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Contribution to multiaxial fatigue analysis of aluminium alloy EN AW 6063.T66

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Introduction

The experimental knowledge of multiaxial fatigue life plays an important role in the design of machine components loaded cyclically. The stress states of components are typically multiaxial [1, 2]. These components are often loaded by combination of bending-torsion [3, 4, 5]. The aim of this article will be a presentation of experimental and numerical research of the multiaxial fatigue criteria for aluminium alloy EN AW 6063.T66. In the centre of attention will be the analysis and comparison of selected multiaxial fatigue criteria, which are confronted with experimental results [1, 6]. Fatigue life surfaces of aluminium alloy (when bending-torsion loading and phase shift $\varphi = 0°$ and $90°$ were combined) have been prepared on this basis [1].

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 [7, 8, 9]. 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 [8, 9]. Aluminium is one of the lightest engineering metals, having strength to weight ratio superior to steel [7]. 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.

Experimental equipment for modelling of bending-torsion combination

Department of Applied Mechanics at the University of Žilina has developed the unique testing device that allows performing fatigue tests under cyclic loading on specimens [1]. The working part of the device is shown in Fig. 1 (left). This experimental equipment is based on mechanical principle. Power of device is secured by two synchronic electromotors with frequency converters from 0.5 Hz to 100 Hz. Loading frequencies are identical with frequency of rotation drive. Synchronization of the electromotors is secured using by electronics and allows synchronization of loading amplitude. Synchronization of electomotors also allows setting phase shift for individual loading levels. The constant rotation is generated by excenter and linkage mechanism. By changing of eccentric magnitude it is possible to change a loading magnitude. Also if we change a length of connecting crank on the experimental equipment, there will be change in a loading cycle character. A sinusoidal waveform was used as command signal. The fatigue tests were conducted with constant strain amplitudes, at room temperature, in air. For evaluation of fatigue curves it needs to know stress and strain conditions on individual loading levels.

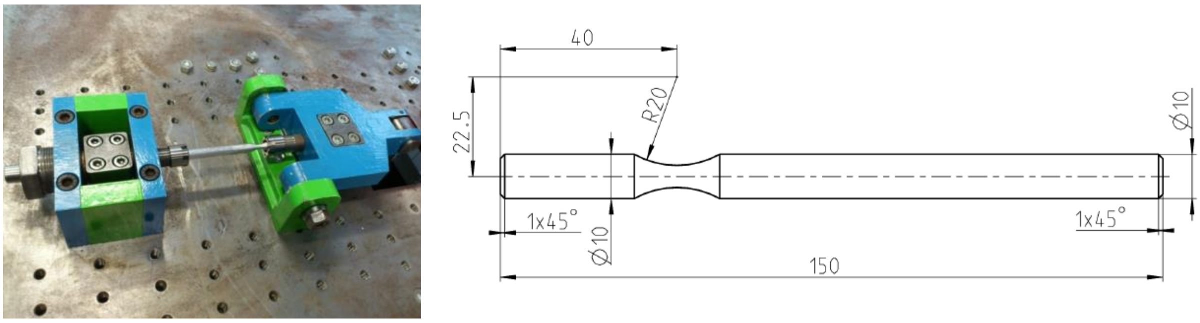

Fig. 1 Unique testing device (left) and geometry of the test specimen (right)

The geometry of the test specimen is shown in Fig. 1 (right). Stress concentrator parameters were determined by calculation according to the manufacturing process and the initial dimensions of the material [6, 7].

Testing material characteristics

As an experimental material to perform multiaxial fatigue tests were chosen the EN AW 6063.T66 aluminium alloy with a normalised chemical composition (Table 1). The material used in this research was delivered in the form of cylindrical shape with a diameter 10 mm. The length of cylindrical bars was 150 mm. The material was in rolled state. The EN AW 6063.T66 is a medium strength alloy, suitable for applications where no special strength properties are required. Simple to complex shapes can be produced with very good surface quality characteristics, and suitable for many coating operations such as anodizing and powder coating. 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 manufacturing process [8].

Tab. 1 Chemical composition of the EN AW 6063.T66 aluminium alloy (weight in [%]) according to EN 573-3

Si	**Fe**	**Cu**	**Mn**	**Mg**	**Cr**	**Zn**	**Ti**	**Other**		**Al**
								Each	**Total**	
0.20-0.60	0.35	0.10	0.10	0.45-0.90	0.10	0.10	0.10	0.05	0.15	rest

Static tensile test with standard specimens had been carried out. Results are summarized in Table 2. The stress-strain diagram contains stresses and true stresses depending up strain (Fig. 2). For FEM analyses by ANSYS were used true stresses [6].

Tab. 2 Mechanical properties of the EN AW 6063.T66 aluminium alloy

Young modulus	62 500 MPa
Ultimate tensile strength	247 MPa
Tensile yield strength	212 MPa

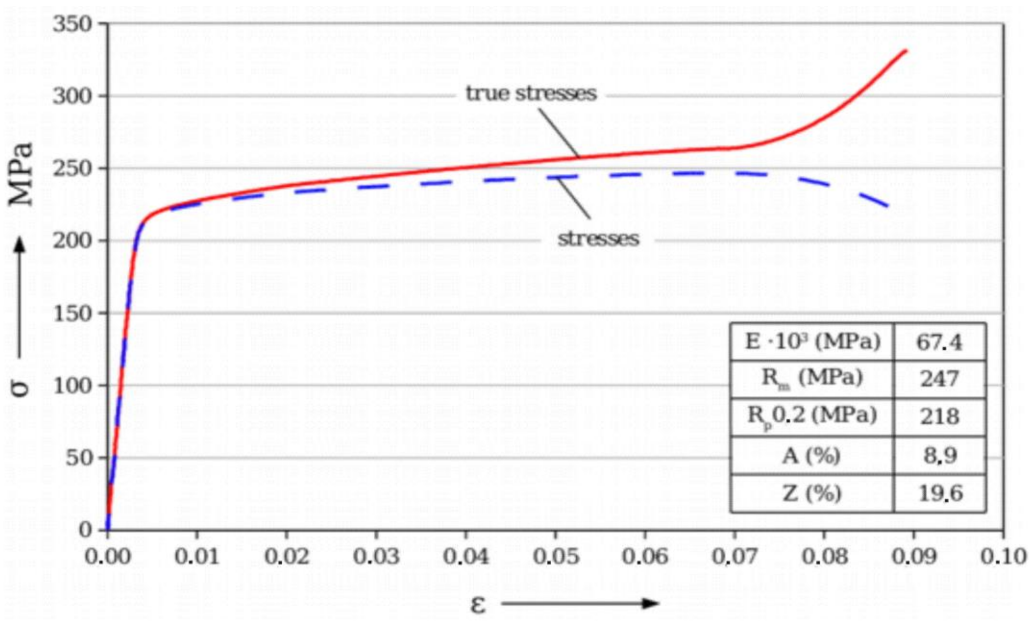

Fig. 2 Stress-strain diagram for EN AW 6063

Results

Cyclic loading of the test specimen was done under controlled amplitude of deformation with a zero mean deformation component. The deformation amplitude was characterised by the value ε_{ac} (ε_{xx}) in the case of alternating bending, and γ_{ac} (γ_{xy}) in the case of alternating torsion. The loading systems are synchronized to each other with a phase shift of $\varphi = 0°$ and 90° at the same frequency. Multiaxial fatigue tests under bending-torsion loading and with phase shift $\varphi = 0°$ were made in the first phase of the experiment to determine the fatigue life of the specimens. The measured values of the number of cycles to fracture are shown in the fatigue surface ε_{xx}-γ_{xy}-$\log N_f$ (Fig. 3) [1].

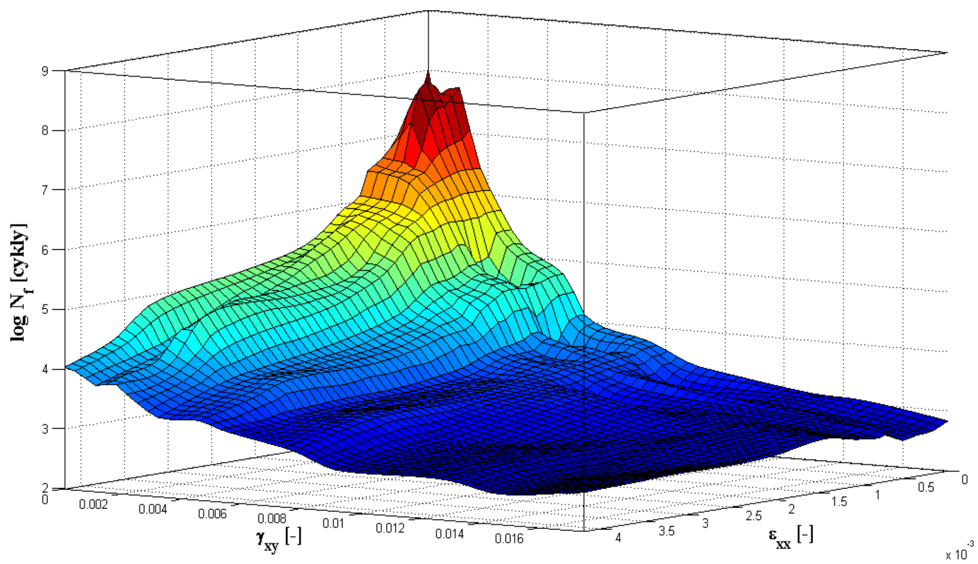

Fig. 3 The original fatigue surface ε_{xx}-γ_{xy}-$\log N_f$

Measured fatigue surface is necessary to approximate by a polynomial function for the mathematical description of the fatigue properties (Fig. 4) [1].

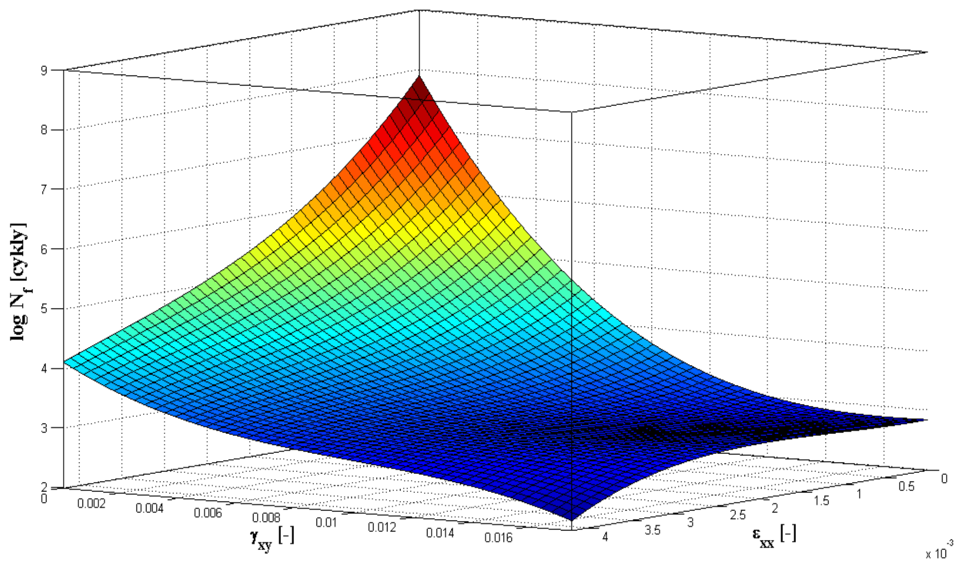

Fig. 4 The fatigue surface ε_{xx}-γ_{xy}-*log* N_f after the approximation of the third degree polynomial

The function of the third degree with a correlation coefficient of 0.9656 was used for the approximation (Eq. 1). Coefficients of the polynomial function are shown in Table 3 [1].

$$\begin{aligned} log\ N_f &= k_1 + k_2.\varepsilon_{xx} + k_3.\gamma_{xy} + k_4.\varepsilon_{xx}^2 + k_5.\varepsilon_{xx}.\gamma_{xy} + k_6.\gamma_{xy}^2 + k_7.\varepsilon_{xx}^3 + \\ &+ k_8.\varepsilon_{xx}^2.\gamma_{xy} + k_9.\varepsilon_{xx}.\gamma_{xy}^2 + k_{10}.\gamma_{xy}^3\ . \end{aligned} \tag{1}$$

Tab. 3 Coefficients of the polynomial function for equation (1)

k_1	7.902	k_3	-819	k_5	$1.894 \cdot 10^5$	k_7	$-2.967 \cdot 10^7$	k_9	$-5.084 \cdot 10^6$
k_2	-1781	k_4	$3.333 \cdot 10^5$	k_6	$4.307 \cdot 10^4$	k_8	$-1.388 \cdot 10^7$	k_{10}	$-7.298 \cdot 10^5$

The fatigue surface arose from experimental values by polynomial function approximation for recalculated stresses obtained by using FEM (Fig. 5). The function of the third degree with a correlation coefficient of 0.9651 was used for the approximation (Eq. 2). Coefficients of the polynomial function are shown in Table 4 [1].

$$\begin{aligned} log\ N_f &= k_1 + k_2.\sigma_{xx} + k_3.\tau_{xy} + k_4.\sigma_{xx}^2 + k_5.\sigma_{xx}.\tau_{xy} + k_6.\tau_{xy}^2 + k_7.\sigma_{xx}^3 + \\ &+ k_8.\sigma_{xx}^2.\tau_{xy} + k_9.\sigma_{xx}.\tau_{xy}^2 + k_{10}.\tau_{xy}^3\ . \end{aligned} \tag{2}$$

Tab. 4 Coefficients of the polynomial function for equation (2)

k_1	4.75	k_3	-0.9301	k_5	0.5524	k_7	-0.08524	k_9	0.07708
k_2	-0.6001	k_4	0.1809	k_6	-0.4967	k_8	-0.1529	k_{10}	-0.1897

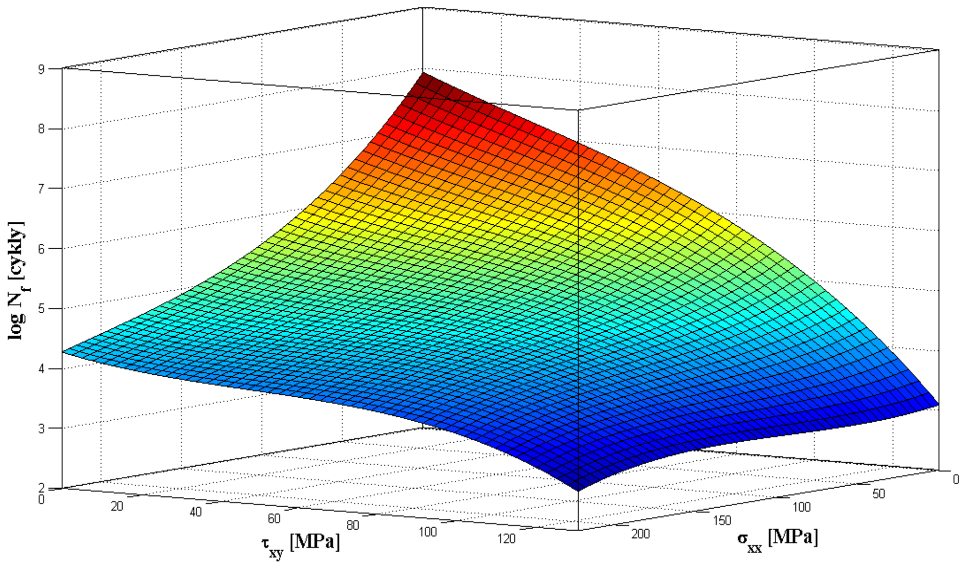

Fig. 5 The fatigue surface σ_{xx}-τ_{xy}-*log* $N_f$of the third degree polynomial function for φ = 0°

Multiaxial fatigue tests under bending-torsion loading and with phase shift φ = 90° were made in the second phase of the experiment to determine the fatigue life of the specimens. Like in previous case, the measured values of the number of cycles to fracture are shown in the fatigue surface ε_{xx}-γ_{xy}-*log* N_f.

The experimentally obtained fatigue surface is shown in Fig. 6 [1].

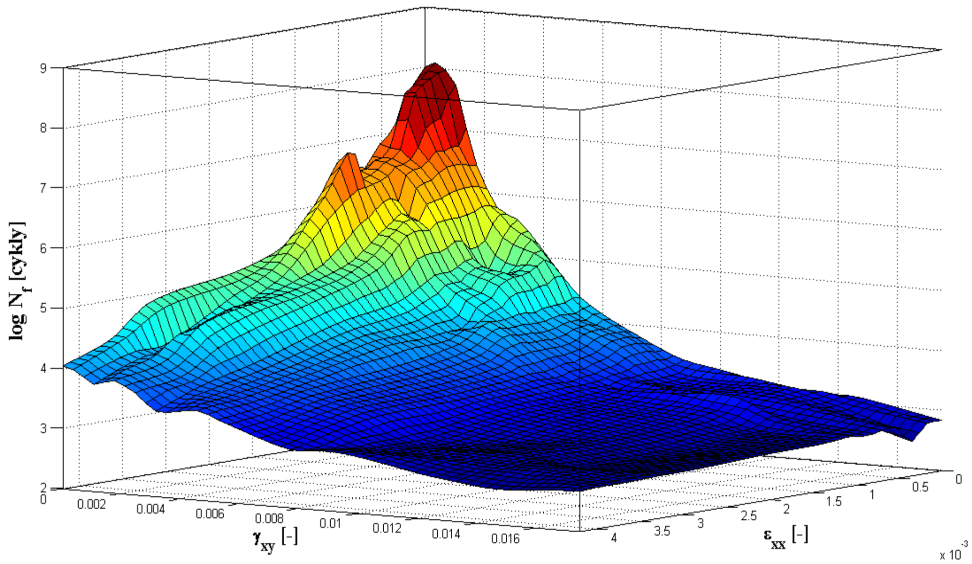

Fig. 6 The fatigue surface ε_{xx}-γ_{xy}-*log* N_f for the bending-torsion cyclic loading with phase shift φ = 90°

Obtained fatigue surface is necessary to approximate by a polynomial function of the third degree with a correlation coefficient of 0.9770. The equation of the polynomial function has the following form and its coefficients are listed in the Table. 5 [1].

$$\begin{aligned} log\ N_f \quad &= k_1 + k_2.\varepsilon_{xx} + k_3.\gamma_{xy} + k_4.\varepsilon_{xx}^2 + k_5.\varepsilon_{xx}.\gamma_{xy} + k_6.\gamma_{xy}^2 + k_7.\varepsilon_{xx}^3 + \\ &+ k_8.\varepsilon_{xx}^2.\gamma_{xy} + k_9.\varepsilon_{xx}.\gamma_{xy}^2 + k_{10}.\gamma_{xy}^3\ . \end{aligned} \tag{3}$$

Tab. 5 Coefficients of the polynomial function for equation (3)

k_1	8.052	k_3	-843.9	k_5	$1.806 \cdot 10^5$	k_7	$-1.169 \cdot 10^7$	k_9	$-5.559 \cdot 10^6$
k_2	-1526	k_4	$1.884 \cdot 10^5$	k_6	$4.488 \cdot 10^4$	k_8	$-9.121 \cdot 10^6$	k_{10}	$-7.64 \cdot 10^5$

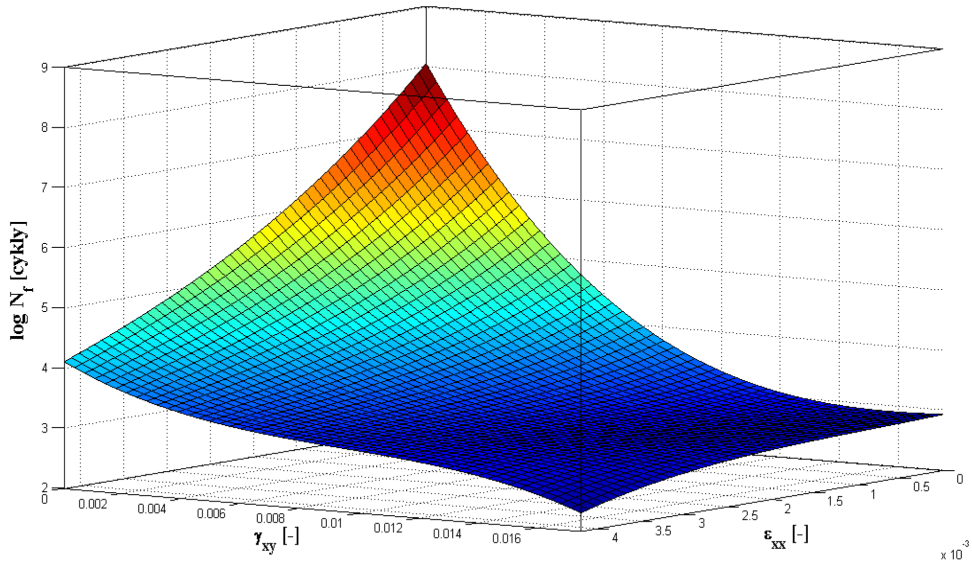

Fig. 7 The fatigue surface ε_{xx}-γ_{xy}-$log\ N_f$ of the third degree polynomial function for $\varphi = 90°$

The fatigue surface arose from experimental values by polynomial function approximation for recalculated stresses obtained by using FEM (Fig. 8). The function of the third degree with a correlation coefficient of 0.9604 was used for the approximation (Eq. 4). Coefficients of the polynomial function are shown in Table 6 [1].

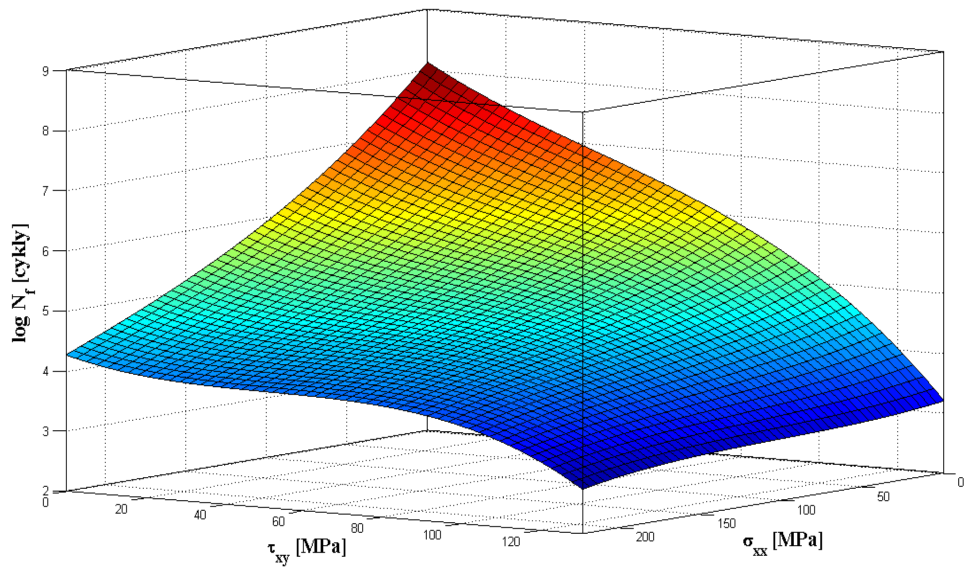

Fig. 8 The fatigue surface σ_{xx}-τ_{xy}-$log\ N_f$ of the third degree polynomial function for $\varphi = 90°$

$$\begin{aligned} log\ N_f &= k_1 + k_2.\sigma_{xx} + k_3.\tau_{xy} + k_4.\sigma_{xx}^2 + k_5.\sigma_{xx}.\tau_{xy} + k_6.\tau_{xy}^2 + k_7.\sigma_{xx}^3 + \\ &+ k_8.\sigma_{xx}^2.\tau_{xy} + k_9.\sigma_{xx}.\tau_{xy}^2 + k_{10}.\tau_{xy}^3\ . \end{aligned} \tag{4}$$

Tab. 6 Coefficients of the polynomial function for equation (4)

k_1	4.906	k_3	-0.9345	k_5	0.5095	k_7	-0.04345	k_9	0.03901
k_2	-0.6343	k_4	0.1164	k_6	-0.5229	k_8	-0.08765	k_{10}	-0.2705

Analysis of selected fatigue criteria

The number of cycles was determined using the program Fatigue Calculator after realizing all experimental measurements [10]. The Fatemi-Socie, Smith-Watson-Topper (SWT), Brown-Miller and Liu criteria were used. The Fatigue Calculator software was created at the University of Illinois. The number of cycles at which fatigue fracture will occur can be detected using this program [1]. This program works with low cycle and high cycle fatigue.

Multiaxial fatigue tests under bending-torsion loading were made to determine the fatigue life of the specimens. The same conditions of combined loading were chosen (sinusoidal cyclic loading) for the purpose of comparison of experimental obtained results with calculated results. The strain values ε_{xx} and γ_{xy} input into the calculation and it is working with the symmetric frequency of loading cycles (30 Hz) and a phase shift $\varphi = 0°$ and $\varphi = 90°$.

The Fatigue Calculator after the calculating the fatigue life shows the number of cycles to fracture for the various models of damage ($N_{f\,(Fatemi\text{-}Socie)}$, $N_{f\,(SWT)}$, $N_{f\,(Brown\text{-}Miller)}$ a $N_{f\,(Liu\ I\ a\ Liu\ II)}$). The calculated values for the multi-axial cyclic loading (bending-torsion) with the phase shift of $\varphi = 0°$ are processed in the spatial fatigue surfaces ε_{xx}-γ_{xy}-$log\ N_f$. Fig. 9 shows the fatigue surface using the fatigue criteria Smith-Watson-Topper (SWT) with phase shift $\varphi = 0°$.

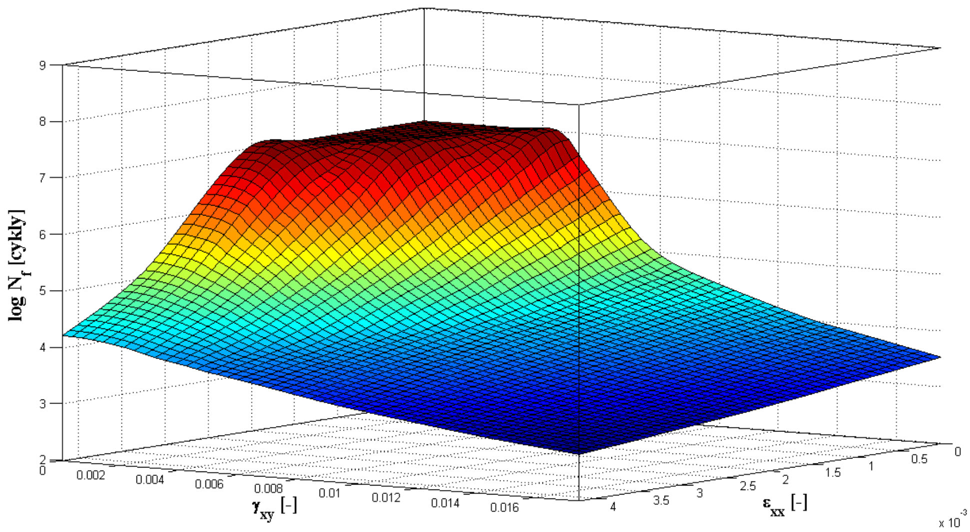

Fig. 9 The fatigue surface ε_{xx}-γ_{xy}-$log\ N_f$ using the fatigue criteria SWT with phase shift $\varphi = 0°$

The calculation of the multi-axial cyclic loading (bending-torsion) with the phase shift $\varphi = 90°$ and with the same input values was performed subsequently. Like in previous case, the number of cycles to fracture are shown in the fatigue surface ε_{xx}-γ_{xy}-$log\ N_f$ (Fig. 10).

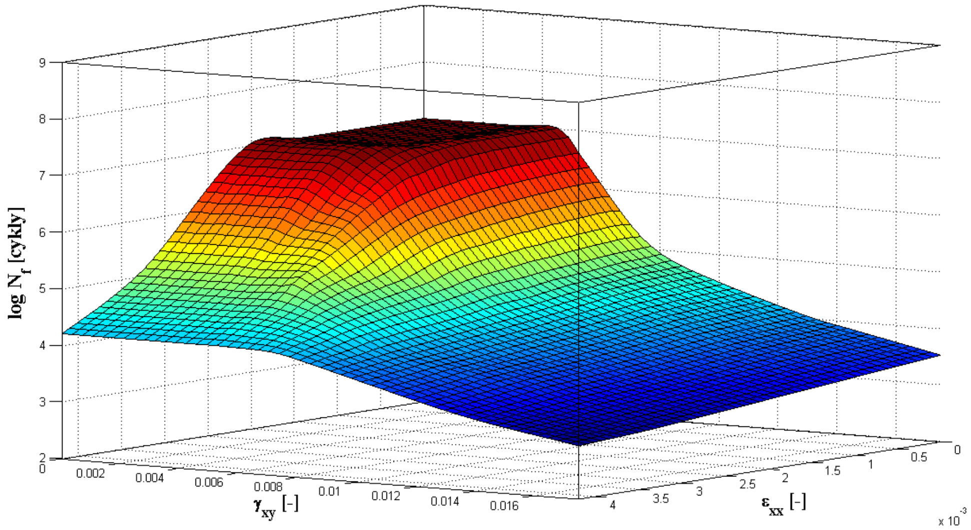

Fig. 10 The fatigue surface ε_{xx}-γ_{xy}-$log\ N_f$ using the fatigue criteria SWT with phase shift φ = 90°

The calculation of the number of cycles to fracture using the Fatigue Calculator was made in addition to the experiment [1]. The numbers of cycles were evaluated by fatigue surfaces ε_{xx}-γ_{xy}-$log\ N_f$ for the various fatigue criteria (Fatemi-Socie, SWT, Brown-Miller and Liu I, II). Fatemi-Socie model shows a lower number of cycles than experiment and Liu model I and II indicates conformity with the experiment results in the lower number of cycles and at higher values of the deformation under torsion (from $\gamma_{xy} \approx 0.008$). Brown-Miller method gives a lower lifetime under all loading amplitudes of both deformations and at the low number of cycles (to the $N_f \approx 10^5$ cycles). SWT method determines a longer lifetime for the whole fatigue surface [1]. Similar results were obtained even with a phase shift φ = 90°.

Conclusions

The article presents multiaxial fatigue resistance of samples from aluminium alloy EN AW 6063.T66 in different variants, using a combined computationally – experimental method. From experimentally measured values of number of cycles to failure was created three-dimensional fatigue surface ε_{xx}-γ_{xy}-$log\ N_f$ for phase shift 0° and 90°.

For further use of these fatigue surfaces was necessary to approximate by appropriate polynomial function. This calculation was carried out using a program MATLAB [1]. Equations of polynomial functions incurred by an approximation, may be used in the compilation of own fatigue criteria for calculating fatigue lifetime, which are based on the experimental obtained results of number of cycles to fracture [1].

Fatigue Calculator software was used for another – computational analyses. This program can quickly calculate fatigue lifetime of selected material. In our calculation we considered with multiaxial criterion SWT described above. From these calculated values of number of cycles to failure were created three-dimensional fatigue curves for phase shift 0° and 90°. However, this criterion do not specify the lifetime more than 10^7 cycles.

Multiaxial criterion SWT applied to fatigue lifetime calculation and also values of number of cycles to failure from experiments for specimens of aluminium alloy EN AW 6063.T66 increases with decreasing strain amplitude continuously in the cycles of number region [1]. Comparing three-dimensional curves is evident that criterion SWT 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, especially at the lower values of amplitude deformation, which was applied in experiment. Our calculations can give a higher value of fatigue lifetime in comparison with experiments in the area of loads.

Acknowledgements

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