,a}} \tag{9}$$

By equalling Eq.(9) to a like Smith-Watson-Topper (SWT) equation expressed as follows:

$$\varepsilon_{a,SWT} = \frac{1}{\sigma_{eq,a}} \left[\frac{(\sigma'_f)^2}{E} (2N_f)^{2b} + \sigma'_f \varepsilon'_f (2N_f)^{b+c} \right] \tag{10}$$

the value of the number of loading cycles to failure, N_f , can be work out. In Equation (10), E is the Young modulus, and $\sigma'_f, \varepsilon'_f, b, c$ are material constants to be determined by running appropriate uniaxial fatigue tests. Note that in Eq.(10) the maximum value of the applied axial stress, $\sigma_{z,max}$, is replaced with the amplitude of an equivalent stress related to the critical plane, $\sigma_{eq,a}$, given by:

$$\sigma_{eq,a} = \sqrt{N_{max}^2 + \left(\frac{\sigma_{af,-1}}{\tau_{af,-1}} \right)^2 C_a^2} \tag{11}$$

where N_{max} is the maximum normal stress and C_a , evaluated according to the procedure presented in Ref.[7], is the shear stress amplitude acting on the critical plane. Further, $\sigma_{af,-1}$ is the fully-reversed normal stress fatigue strength, and $\tau_{af,-1}$ is the fully-reversed shear stress fatigue strength. Such a proposal (see Eq.(10)) allows us to apply the criterion even in the case of pure torsion (that is, $\sigma_{z,max} = 0$). Note that Eq.(11) is equal to that implemented in the critical plane-based criterion proposed by Carpinteri et al. formulated in terms of stress [8].

4. Results

The test data presented in Section 2 are examined through the methodology herein proposed. The material mechanical and fatigue properties are listed in Table 2, whereas the effective Poisson ratio ν_{eff} is equal to 0.5.

Table 2. Mechanical and fatigue properties of Inconel 718.

E [MPa]	σ'_f [MPa]	b (-)	ε'_f [-]	c [-]	$\sigma_{af,-1}$ [MPa]	$\tau_{af,-1}$ [MPa]
208500	3950	-0.151	1.5	-0.761	442	251

Figure 2 shows the comparison between experimental data and theoretical estimations in terms of fatigue life. The solid line indicates $N_{exp} = N_f$, the dashed lines correspond to

N_{exp} / N_f equal to 0.5 and 2 (scatter band 2), and the dot-dashed lines correspond to N_{exp} / N_f equal to 1/3 and 3. Figure 2 demonstrates that 71% of the estimated results are conservative. Further, 94% of the estimated results fall within the scatter band 2, whereas all of them fall within the scatter band 3.

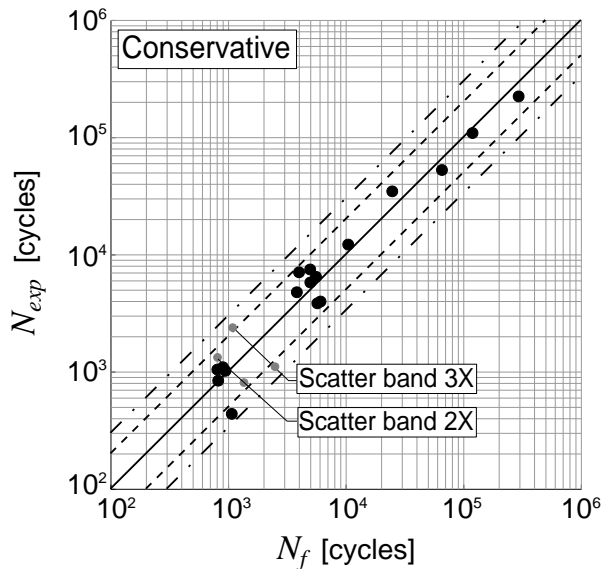


Fig.2. Comparison of the experimental fatigue lifetimes and the theoretical ones, estimated through the proposed methodology.

5. Conclusions

Fatigue tests related to Inconel 718 specimens have been analysed by using the critical plane-based multiaxial fatigue criterion by Carpinteri et al. formulated in terms of strain in conjunction with a model similar to that by Smith-Watson-Topper (SWT).

The proposed modification of the SWT equation consists in replacing the maximum value of the applied axial stress with the amplitude of an equivalent normal stress, related to the critical plane. Such a replacement allows us to apply the criterion even in the case of pure torsion.

Fatigue life has been analytically computed through the above procedure and compared with the experimental one, in terms of number of loading cycles needed to form a surface crack whose length is equal to 1 mm.

The agreement is quite satisfactory. Therefore, the implementation of a like SWT equation in the Carpinteri et al. criterion seems to be a promising tool to assess the fatigue life of metallic structural components under LCF regime and strain control, characterised by strain hardening, strain softening or mean stress relaxation.

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