Three-dimensional S-N curve method to estimate fatigue life of EN AW 6063.T66 aluminium alloy during combined loading under in-and-out of phase shift 0° and 90° and comparing with fatigue criteria


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Abstract: The article deals with determining of fatigue lifetime of structural materials during by multiaxial cyclic loading. The theoretical part deals with the fatigue and with criteria for evaluation of multiaxial fatigue lifetime, especially Fatemi-Socie, Smith-Watson-Topper, Brown-Miller and Liu. The experimental part deals with testing of specimens for identification of the strain-life behaviour of material and determining the number of cycles to fracture of aluminium alloy for phase shift 0° and 90°. Extensive fatigue experiments were conducted using 6063.T66 aluminium alloy under multiaxial bending-torsion loading.

KEYWORDS: ALUMINIUM ALLOY, MULTIAXIAL FATIGUE, FATIGUE LIFETIME, CRITERIA, CYCLIC LOADING

1. Introduction

Aluminium is one of the lightest engineering metals, having a high electrical conductivity. It is widely used for foil and packaging foils [1, 2, 3]. The versatility of aluminium makes it the most widely used metal in an ever-increasing number of applications. This array of products ranges from structural materials to thin packaging foils [1, 2, 3].

Fatigue failures in metallic structures are a well-known technical problem. In a specimen subjected to a cyclic load, a fatigue crack nucleus can be initiated on a microscopically small scale, followed by crack grows to a macroscopic size, and finally to the material surface is zero [6]. Another relatively simple idea could be successfully employed even by using the maximum stress normal to the critical plane, because the growth rate mainly depends on the stress component normal to the fatigue crack. Starting from this assumption, he proposed two different formulations according to the crack growth mechanism: when the crack propagation is mainly MODE I dominated, then the critical plane is that of maximum shear stress amplitude and the fatigue life can be estimated by using the torsion Manson-Coffin curve [9]. Criterion has the following form:

\[
\frac{\Delta y}{2} \times \left( 1 + k \times \frac{\sigma_{\text{max}}}{\sigma_y} \right) = \frac{\gamma'}{G} \times (2 \times \nu) + \gamma' \times (2 \times \nu)' \quad (1)
\]

Smith, Watson and Topper (SWT) created a parameter for multiaxial load, which is based on the main deformation range \(\Delta \varepsilon_l\) and maximum stress \(\sigma_{\text{max}}\) to the main plane. Criterion has the following form:

\[
\sigma_{\text{max}} \times \frac{\Delta \varepsilon}{2} = \frac{\sigma_y^2}{E} \times (2 \times \nu) + \sigma_y' \times (2 \times \nu)'' \quad (2)
\]
Brown and Miller [12] observed that the fatigue life prediction could be performed by considering the strain components normal and tangential to the crack initiation plane. Moreover, the multiaxial fatigue damage depends on the crack growth direction. Different criteria are required if the crack grows on the component surface or inside the material. In the first case they proposed a relationship based on a combined use of a critical plane approach and a modified Manson-Coffin equation, where the critical plane is the one of maximum shear strain amplitude. Criterion, which was created, has the following form:

\[
\frac{\Delta \gamma_{\max}}{2} + S \times \Delta \varepsilon_{\alpha} = A \times \frac{\sigma_f - 2 \times \sigma_{\alpha,\text{mean}}}{E} \times (2 \times N_f)^b + B \times \varepsilon_f \times \left(2 \times N_f\right)^c \tag{3}
\]

Liu created a virtual model of the deformation energy, which is a generalization of the axial energy on the basis of prediction of fatigue life. Criterion has the following form:

\[
\Delta W = 4 \times \sigma_f \times \varepsilon_f \times (2 \times N_f)^{b_{c}} + \frac{4 \times \sigma_f^2}{E} \times (2 \times N_f)^{2b} \tag{4}
\]

Where: \(\gamma_f\) is the fatigue ductility coefficient in torsion; \(\varepsilon_f\) is the fatigue ductility coefficient; \(\sigma_f\) is the fatigue strength coefficient; \(\sigma_{\alpha,\text{mean}}\) is the maximum stress; \(\sigma_{\alpha,\text{mean}}\) is the mean stress; \(\sigma_f\) is the stress in the direction of the axis y; \(\varepsilon_f\) is the fatigue strength coefficient in torsion; \(\Delta \gamma_{\max}\) is the maximum shear strain range; \(\Delta \varepsilon_{\alpha}\) is the normal strain range; \(\Delta W\) is the virtual strain energy; \(b\) is the fatigue strength exponent; \(b_t\) is the fatigue strength exponent in torsion; \(c\) is the fatigue ductility exponent; \(\varepsilon_f\) is the fatigue ductility exponent in torsion; \(N_f\) is the number of cycles to fracture; \(A, B, S, k, a\) are material parameters; \(E\) is the elasticity modulus in tension; \(G\) is the elasticity modulus in torsion.

3. Test material

The research was conducted on an AlMgSi07.F25 aluminium alloy: the EN AW 6063.T66 aluminium alloy. The EN AW 6063.T66 is a medium strength alloy, suitable for applications where no special strength properties are required. The T66 treatment corresponds to solution heat-treated and then artificially aged (precipitation hardened) to a higher level of mechanical properties through special control of a manufacturing process. The material used in this research was delivered in the form of a cylindrical shape with a diameter 10 mm. The length of cylindrical bars was 150 mm. The material was in a rolled state. The shape of test bar is shown in Fig.1. This test bar had a defined section, in which was expected an increased concentration of stress and creation a fatigue fracture.

4. Experimental strain-life data results

One hundred and ninety-five smooth specimens for phase shift 0° and one hundred and ninety-five smooth specimens for phase shift 90°, were tested under strain controlled conditions in order to identify the strain-life behaviour of the experimental material. After machining, the specimen surfaces were mechanically polished. The experiments were carried out in an electro mechanic fatigue test machine developed on University of Žilina (Fig.2 and Fig. 3). For evaluation of fatigue curves it needs to know stress and strain conditions on individual loading levels. A sinusoidal waveform was used as command signal. The fatigue tests were conducted with constant strain amplitudes, at room temperature, in air. The specimens were cyclic loaded under strain control with symmetrical proportional bending- torsion loading, with a nominal strain ratio, \(R_s = -1\).

The computational fatigue tests were performed under in-phase cyclic loading with the zero mean value. All tests were performed under controlled bending and torsion moments. Frequency of each analysis was equal to 30 Hz.

This research was conducted on an EN AW 6063.T66 aluminium alloy. This material is a medium strength alloy, suitable for applications where no special strength properties are required.
From experimentally measured values of number of cycles to failure was created three-dimensional fatigue curve $\varepsilon_{xx} - \gamma_{xy} - N_f$ for phase shift 0°, which is shown in Fig. 4.

For another analysis was used a Fatigue Calculator software [13]. This program can quickly calculate fatigue lifetime of selected material. In our calculation we considered with four multiaxial criteria described above.

From those calculated values of number of cycles to failure were created three-dimensional fatigue curves for phase shift 0°. In Fig. 5 is shown a three-dimensional fatigue curve for Fatemi-Socie criterion, in Fig. 6 is for SWT criterion, in Fig. 7 is for Brown-Miller criterion and in Fig. 8 is for Liu criterion.

From the experimentally measured fatigue values there was created three-dimensional fatigue curve $\varepsilon_{xx} - \gamma_{xy} - N_f$ for phase shift 90°, which is shown in Fig. 9.

Using by Fatigue Calculator software there were calculated values of number of cycles to failure of three-dimensional fatigue curves for phase shift 90°. From the Fig. 10 it can be seen a three-dimensional fatigue curve for Fatemi-Socie criterion, in Fig. 11 can be seen fatigue results for SWT criterion, in Fig. 12 can be seen fatigue results for Brown-Miller criterion and in Fig. 13 can be seen fatigue results for Liu criterion.
5. Conclusion

Every multiaxial criteria applied to fatigue lifetime calculation and also values of number of cycles to failure from experiment for specimens of aluminium alloy EN AW 6063.T66 increases with decreasing strain amplitude continuously in the cycles of number region. Comparing three-dimensional curves is evident that criteria from Fatigue Calculator give higher lifetime than experiment in the whole area of the number of cycles at the same load amplitudes. This may be caused by different material parameters, which were used for each models of damage. They probably do not include all real parameters and properties of the comparison of the experimental material that probably affected the sensitivity of the numerical calculation.

6. Acknowledgements

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7. References

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