Multiaxial Fatigue Behaviour of Selected Aluminium Alloys under Bending with Torsion Loading Condition

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ABSTRACT. *This publication presents an analysis of the multiaxial fatigue properties of selected aluminium alloys. Several experimental results were used to perform the analysis e.g. the latest experimental results done in Opole University of Technology on PA6 (2017 A), PA4 (6068) under bending, torsion, and combined bending with torsion. Analyses of the results were done to find similarities of the multiaxial fatigue behaviour of selected aluminium alloys. Based on the (σ_a-τ_a) curves, prepared for a fixed number of cycles, it is possible to show some tendencies of the multiaxial fatigue behaviour of selected material group. This is an important indicator while selecting proper multiaxial fatigue failure criterion suitable to perform fatigue life assessment of aluminium alloys.*

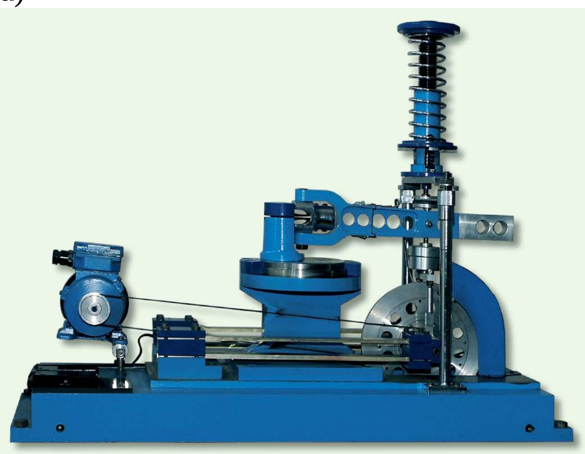
INTRODUCTION

Fatigue is the main subject matter in integrity, safety, and energy savings issues of nearly all mechanical structures. In view of this, scientists and engineers are continuously searching for a universal method, which would be able to describe the metal fatigue correctly. In particular, it is difficult to describe the fatigue behaviour under multiaxial loading, especially under loadings that lead to varying principal stress directions [1–3]. Many models have been proposed by researchers to solve this issue [4, 5]. A variety of ideas according to the damage mechanics of material, several material constants, and advanced relations coming from theory of solid mechanics and mathematics have been used. Due to the great theoretical diversity of the proposed models, it is difficult to compare or classify them, without assessment against results from experimental studies. It is also clear that not all of the models will describe the behaviour of each material group properly. In recent years, great interest in modern aluminium alloys are noted, which have high strength, low weight as well relatively low cost. Therefore, in this paper, two series of experimental results performed on selected aluminium alloys were used to show some typical multiaxial fatigue behaviour of those alloys. Some multiaxial fatigue failure criteria are compared with these tests results in order to show the best one for such kind of material group.

EXPERIMENTAL RESULTS

For the purpose of verification, experimental data obtained during fatigue tests in the research laboratory of Opole University of Technology, were used. Fatigue testing was performed on the MZGS-100 stand under the combination of bending with torsion as presented in Fig. 1 (a) [6]. The stand MZGS-100 is a device designed for fatigue testing of standard specimens made of various materials, Fig. 1 (b). The major components include a frame with a rotary table, a lever and disc driven by an electric motor with speed control. Because of the rotation of unbalanced disc centrifugal force arise and a moment M is acting on the tested specimen over the arm.

a)



b)

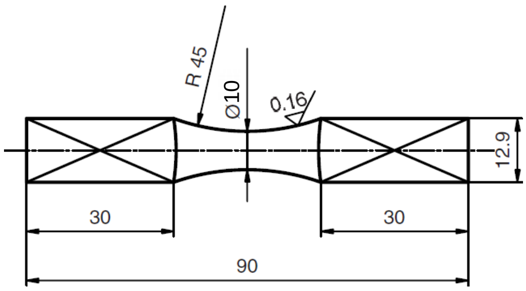


Figure 1. Test stand MZGS-100 (a) and the shape of specimen used in the tests (b).

The specimen is fixed at one end to the lever and at the other side is attached to the holder placed at a rotary table as presented on the Fig. 2 (a). Through a suitable rotation over the angle α_M in the range of $0 \div \pi/2$ the moment M of the tested specimen could be resolved into two component moments – bending M_σ and torsional M_τ, see Fig. 2 (b). Two extreme cases could be distinguished: when the specimen axis is parallel to the axis of the lever – in which case the specimen loading is limited to pure bending moment $M = M_\sigma$ and the case in which the axes of the specimen and lever form a right angle and a distinct case of the pure torsion is involved $M = M_\tau$. Therefore, for the case of MZGS-100 stand the tests could involve an arbitrary combination of bending and torsional moments fully correlated to each other, i.e. proportional loading.

Apart from that, the test stand includes a personal computer with input/ output card. The stand includes a limit switch for the control of maximum deflection of the arm. As the preset limit is exceeded the engine and test timer switches are turned off. As the occurrence of fatigue failure induces a rapid and large loss of specimen rigidity (inclination of the lever increases), a limit switch is applied for the determination of experimental fatigue life N_{exp}. The measurement of strain at the lever with a strain gauge indicates the instantaneous values of moment M.

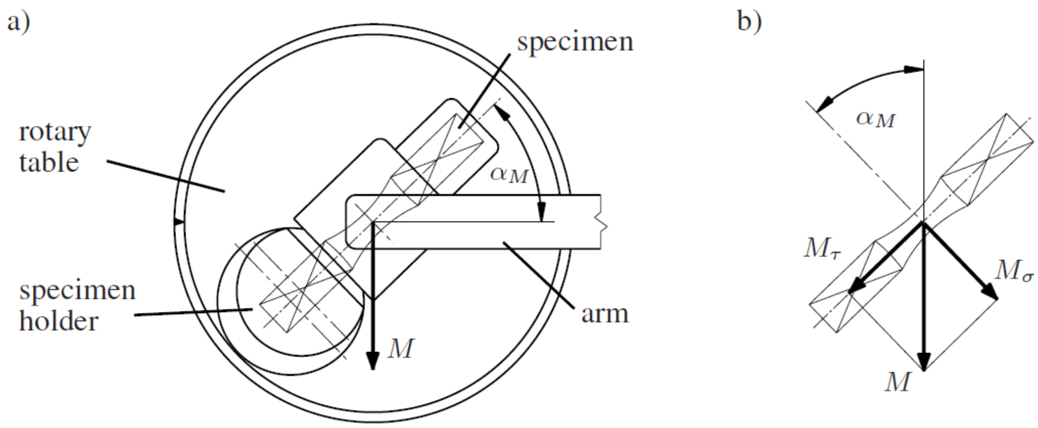


Figure 2. Rotary table of MZGS-100 stand with fixed specimen (a) and graphical representation of moment of force M resolved into bending moment M_σ and torsional moment M_τ of specimen (b).

Two aluminium alloys were tested using the test stand described before. Four series of fatigue tests were performed for each material, i.e. pure bending, pure torsion and combined bending with torsion with $\lambda = 0.5$ and $\lambda = 1.0$, where

$$\lambda = \frac{\tau_a}{\sigma_a}. \quad (1)$$

Aluminum alloys are increasingly used in the industry for construction of machine parts and equipment. Good strength properties and low specific gravity allow one to extensively use PA6 alloy in various fields of industry, e.g. in civil engineering, aeronautical industry. Aluminum alloy PA4 is characterized by high mechanical strength, impact strength, and good corrosion resistance. It is used for load-bearing parts of trucks, buses, trailers, ships, cranes, rail and bridges. Chemical composition of the considered materials is shown in Table 1. Mechanical properties of the considered materials are shown in Table 2.

Table1. Chemical composition of tested materials.

Material	Cu	Mg	Mn	Si	Fe	Zr+Ti	Zn	Cr
PA6	3.5 ÷4.5	0.4 ÷1.0	0.4÷1.0	0.2 ÷ 0.8	<0.7	<0.25	<0.25	<0.10
PA4	<0.1	0.6÷1.2	0.4÷1.0	0.7÷1.3	<0.5	<0.1	<0.2	<0.25

Table 2. Mechanical properties of tested materials.

Material	Yield stress R_e (MPa)	Ultimate stress R_m (MPa)
PA6	395	545
PA4	200-260	270-310

COMPARISON OF THE TO SELECTED MULTIAXIAL FATIGUE FAILURE CRITERIA

The in-phase constant amplitude loading realised as combination of bending with torsion (two components of loading) allow as to present the results in the (σ_a-τ_a) graph as a set of curves each for constant number of cycles. Two values of cycles were selected, $N_1 = 3{\cdot}10^5$ and $N_2 = 3{\cdot}10^6$, while preparing the Figs. 5 and 6. Plotted experimental points were read from the Wöhler curves from Figs. 3 and 4 and connected with dotted line. Additionally, five curves have been plotted according to selected multiaxial fatigue failure criteria.

Gough and Pollard proposed a non-linear multiaxial fatigue criterion [7]. From investigations of in-phase combined bending and torsion on steel alloys they suggested a multiaxial fatigue strength criterion based on the applied stresses

$$\left(\frac{\sigma_a}{\sigma_{af}}\right)^2 + \left(\frac{\tau_a}{\tau_{af}}\right)^2 \le 1. \qquad (2)$$

Eq. (2) is also called the Gough-Pollard ellipse and it suggested to using it for fatigue assessment of ductile materials. In the case of brittle materials second criterion in a form of inequality was elaborated as follow

$$\left(\frac{\tau_a}{\tau_{af}}\right)^2 + \left(\frac{\sigma_a}{\sigma_{af}}\right)^2 \left(\frac{\sigma_{af}}{\tau_{af}} - 1\right) + \left(\frac{\sigma_a}{\sigma_{af}}\right)\left(2 - \frac{\sigma_{af}}{\tau_{af}}\right) \le 1. \qquad (3)$$

In the case of simple combination of fatigue loading the Mises stress are still widely used. According to this criterion, assuming in-phase constant amplitude bending with torsion, the equivalent uniaxial stress amplitude can be computed

$$\sigma_{a,eq} = \sqrt{\sigma_a^2 + 3\tau_a^2}\ . \qquad (4)$$

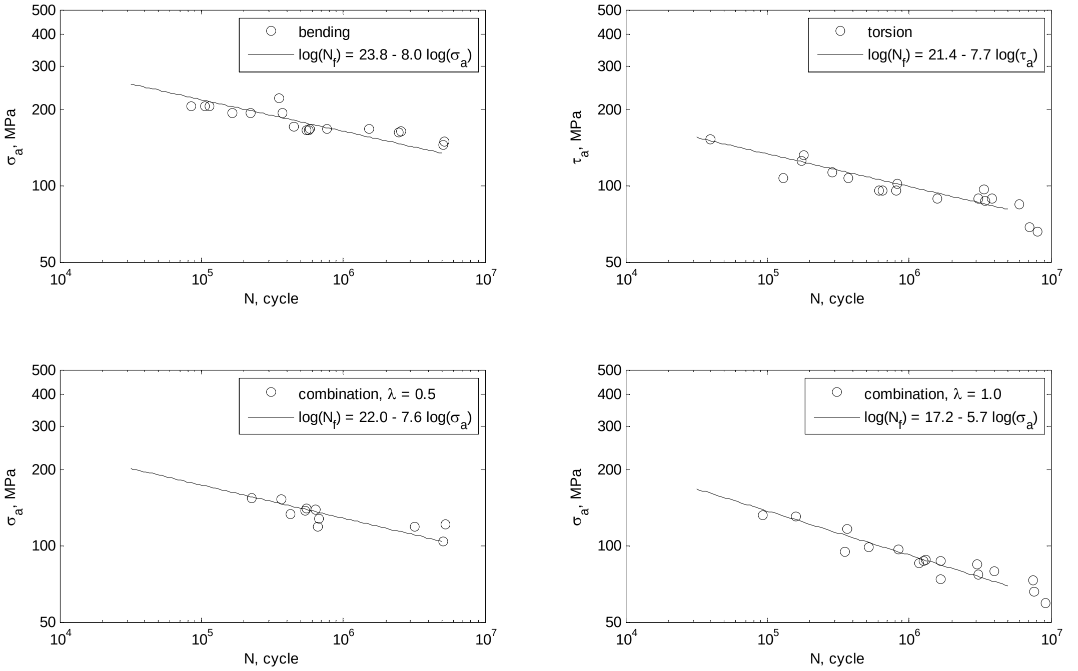


Figure 3. Experimental results for PA4 aluminium alloy.

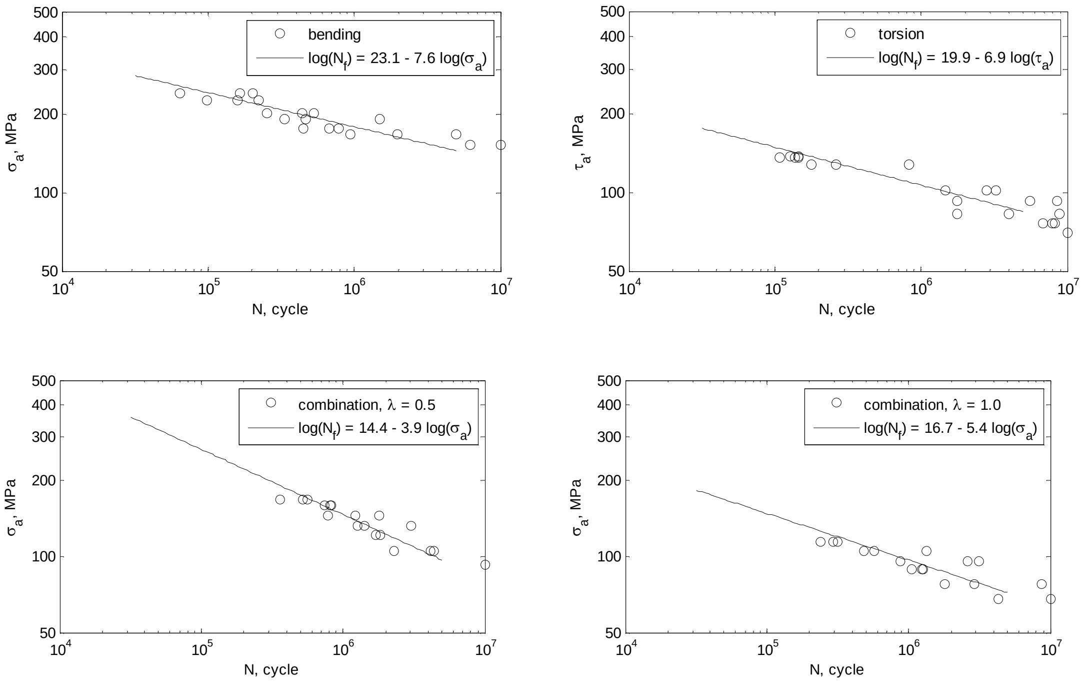


Figure 4. Experimental results for PA6 aluminium alloy.

At the time of the analysis of experimental results under multiaxial cyclic loading it was observed that for the case of brittle materials the fracture plane is perpendicular to normal stress with the highest amplitude or variance. For ductile materials, the fracture plane takes one of two positions for which shear stresses reach maximum amplitude. Because of that several criteria based on the critical plane concept were proposed [5]. One of them is the criterion of shear and normal stress in the plane of maximum shear stress [8]

$$\sigma_{eq}(t) = \frac{\sigma_{af}}{\tau_{af}} \max_t \{\tau_{\eta s}(t)\} + \left(2 - \frac{\sigma_{af}}{\tau_{af}}\right)\sigma_\eta(t) . \qquad (5)$$

Wide range of multiaxial fatigue criteria are based on stress invariants. One of them is the Crossland criterion which utilises first and second stress invariants. Additionally, two material constants obtained from fatigue testing under uniaxial and pure torsion tests conditions are used to calibrate the model [9]

$$\sigma_{a,eq} = \frac{\sigma_{af}}{\tau_{af}}\left(\sqrt{J_2}\right)_a + \left(3 - \sqrt{3}\frac{\sigma_{af}}{\tau_{af}}\right)\sigma_{H,\max} , \qquad (6)$$

where $\sqrt{J_2}$ is the second invariant of the stress tensor deviator and $\sigma_{H,max}$ is the maximum of the hydrostatic pressure. Please note that for the analyzed loading type the Gough-Pollard ellipse elaborated for ductile materials (3) and the critical plane model (5) gives the same results.

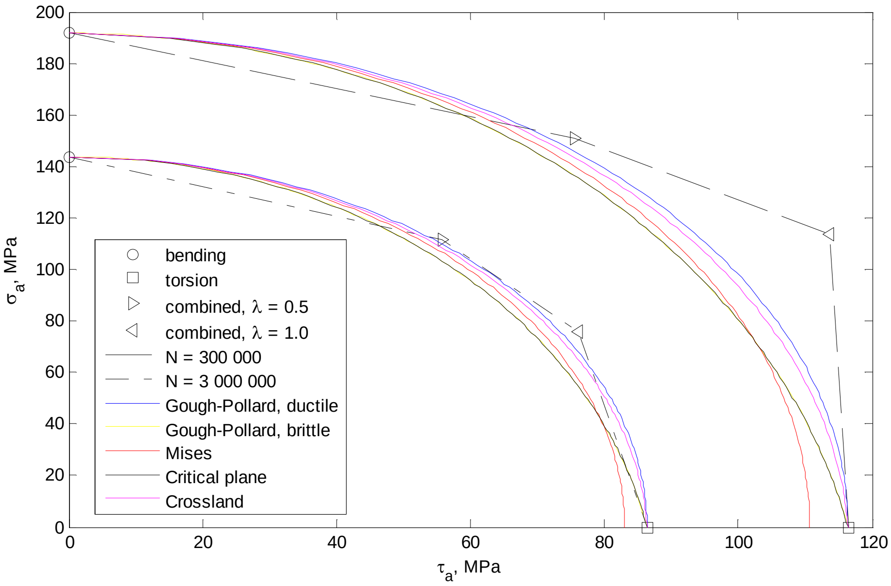


Figure 5. In-phase bending with torsion behaviour of PA4 aluminium alloy presented for two number of cycles $N_1 = 3{\cdot}10^5$ and $N_2 = 3{\cdot}10^6$.

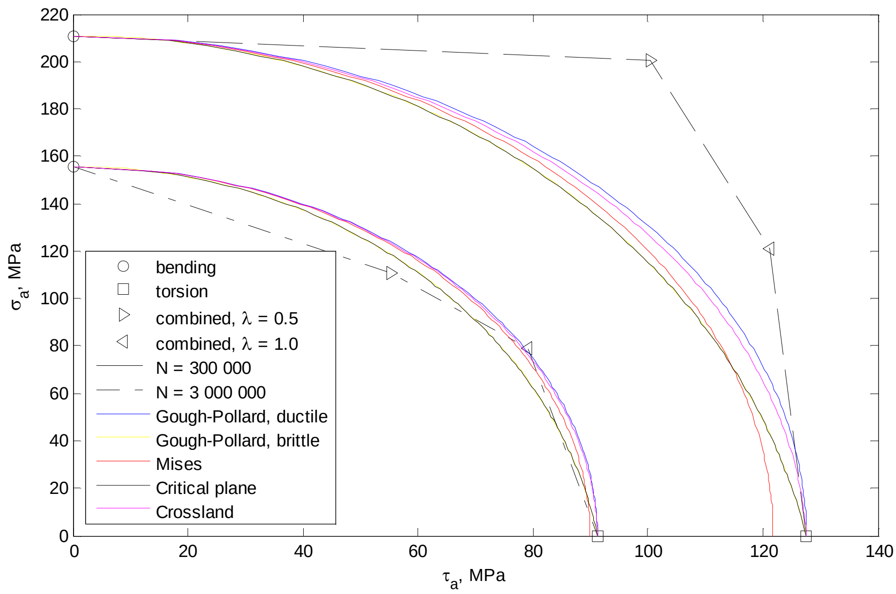


Figure 6. In-phase bending with torsion behaviour of PA6 aluminium alloy presented for two number of cycles $N_1 = 3{\cdot}10^5$ and $N_2 = 3{\cdot}10^6$.

CONCLUSIONS

Two series of experimental results performed on PA4 and PA6 aluminium alloys under in-phase constant amplitude bending with torsion were presented. S-N curves were prepared for bending, torsion and two values of amplitude ratio $\lambda = 0.5$ and $\lambda = 1.0$, Eq. (1). On the (σ_a-τ_a) graphs, for a fixed number of cycles, points obtained from the experiments are compared to curves corresponding to the selected multiaxial fatigue failure criteria. On the basis of that comparison conclusions are formulated as follow:

1. Widely accepted classification, which divides the criteria for those to be used for brittle materials, ductile and intermediates, must be refined. It is proposed that this division should be carried out due to the behavior of particular groups of materials, such as aluminum alloy, stainless steel, alloyed steel etc. It should be specify which of the known multiaxial fatigue criteria correctly describe the fatigue phenomenon of particular group.
2. Two materials which have been analyzed shown the ratio of fatigue strength for pure bending and torsion near constant and equal to 1.65. This value is close to $\sqrt{3} = 1.73$ which also results from theoretical deliberation of the static Mises hypothesis. This suggests that for preliminary calculations in engineering practice, for the case of in-phase loading and analyzed type of material, Mises criterion can be used.
3. To increase the accuracy of fatigue life estimation of analysed aluminium alloys new model should be developed that will better describe the fatigue behaviour of such materials in the range of the λ ratio < 1.0. This is especially required in middle-cycle

fatigue range (see curves on Fig. 5 and 6 for N_1 = 300 000) where low influence of the normal component (bending) to the fatigue life was observed.

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