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 the world’s most abundant metal and is the third most common element, comprising 8% of the earth’s crust. The versatility of aluminium makes it the most widely used metal after steel. Pure aluminium is soft, ductile, corrosion resistant and has a high electrical conductivity. It is widely used for foil and conductor cables, but alloying with other elements is necessary to provide the higher strengths needed for other applications. Aluminium is one of the lightest engineering metals, having strength to weight ratio superior to steel. By utilising various combinations of its advantageous properties such as strength, lightness, corrosion resistance, recyclability and formability, aluminium is being employed in an ever-increasing number of applications. This array of products ranges from structural materials through 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 specimen failure in the last cycle of the fatigue life. Understanding of the fatigue mechanism is essential for considering various technical conditions which affect fatigue life and fatigue crack growth, such as the material surface quality, residual stress, and environmental influence. This knowledge is essential for the analysis of fatigue properties of an engineering structure [4, 5].

Fatigue under combined loading is a complex problem. A rational approach might be considered again for fatigue crack nucleation at the material surface. The state of stress at the surface is two-dimensional because the third principal stress perpendicular to the material surface is zero [6]. Another relatively simple combination of different loads is offered by an axle loaded under combined bending and torsion. This loading combination was tested in our and also in many others experiments [7, 8]. In spite of this fact, fatigue mechanisms are still not fully understood. This is partly due to the complex geometrical shapes and also complex loadings of engineering components and structures which result in multiaxial cyclic stress-strain states rather than uniaxial.

2. Fatigue criteria

There are plenty of hypotheses used for evaluating a degree of damage caused by variable load [9, 10]. Life prediction methods which presume homogeneous material (free from cracks, inclusions or defects) at the outset of the investigation can be divided into strain-based (low-cycle fatigue) and stress-based (high-cycle fatigue) methods. Low-cycle fatigue is characterized by repeated plastic strains during cyclic loading conditions where fatigue failure occurs after relative low number of load cycles (in the order of 10^4 cycles). This design approach is normally used in fatigue assessment of local areas where high stress concentrations exist and the material response locally is repeated plastic deformation. In addition, stress-based approaches use the elastic stress range (or amplitude) as the governing load parameter. There were chosen four fatigue criteria: Fatemi-Socie, SWT, Brown-Miller and Liu fatigue criterion.

Fatemi and Socie [11] observed that the Brown and Miller’s 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 the one that experiences the maximum normal stress amplitude and the fatigue lifetime can be calculated by means of the uniaxial Manson-Coffin curve; on the other hand, when the growth is mainly MODE II governed, 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:

$$\frac{\Delta\gamma}{2} \times \left(1 + k \times \frac{\sigma_{n,max}}{\sigma_y}\right) = \frac{\tau_f^{'}}{G} \times \left(2 \times N_f\right)^{b_\gamma} + \gamma_f^{'} \times \left(2 \times N_f\right)^{c_\gamma} \qquad (1)$$

Smith, Watson and Topper (SWT) created a parameter for multiaxial load, which is based on the main deformation range $\Delta\varepsilon_1$ and maximum stress $\sigma_{n,max}$ to the main plane. Criterion has the following form:

$$\sigma_{n,max} \times \frac{\Delta\varepsilon_1}{2} = \frac{\sigma_f^{'2}}{E} \times \left(2 \times N_f\right)^{2b} + \sigma_f^{'} \times \varepsilon_f^{'} \times \left(2 \times N_f\right)^{b+c} \qquad (2)$$

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:

$$\frac{\Delta\gamma_{max}}{2} + S \times \Delta\varepsilon_n = A \times \frac{\sigma_f - 2 \times \sigma_{n,mean}}{E} \times \left(2 \times N_f\right)^b + B \times \varepsilon_f' \times \times \left(2 \times N_f\right)^c \quad (3)$$

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:

$$\Delta W = 4 \times \sigma_f' \times \varepsilon_f' \times \left(2 \times N_f\right)^{b+c} + \frac{4 \times \sigma_f'^2}{E} \times \left(2 \times N_f\right)^{2b} \quad (4)$$

Where: γ_f' is the fatigue ductility coefficient in torsion; ε_f' is the fatigue ductility coefficient; σ_f' is the fatigue strength coefficient; $\sigma_{n,max}$ is the maximum stress; $\sigma_{n,mean}$ is the mean stress; σ_y is the stress in the direction of the axis y; τ_f' is the fatigue strength coefficient in torsion; Δy_{max} is the maximum shear strain range; $\Delta\varepsilon_n$ is the normal strain range; ΔW is the virtual strain energy; b is the fatigue strength exponent; b_γ is the fatigue strength exponent in torsion; c is the fatigue ductility exponent; c_γ is the fatigue ductility exponent in torsion; N_f is the number of cycles to fracture; A, B, S, k, α 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.

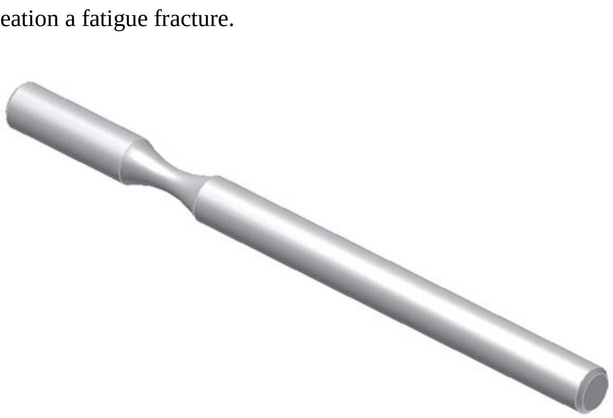

Fig.1 *The shape of a test bar*

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).

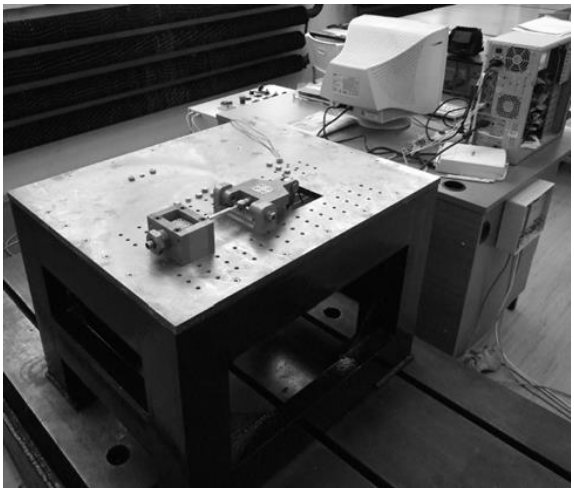

Fig.2 *Electro mechanic fatigue test machine*

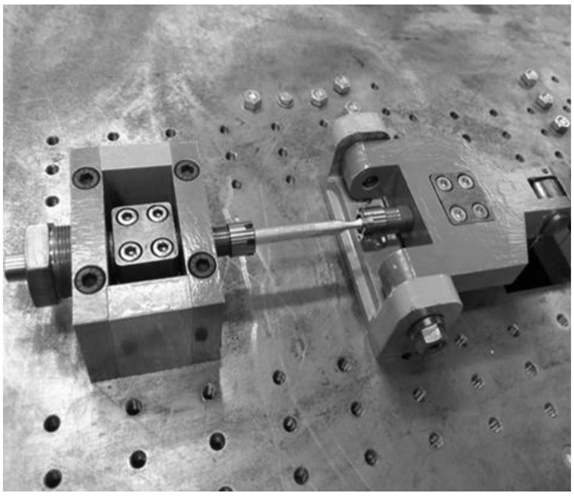

Fig.3 *A gripping attachment of test machine*

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, $R_\varepsilon = -1$.

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.

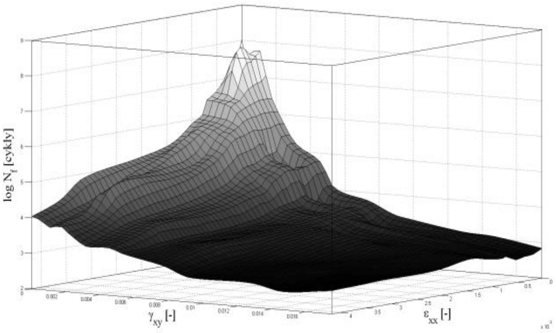

Fig.4 *Three-dimensional fatigue curve ε_{xx} - γ_{xy} - N_f for multiaxial fatigue with phase shift 0°*

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.

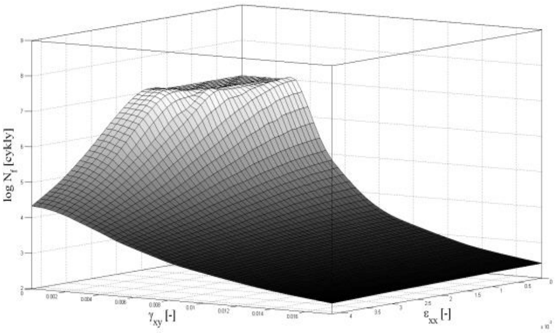

Fig.5 *Three-dimensional fatigue curve ε_{xx} - γ_{xy} - N_f for multiaxial Fatemi-Socie criterion with phase shift 0°*

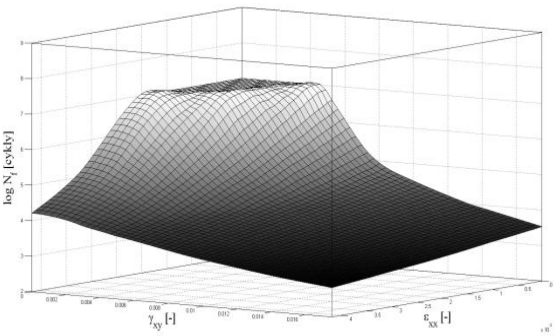

Fig.6 *Three-dimensional fatigue curve ε_{xx} - γ_{xy} - N_f for multiaxial SWT criterion with phase shift 0°*

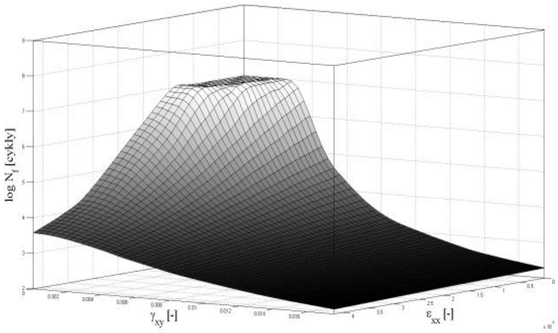

Fig.7 *Three-dimensional fatigue curve ε_{xx} - γ_{xy} - N_f for multiaxial Brown-Miller criterion with phase shift 0°*

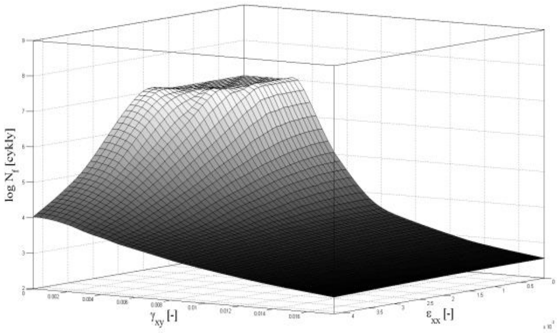

Fig.8 *Three-dimensional fatigue curve ε_{xx} - γ_{xy} - N_f for multiaxial Liu criterion with phase shift 0°*

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.

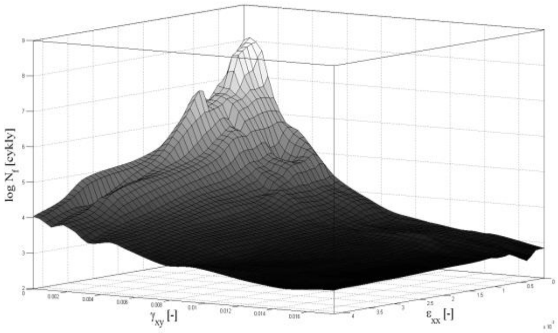

Fig.9 *Three-dimensional fatigue curve ε_{xx} - γ_{xy} - N_f for multiaxial fatigue with phase shift 90°*

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.

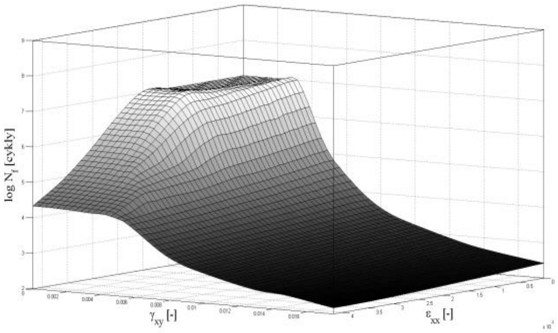

Fig.10 *Three-dimensional fatigue curve ε_{xx} - γ_{xy} - N_f for multiaxial Fatemi-Socie criterion with phase shift 90°*

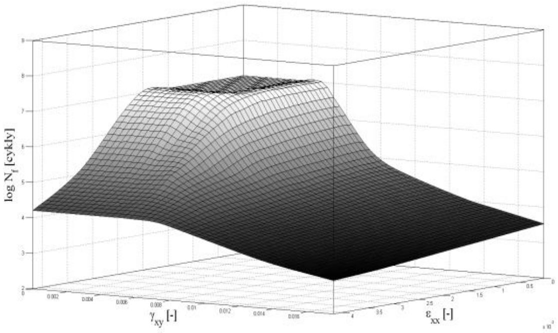

Fig.11 *Three-dimensional fatigue curve ε_{xx} - γ_{xy} - N_f for multiaxial SWT criterion with phase shift 90°*

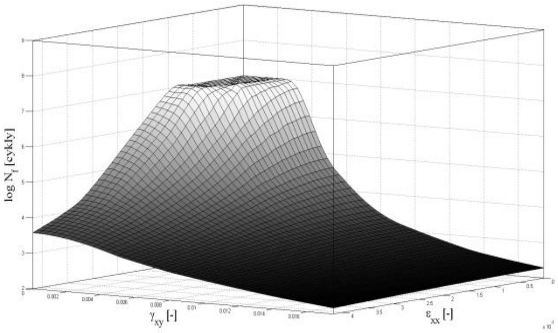

Fig.12 *Three-dimensional fatigue curve ε_{xx} - γ_{xy} - N_f for multiaxial Brown-Miller criterion with phase shift 90°*

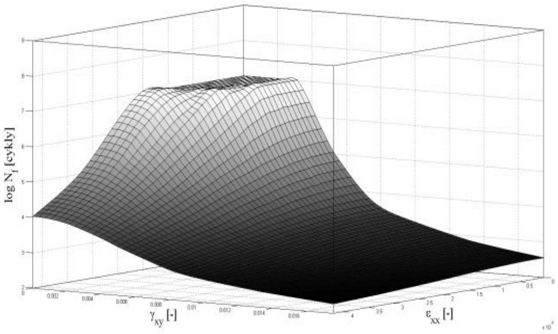

Fig.13 *Three-dimensional fatigue curve ε_{xx} - γ_{xy} - N_f for multiaxial Liu criterion with phase shift 90°*

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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