FATIGUE LIFE OF AlCu4Mg1 ALUMINIUM ALLOY UNDER CONSTANT-AMPLITUDE IN- AND OUT-OF-PHASE BENDING WITH TORSION

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ABSTRACT

Fully reversed bending/torsion fatigue tests were performed with use of solid cylindrical smooth specimens under the moment control. The specimens were subjected to AlCu4Mg1 constant-amplitude pure bending, pure torsion and two combinations of proportional and of nonproportional bending with torsion. The investigated fatigue lives ranged between $5 \cdot 10^4$ and 10^7 cycles to failure. All the results can be described with one criterion of the parameter of strain energy density in the critical plane. The critical plane is the plane where the parameter of shear strain energy density reaches its maximum value. The fatigue life is influenced by a sum of parameters of normal and shear strain energy densities with some coefficients in the assumed critical plane. The calculated fatigue lives are included in the scatter band of the experimental data of a factor 3 as for pure bending.

1 INTRODUCTION

Many machine elements are subjected to complex fatigue loading that generate a multiaxial state of stress. At present, multiaxial fatigue of materials is intensively tested by many researchers. There are many criteria of multiaxial fatigue based on stresses, strains and strain energy density. The energy criteria are very often applied at present. They include both stress and strain states. From among the energy criteria we can distinguish a certain group of criteria including strain and stress states in a certain plane, so-called critical plane. These criteria reduce the multiaxial stress state to the equivalent uniaxial one. Varvani-Farahani [1] proposed the criterion determining fatigue life on the basis of a sum of normal and shear strain energy densities in the plane of maximum shear strain. Fractions of particular energies in the damage process are determined on the basis of the material constants. This parameters can be, however, applied only under cyclic loading and in the plane stress state. A similar criterion was proposed by Pan at al. [2]. It is based on the Glinka criterion and uses some other weights of particular strains. The criterion proposed by Lee et al. [3] also includes the sum of shear and normal strains with a certain coefficient. This criterion includes energy densities of both elastic and plastic strains in the critical plane. Lately the generalized criterion of multiaxial random fatigue was proposed [4]. It is an energy criterion based on the critical plane idea [5, 6]. In enables to determine fatigue life under multiaxial stress state for cyclic, variable-amplitude, proportional and non-proportional loading. In this paper the authors describe fatigue tests for constant-amplitude pure bending, pure torsion and two combinations of in-phase and out-of-phase bending with torsion using the proposed energy criterion.

The aim of this paper is determination of usability of the strain energy density parameter for fatigue life assessment of duralumin AlCu4Mg1 under in-phase and out-of phase bending with torsion.

2 FATIGUE TESTS

The material chemical composition and mechanical properties of AlCu4Mg1 aluminium are given in Tables 1 and 2. The tests were performed under cyclic in- and out-of-phase loading with the zero mean value. All the tests were performed under controlled bending and torsional moments. Diameters of the specimens were 10 mm for pure bending, pure torsion and in-phase bending with torsion. For out-of-phase bending with torsion, the diameter was 8.5 mm. Geometry of the specimens is shown in Fig. 1.

Table 1: Chemical composition of the tested AlCu4Mg1 aluminium alloy [%]

Material	Cu	Mg	Si	Mn	Fe	Ti	Zn	Cr
AlCu4Mg1	3.5-4.7	0.4-1.0	0.2-0.8	0.3-1.0	0.7	0.2	0.5	0.1

Table 2: Mechanical properties of AlCu4Mg1 aluminium alloy

Material	E [MPa]	$R_{0.2}$ [MPa]	R_m [MPa]	ν
AlCu4Mg1	72 060	395	545	0.32

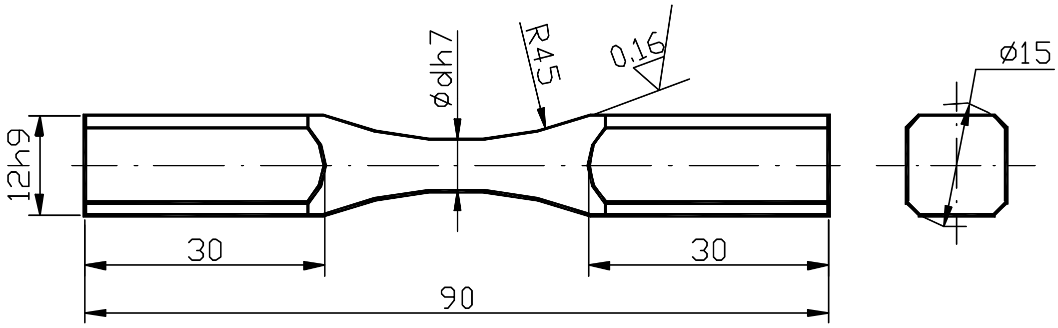

Figure 1: Geometry of the specimen for fatigue tests

The tests were performed at two fatigue tests stands: MZGS 100 and MZGS 200L. More than 150 specimens were tested. The results of this research are presented as graphs in Figs.2-4. The fatigue test results are included in the scatter band with the coefficient 3. It can be observed that Wöhler's curves for pure bending (m=7.0275) and pure torsion (m=6.8683) are parallel in practice, however the fatigue life for pure bending is much higher than that for pure torsion.

We can find that in the tested material phase displacement influences fatigue life increase for both $\tau_a=\sigma_a$ and $\tau_a=0,5\sigma_a$. Increase of torsional stress participation in the loading combination influences reduction of fatigue life.

3 THE ENERGY CRITERION OF MULTIAXIAL FATIGUE

An energy parameter for the multiaxial loading state was proposed in [4]. The damage parameter can be characterized by three basic assumptions:

1. Fatigue cracking is caused by the part of strain energy density which corresponds to work of normal stress $\sigma_\eta(t)$ on normal strain $\varepsilon_\eta(t)$, i.e. $W_\eta(t)$ and work of shear stress $\tau_{\eta s}(t)$ on shear strain $\varepsilon_{\eta s}(t)$ in direction $\overline{s}$, on the plane with normal $\overline{\eta}$, i.e. $W_{\eta s}(t)$;

2. Direction $\overline{s}$ on the critical plane coincides with the mean direction where the shear strain energy density reaches its maximum, $W_{\eta s\max}(t)$;
3. In the limit state, the material strength is determined by the maximum value of a linear combination of parameters of normal $W_{\eta}(t)$ and shear $W_{\eta s}(t)$ strain energy densities, i.e.

$$\max_{t}\{\beta W_{\eta s}(t)+\kappa W_{\eta}(t)\}=Q\,, \tag{1}$$

where β is constant for selection of a particular form of (1) and κ, Q are material constants obtained from uniaxial fatigue tests.

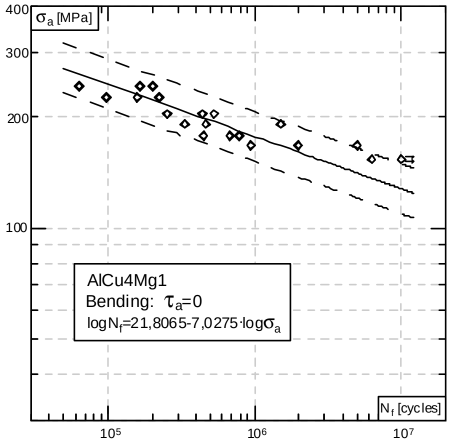

Figure 2: Wöhler fatigue curves for pure bending and pure torsion for AlCu4Mg1 aluminium alloy

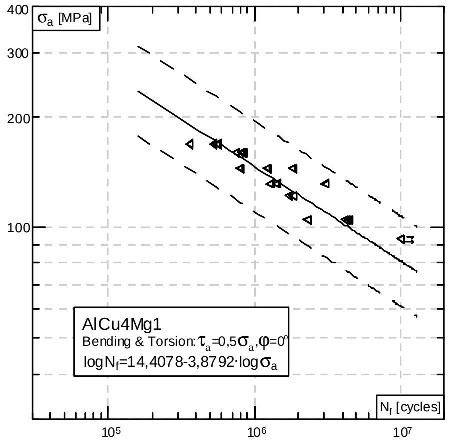

Figure 3: In-phase bending with torsion - Wöhler fatigue curves for AlCu4Mg1 aluminium alloy ($\lambda=\tau_a/\sigma_a=0{,}5$, $\varphi=0°$) and ($\lambda=\tau_a/\sigma_a=1$, $\varphi=0°$)

Depending on a material, the damage parameter can be determined in the plane of maximum parameter of normal or shear strain energy density. From theoretical considerations for different materials it results that the first criterion is better only for cast irons. For other materials (also aluminium), we can obtain better results using the plane where the shear strain energy density parameter reaches its maximum value as the critical plane. This plane was assumed as the critical plane in this paper.

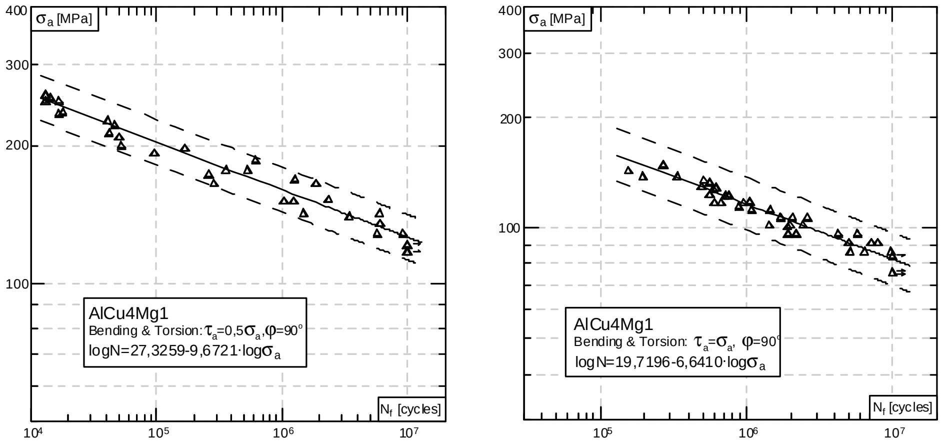

Figure 4: Out-of-phase bending with torsion - Wöhler fatigue curves for AlCu4Mg1 aluminium alloy ($\lambda=\tau_a/\sigma_a=0{,}5$, $\varphi=90°$) and ($\lambda=\tau_a/\sigma_a=1$, $\varphi=90°$)

In [4], the authors proposed the criterion in which the equivalent strain energy density is a linear combination of normal and shear strain energy densities. Participation of particular energies in the damage process depends on constants β and κ. In this case, the critical plane is determined by the parameter of shear strain energy density. It is assumed that $Q=W_{af}$ and the critical plane with normal $\overline{\eta}$ and tangent $\overline{s}$ is determined as the mean position of one of two planes where the maximum shear strain energy density occurs. The scalar product $\overline{\eta}\circ\overline{s}=0$.

Thus, the criterion can be written as:

$$W_{eq}(t)=\frac{k}{(1+\nu)}W_{\eta s}(t)+\frac{4-k}{(1-\nu)}W_{\eta}(t)\,, \tag{2}$$

where the coefficient k is expressed as

$$k=\frac{\sigma_{axx}^{2}\left(N_f\right)}{\tau_{axy}^{2}\left(N_f\right)}\,. \tag{3}$$

Depending on constant k and the assumed life level N_f determined from Eqn. (3), we obtain particular forms of the criteria presented in [6].

The obtained test results for duralumin AlCu4Mg1 were applied for verification of the presented criterion (Eqn (2)). At the first stage, the critical plane position was determined. Next, on this plane energy courses were determined according to criterion (Eqn (2)), where the shear strain energy density parameter is expressed as

$$W_{\eta s}(t)=\frac{1}{2}\tau_{\eta s}(t)\varepsilon_{\eta s}(t)\operatorname{sgn}\left[\tau_{\eta s}(t),\varepsilon_{\eta s}(t)\right], \tag{4}$$

where

$$\tau_{\eta s}\left(t\right)=\hat{l}_{\eta}\hat{l}_{s}\sigma_{xx}\left(t\right)+2\hat{l}_{\eta}\hat{m}_{s}\sigma_{xy}\left(t\right), \tag{5}$$

$$\varepsilon_{\eta s}\left(t\right)=\hat{l}_{\eta}\hat{l}_{s}\varepsilon_{xx}\left(t\right)+\hat{m}_{\eta}\hat{m}_{s}\varepsilon_{yy}\left(t\right)+\hat{n}_{\eta}\hat{n}_{s}\varepsilon_{zz}\left(t\right)+2\hat{l}_{\eta}\hat{m}_{s}\varepsilon_{xy}\left(t\right), \tag{6}$$

$$\hat{l}_{s}=-\sin\alpha,\quad \hat{m}_{s}=\cos\alpha,\quad \hat{n}_{s}=0\,,\ \hat{l}_{\eta}=\cos\alpha,\quad \hat{m}_{\eta}=\sin\alpha,\quad \hat{n}_{\eta}=0 \tag{7}$$

and the parameter of normal strain energy density is determined according to

$$W_{\eta}(t)=\frac{1}{2}\sigma_{\eta}(t)\varepsilon_{\eta}(t)\operatorname{sgn}\left[\sigma_{\eta}(t),\varepsilon_{\eta}(t)\right], \tag{8}$$

where

$$\sigma_{\eta}\left(t\right)=\hat{l}_{\eta}^{2}\sigma_{xx}\left(t\right)+2\hat{l}_{\eta}\hat{m}_{\eta}\tau_{xy}\left(t\right), \tag{9}$$

$$\varepsilon_{\eta}\left(t\right)=\hat{l}_{\eta}^{2}\varepsilon_{xx}\left(t\right)+\hat{m}_{\eta}^{2}\varepsilon_{yy}\left(t\right)+\hat{n}_{\eta}^{2}\varepsilon_{zz}\left(t\right)+2\hat{l}_{\eta}\hat{m}_{\eta}\varepsilon_{xy}\left(t\right). \tag{10}$$

Figure 5 shows the correlation of estimated fatigue life N_{cal} calculated by Eqn. 2 versus experimental fatigue life N_{exp}. For all the considered cases we obtained a good agreement between theoretical and experimental results. The most calculation results for the equivalent amplitude of the strain energy density parameter against the results for pure bending are included in the experimental scatter band with the coefficient 3. Only some values obtained under combined bending with torsion $\tau_a=\sigma_a$ and a very few values from the remaining results are located outside this range, but on the safe side.

4 CONCLUSIONS

From the fatigue test results obtained for duralumin AlCu4Mg1 under constant-amplitude pure torsion, pure bending and two combinations of in-phase and out-of-phase bending with torsion ($\tau_a=0.5\sigma_a$, $\tau_a=\sigma_a$) we can draw the following conclusions.

1. Fatigue life of the tested material reduces with increase of torsional stress participation.
2. Phase displacement influences increase of fatigue life of the tested material.
3. The criterion of normal and shear strain energy density parameter in the critical plane, applied for determination of fatigue life of a material similar to AlCu4Mg1 enables to obtain the results similar to the experimental ones. The critical plane is determined with the maximum parameter of shear strain energy density.

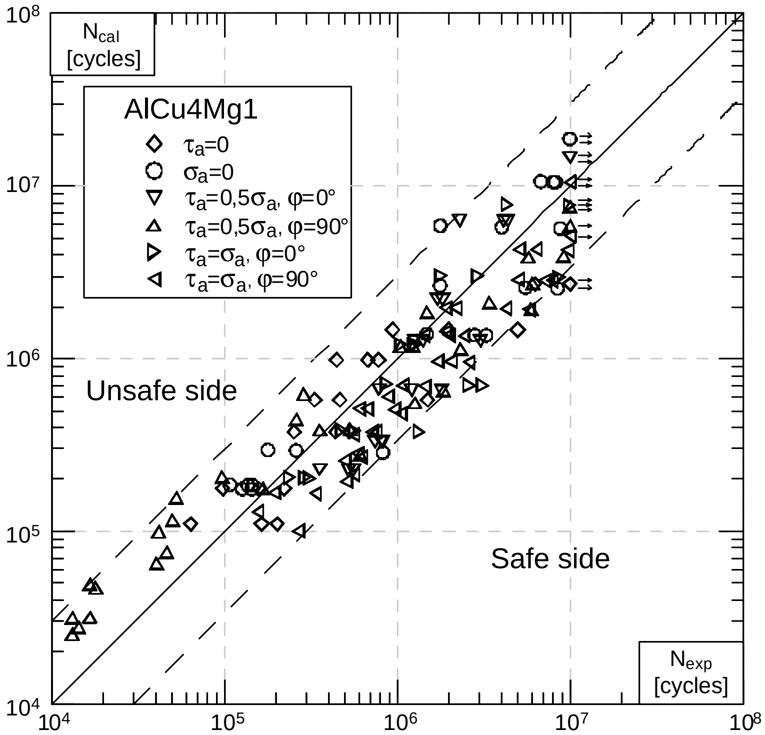

Figure 5: Experimental fatigue life N_{exp} vs. calculated fatigue life N_{cal} for AlCu4Mg1 aluminium alloy with the scatter band of a factor 3

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With the support of the Commission of the European Communities under the FP5 contract No. GIMA-CT-2002-04058 (CESTI).