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Multiaxial fatigue behavior of 2618 aluminum alloy

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Abstract. The purpose of the present research project is to study multiaxial fatigue behavior of 2618 alloy. The influence of mean stress on the fatigue behavior under tension and torsion is particularly investigated. Fatigue tests under combined tensile-torsion, in or out of phase, as well as combined tensile-torsion-internal pressure tests have also been conducted. Multiaxial fatigue results are analyzed according to Fatemi-Socie criterion to predict the fatigue life.

1 Introduction

Aluminum alloys take the first rank in nonferrous materials and are the engineering materials of choice for several industrial applications; they are for instance widely used in aeronautic construction because of their good mechanical properties and low density.

Numerous fatigue studies concerning these materials are focused on uniaxial loading. However, the aeronautical parts usually experience multiaxial fatigue loading during service and previous studies [1,2] showed that mean shear stress could have a detrimental effect on fatigue life. Evaluating fatigue life under complex loading conditions is therefore essential to understand the behavior of the component or the structure and to assess its safety and durability.

Very few studies dealing with the effect of mean shear stress on the fatigue lifetime of aluminum alloys have been done, but in fact, this effect is very important because it makes the fatigue life decreased [1,2,3] and several components are subjected to unsymmetrical loading while in service.

Many authors reached the conclusion that mean shear stress does not affect the fatigue life [4,5] as long as the maximum shear stress is below the yield strength. The effect of the mean shear stress is not clear in the high cycle fatigue, but become obvious in the low cycle fatigue [6].

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In addition, it has been demonstrated for an aluminum alloy from 2xxx series that fatigue life gradually reduces with increasing mean shear stress when this latter is lower than a threshold value [1,7].

In the current study, the purpose of the research project about 2618 alloy is to study its multiaxial fatigue behavior. The influence of mean stress on the fatigue behavior under tension and torsion is particularly investigated. Fatigue tests under combined tensile-torsion, in or out of phase, as well as combined tensile-torsion-internal pressure tests have also been conducted. It is important to note that research works with internal pressure loading is rare [8]. Multiaxial fatigue results are analyzed according to Fatemi-Socie multiaxial fatigue criterion to predict the fatigue life. Fracture surface observations and in particular crack initiation sites were also performed in order to broaden this analysis.

2 Material and experimental procedures

2.1 Material

The material used in the present study is 2618-T851 aluminum-copper alloy developed by Rolls Royce (RR58) and characterized by high mechanical characteristics and low density. The chemical composition and mechanical properties are respectively presented on table 1 and table 2.

The material has been heated at $530^{\circ}\text{C}\pm 5^{\circ}\text{C}$ to dissolve some intermetallic particles such as Al_2CuMg , Al_2Cu et $\text{Al}_7\text{Cu}_4\text{Ni}$ [9,10], water quenched then tempered at 190°C (the maximal hardness is obtained at this temperature [11]). The material is deformed by tension and then quenched and tempered at 200°C during some minutes to give the mechanical properties cited in table 2.

Table 1. Chemical composition of 2618-T851.

	Cu	Fe	Mg	Si	Ni	Ti	Zn	Mn	Al
atomic %	0,9-1,5	0,4-0,6	1,5-2	0,2	0,2-0,6	0,15	<0,1	<0,15	Rest

Table 2. Mechanical properties of 2618-T851 alloy.

Young modulus E (GPa)	Ultimate tensile strength (MPa)	Tensile yield strength (0,2%) (MPa)	Shear modulus G (GPa)	Shear yield strength (0,2%) (MPa)	Ratio σ_y/τ_y
72	464	438	27	260	1,69

For the microstructure, 2618-T851 alloy is characterized by the presence of many various intermetallic precipitates localized in grains and grain boundaries and divided in two types, the coarse particles ($\geq 1\mu\text{m}$) and hardened particles ($\leq 200\text{nm}$) as shown in figure 1.

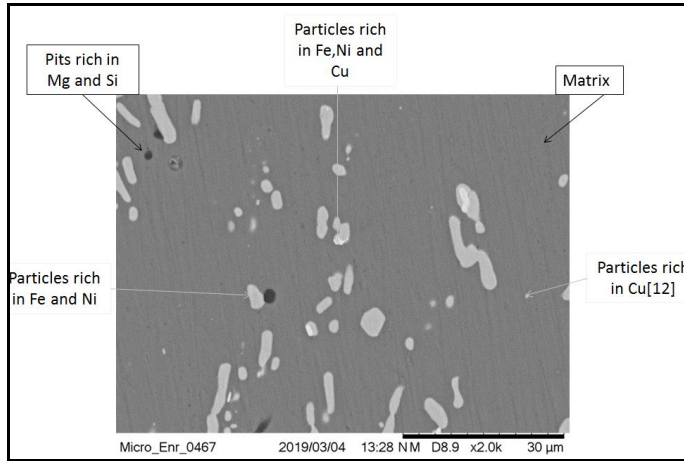


Fig. 1. Microstructure of 2618-T851 aluminum alloy.

2.2 Fatigue tests

In this study, all the load-controlled fatigue tests were carried out at room temperature by a special testing MTS-809 machine. The testing machine is hydraulic multiaxial fatigue machine that can combine tension, torsion, and cyclic internal pressure loading until 1200 bars.

Two different specimen geometries are used as shown in figures 4 and 5. One is the full cylindrical specimen (figure 2) used for tension and/or torsion loading, and the other is the hollow cylindrical specimen (figure 3) used for internal pressure loading.

The surface roughness is 0,8 μm for all the specimens. It was shown in a previous study that surface roughness has no effect on fatigue life of 2618-T851 with different surface arithmetic roughness levels corresponding to general industrial values in tension and torsion [13].

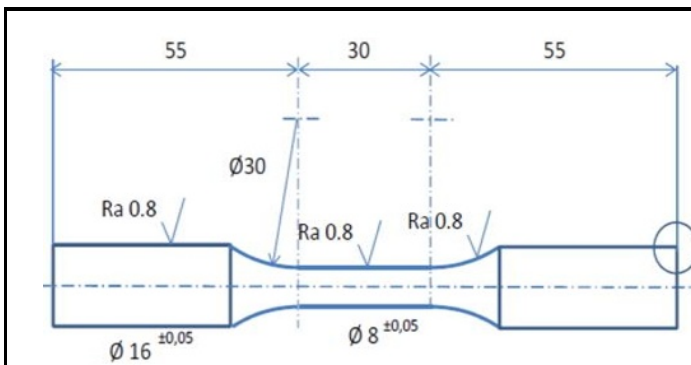


Fig. 2. Cylindrical specimen geometry (dimensions are in mm).

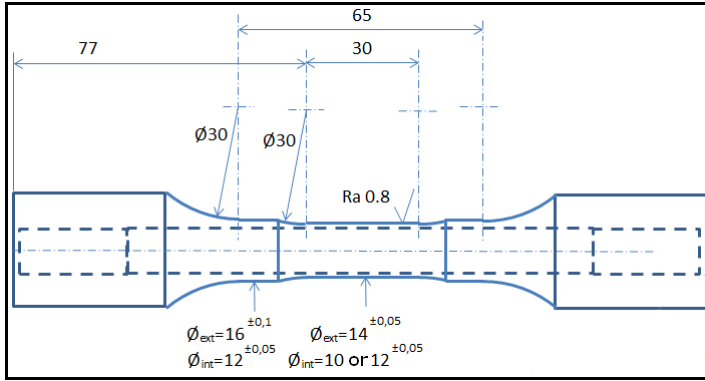


Fig. 3. Hollow cylindrical specimen geometry (dimensions are in mm).

Uniaxial fatigue tests have been conducted under several stress ratios (-2, -1 and 0,1) with a frequency of 10 Hz, the variation of strain time dependency was determined using biaxial extensometer.

2.3 Multiaxial stress states of hollow specimen

When the internal pressure is applied, the stress state in cylindrical coordinates is given by the following equations:

$$\sigma_r(t) = \frac{Ri^2 p_i(t)}{Re^2 - Ri^2} \left(1 - \frac{Re^2}{r^2} \right) \quad (1)$$

$$\sigma_\theta(t) = \frac{Ri^2 p_i(t)}{Re^2 - Ri^2} \left(1 + \frac{Re^2}{r^2} \right) \quad (2)$$

$$\sigma_{r\theta}(t) = 0 \quad (3)$$

The variation of the three stresses along the radius 'r' is shown in figure 4 where the stress components coming from the analytical analysis and from finite element computing are compared. Figure 4 illustrates the perfect coherence between the analytical and the numerical models.

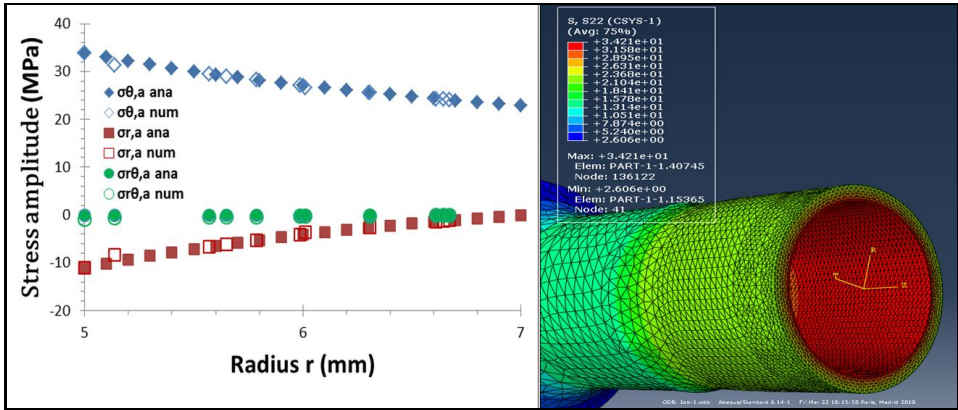


Fig. 4. Left side: variation of stresses (analytical and numerical) along the radius r. Right side: hoop stress. $P_{max}=244$ bars and $R=0,1$.

Understanding the variation of hoop and radius stresses along the radius in the case of a loading including internal pressure is of high importance to fully determine the stress states during combined loading and, in particular the position of the critical plane with the maximum shear stress for example, as seen in the following section.

3 Results and discussion

3.1 Effect of load ratio

In a previous study, tensile tests conducted with a positive stress ratio (0,1) and a negative stress ratio (-2) have shown that a positive mean stress makes the fatigue life decrease significantly [13]. This effect is well known and is observed for numerous metallic alloys [14].

Results for pure torsion fatigue tests are shown in figure 5. A positive mean shear stress reduces the fatigue life [2,3] even if the maximum shear stress is below the yield strength. This sensitivity is more important at low stress amplitude.

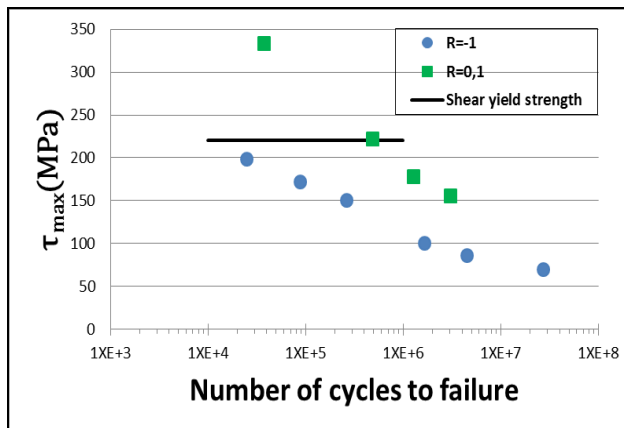


Fig. 5. Torsion S-N curve under different values of mean shear stress.

From these results, it is clear that the effect of mean shear stress must be taken into account to estimate fatigue life under multiaxial stress states.

3.2 Multiaxial loading results

Multiaxial fatigue tests have been carried out under tension-torsion loading with different mean normal/shear stress in-phase and out-phase (Table 3) and under multiaxial cyclic loading including internal pressure in different cases (Table 4).

Results of pure tension and torsion tests and internal pressure with tension or torsion are illustrated in figure 6. All the tests have been conducted with a stress ratio equal to 0,1 in each loading axe.

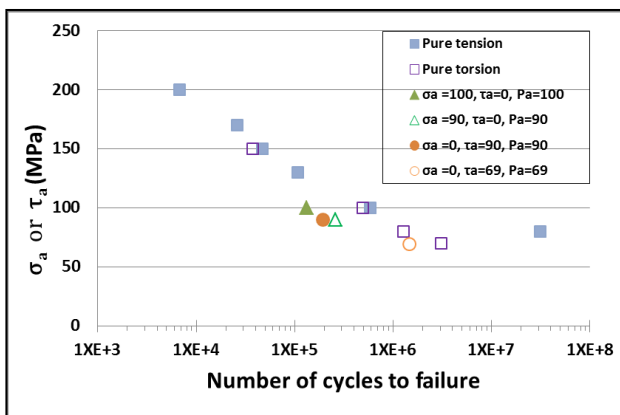


Fig. 6. Results of pure uniaxial tests and uniaxial tests combined with internal pressure; stresses are in MPa and pressure in bars, $R=0,1$.

Table 3. Tension-torsion fatigue test results, $f=10$ Hz.

σ_a (MPa)	τ_a (MPa)	σ_m (MPa)	τ_m (MPa)	ϕ ($^\circ$)	N_f (Cycles)
40	110	0	0	0	$1,24 \cdot 10^6$
95	193	0	0	0	$2,05 \cdot 10^4$
150	70	0	0	90	$2,81 \cdot 10^5$
150	70	0	0	0	$2,64 \cdot 10^5$
40	110	0	0	90	$1,17 \cdot 10^6$
137	97	0	0	0	$1,36 \cdot 10^6$
150	70	0	85,55	0	$9,95 \cdot 10^4$
150	100	0	122,22	90	$7,42 \cdot 10^4$
150	70	183,33	0	90	$3,36 \cdot 10^4$

Table 4. Multiaxial fatigue test results including internal pressure, $\phi=0^\circ$, $f=1$ Hz and $R=0,1$.

σ_a (MPa)	τ_a (MPa)	P_a (bars)	N_f (Cycles)
100	100	100	$1,9357 \cdot 10^4$
69	69	69	$1,13993 \cdot 10^5$
50	50	50	$>10^6$ (Whitout failure)
90	0	90	$2,586 \cdot 10^5$
100	0	100	$1,3295 \cdot 10^5$
0	135	90	16
0	90	90	$1,95 \cdot 10^5$
0	69	69	$1,4667 \cdot 10^6$

Results in Figure 6 show that for a given stress amplitude, the fatigue life is similar in tension and in torsion.

This is consistent with the case of cast aluminum alloys where the ratio (τ_D/σ_D) is usually close to 1,1 [15] (τ_D and σ_D are respectively fatigue limits in torsion and tension).

Adding internal pressure to uniaxial loading (tension or torsion) reduces the fatigue life and it seems that this detrimental effect is similar whatever the type of uniaxial loading combined with internal pressure (similar fatigue life time for tests performed with internal pressure of 90 bars combined with tension or torsion loading with a stress amplitude of 90 MPa) .

The results of the others tests combining tension and torsion in phase and out of phase as well as tension-torsion- internal pressure in phase will be analyzed in the last section.

3.2 Surface fracture analysis

Fracture surfaces observations were made to identify the different modes of fracture under the various load paths. The main microscopic fracture features are a combination of ductile intergranular and transgranular fracture. When torsion is applied, some abrasion marks appeared in some regions.

Whatever the nature of the loading, in the high cycle fatigue, the fatigue cracks initiated on a single site at the surface, and a coarse precipitate is found at the initiation site, as shown in figure 7. For two specimens tested in pure tension and broken over 10^7 cycles, the cracks initiated in sub-surface ($\sim 200 \mu\text{m}$ and $700 \mu\text{m}$ from the surface) on coarse grain.

It is also important to note that for hollow specimen tested with a loading including internal pressure, initiation sites were always on the outer surface, whatever the combinations and the values of the axial and/or shear stress amplitude.

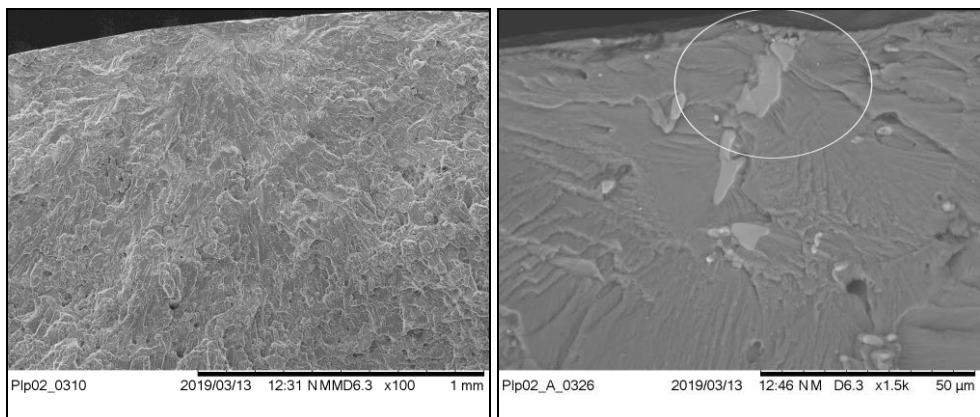


Fig. 7. Fatigue crack initiation site specimen tested in tension-internal pressure, $\sigma_a=100 \text{ MPa}$, $P_a=110$ bars and $R=0,1$ in each loading axe.

3.3 Fatigue life predictions

Critical plane-based fatigue life analyses were performed using Fatemi-Socie [16] concept to predict fatigue life for multiaxial loading. Fatemi and Socie defined the critical plane as the plane associated with the maximum shear strain amplitude.

Fatigue damage is supposed to be governed by the maximum shear stress amplitude ($\Delta\gamma_{max}/2$) and the maximum normal stress ($\sigma_{n,max}$) that are expressed on the model by the equation 4 below:

$$\frac{\Delta\gamma_{max}}{2} \left(1 + k \frac{\sigma_{n,max}}{S_y}\right) = \frac{\tau_f'}{G} (2N_f)^{b_0} + \gamma_f' (2N_f)^{c_0} \quad (4)$$

Where S_y is the material monotonic yield strength; it serves to normalize the maximum normal stress in order to preserve a dimensionless term, k is a material constant depending on number of cycles to failure. G is the shear modulus, τ_f' is the shear fatigue strength coefficient, γ_f' is the shear fatigue ductility coefficient, b_0 and c_0 are shear fatigue strength and shear fatigue ductility exponents, respectively.

In a first step, the identification of Fatemi-Socie approach parameters has been carried out from experimental tests obtained from uniaxial loading in tension ($R=-2$) and torsion ($R=-1$), using the least square method on the whole set of fatigue data.

In a second step, results of multiaxial fatigue tests have been compared to fatigue life predictions given by Fatemie-Socie model as illustrated in figure 8.

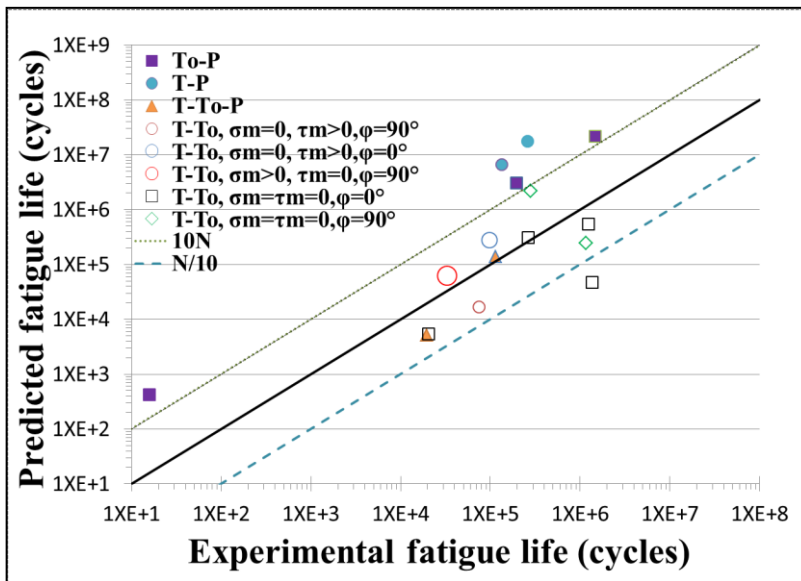


Fig. 8. Experimental vs Predicted fatigue life by FS model, ‘T, To and P’ refer, respectively, to tension, torsion and internal pressure, ϕ is the phase angle.

A very large scatter of the results is observed in figure 8. This shows that this criterion is not able to reproduce multiaxial fatigue behavior of 2618 aluminum alloy. In addition, in some cases, the model predicts that critical plane is in the inner surface. This is obviously contradictory to experimental observations that show systematic initiation on the outer surface.

4 Conclusion

In the present study, it has been proved that a mean shear stress has a negative impact on the fatigue life of 2618 alloy.

In the high cycle regime, the cracks occur on surface from coarse intermetallic particles and at more than 10^7 cycles, the cracks initiated on coarse grain in the sub-surface.

The predictions obtained using Fatemi-Socie model for this alloy are not in good agreement with experimental results. Other multiaxial fatigue criteria are currently under investigation.

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