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PRACTICAL IMPLEMENTATION OF SELECTED MEAN STRESS MODELS FOR RESULTS OF FATIGUE TESTS REALIZED FOR MINI SPECIMEN

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Abstract: *The cyclic properties of structural materials may be identified by means of mini specimens only. The method is limited by specimen geometry and test conditions. The mini specimens are characterised by low rigidity with a tendency to buckling. Within the range of stresses used, the tests may be based on a one-sided cycle only, which eliminates compressive stress. It requires determination of symmetric stress cycles (R = -1) characteristics. An experimental σ_a-N curve for cycle with stress ratio R = 0.1 was determined based on mini specimen testing. The curve was further used to determine a curve for symmetric stress cycles R = -1 using selected mean stress models.*

Keywords: Mini specimen, Mean stress, High-cycle fatigue, Aluminum alloy, Schütz curve.

1. Introduction

Time-variable stresses result in the fatigue cracks and damage to machine components. A fatigue is described as a phenomenological process where known relations have narrow and strictly determined ranges of application. The process is complex and cannot be described by a single general model. The development of new production technologies, e.g. thin-walled structures, results in a lack of reliable procedures for the assessment of material and product (structural component) fatigue properties. It is thus advisable to develop new test methods which will expand on the currently utilised procedures (normative requirements).

The tests to identify cyclic properties of materials using mini specimens have been developed to verify new test methods. Specimen geometry is defined below standard dimensions (PN-74/H-04327). A small size of the specimen allows to extend the scope of material fatigue tests to the products where taking normative samples is not feasible. Its low volume also facilitates comprehensive fatigue test in case of limited availability of the tested material. It applies to the assessment of a damage extent of components in use compared to new components (Lord et al., 2002). It also seems that the use of the mini specimens may reduce the high costs of fatigue tests resulting mostly from the availability of the testing machines, through the reduced range of forces used (lower specimen cross-section) and use of less expensive loading systems.

The mini specimen geometry is characterised by a low cross-section and a low rigidity thus resulting in a low buckling resistance, which requires use of tensile stress only (stress ratio ($R = \sigma_{min}/\sigma_{max}$) higher than zero). The data for symmetric stress cycles (R = -1) or cycles pulsating from zero (R = 0) are used in the fatigue strength engineering calculations. The test results (fatigue strength) obtained for the mini specimen based on the resulting equations (R – actual) must be estimated to the equations for R = -1 or R = 0.

The aim of the study is to determine the fatigue strength for R = -1 cycles based on the σ_a-N characteristics empirically determined for R = 0.1 (for a mini specimen) and to analyse selected analytical mean stress models. The tests are performed on the aluminum alloy specimens.

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2. Stress Cycle Asymmetry

A fatigue life depends on stress amplitude (σ_a) and a mean stress (σ_m). The ratio varies for different metals and determines material sensitivity to the stress cycle asymmetry (ψ_σ). Its value within the fatigue limit is expressed as the following equation:

$$\psi_\sigma = \frac{2\sigma_{(-1)} - \sigma_{(0)}}{\sigma_{(0)}} \tag{1}$$

where:

$\sigma_{(-1)}$ – fatigue life for R = -1,

$\sigma_{(0)}$ – fatigue life for R = 0.

The increase in coefficient ψ_σ indicates higher sensitivity of material to the stress cycle asymmetry. The aluminum alloys does not feature a sharply outlined fatigue limit (Sonsino, 2007). The coefficient ψ_σ was verified at a fatigue strength corresponding to the fatigue life of 2x10^6 (σ_a-N curve break).

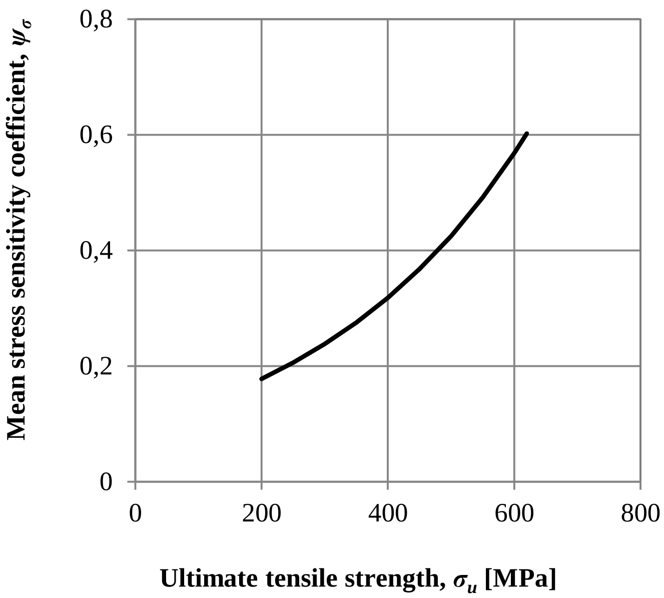

Fig. 1: Relation between the mean stress sensitivity coefficient and the ultimate tensile strength (Schütz curve (Schijve, 2004)).

Tab. 1: Models of mean stress effects (Ligaj et al., 2011; Sekercioglu et al., 2013).

Author	Form	Author	Form
Gerber	$\sigma_a = \sigma_{(-1)}\left[1-\left(\frac{\sigma_m}{\sigma_u}\right)^2\right]$	Goodman	$\sigma_a = \sigma_{(-1)}\left[1-\left(\frac{\sigma_m}{\sigma_u}\right)\right]$
Haigh	$\sigma_a = \sigma_{(-1)}\left[1-\left(\frac{\sigma_m}{\sigma_u}\right)^2\right]^{1/2}$	Soderberg	$\sigma_a = \sigma_{(-1)}\left[1-\left(\frac{\sigma_m}{\sigma_y}\right)\right]$
Morrow	$\sigma_a = \sigma_{(-1)}\left[1-\left(\frac{\sigma_m}{\sigma_f}\right)\right]$	Smith-Watson-Topper	$\sigma_a = \frac{\sigma_{(-1)}}{\sqrt{\frac{2}{1-R}}}$
Bagci	$\sigma_a = \sigma_{(-1)}\left[1-\left(\frac{\sigma_m}{\sigma_y}\right)^4\right]$	ASME-elliptic	$\sigma_a = \sigma_{(-1)}\left[1-\left(\frac{\sigma_m}{\sigma_y}\right)^2\right]^{1/2}$
Clemson	$\sigma_a = \sigma_{(-1)}\left[1-\left(\frac{\sigma_m}{\sigma_y}\right)^{\sigma_y/\sigma_{(-1)}}\right]$	Sekercioglu	$\sigma_a = \sigma_{(-1)}\left[1-\left(\frac{\sigma_m}{\sigma_y}\right)^2\right]^k$

The strength and fatigue properties of aluminum alloys were used to analyse the mean stress effect (literature: 24S-T3 (Grover et al., 1954), 75S-T6 (Grover et al., 1954), 6061-T6 (Sekercioglu et al., 2013), D16CzATW (Szala et al., 2005), own studies: AW-6063-T6). The coefficient ψ_σ is related to a tensile strength. The relation is shown as a curve in Fig. 1. The mean stress effect increases in materials with a higher tensile strength.

A model of the mean stress effect is also used to describe the relation between the stress amplitude (σ_a) and the mean stress (σ_m) (see Tab. 1). It determines fatigue strength for cycles at different stress ratio (R). Goodman, Morrow and Sederberg model are used for the linear relation between σ_a and σ_m. Other models describe the relation as a parabola. A material strength property (σ_u, σ_y, σ_f) and the equation are variable model parameters.

3. Verification of the Effect of Mean Stress on Aluminum Alloys

Mini specimen test results may create problems with the effect of scale and mean stress. The analyses including the identification of the effect of scale were discussed in relevant studies (Tomaszewski et al., 2012; Tomaszewski et al., 2014). This article focuses on the effect of mean stress. The curve σ_a-N (R = -1) was determined based on the characteristics of determined experimentally for R = 0.1 cycles with selected models of the effect of mean stress.

The model analysis was performed for EN AW-6063 aluminum alloy (see Fig. 2). The characteristics were determined experimentally for a mini specimen with a cross-section of 3.5 mm^2. The tests of high-cycle fatigue with controlled stress were performed. The detailed test conditions are detailed in the relevant study (Tomaszewski et al., 2012).

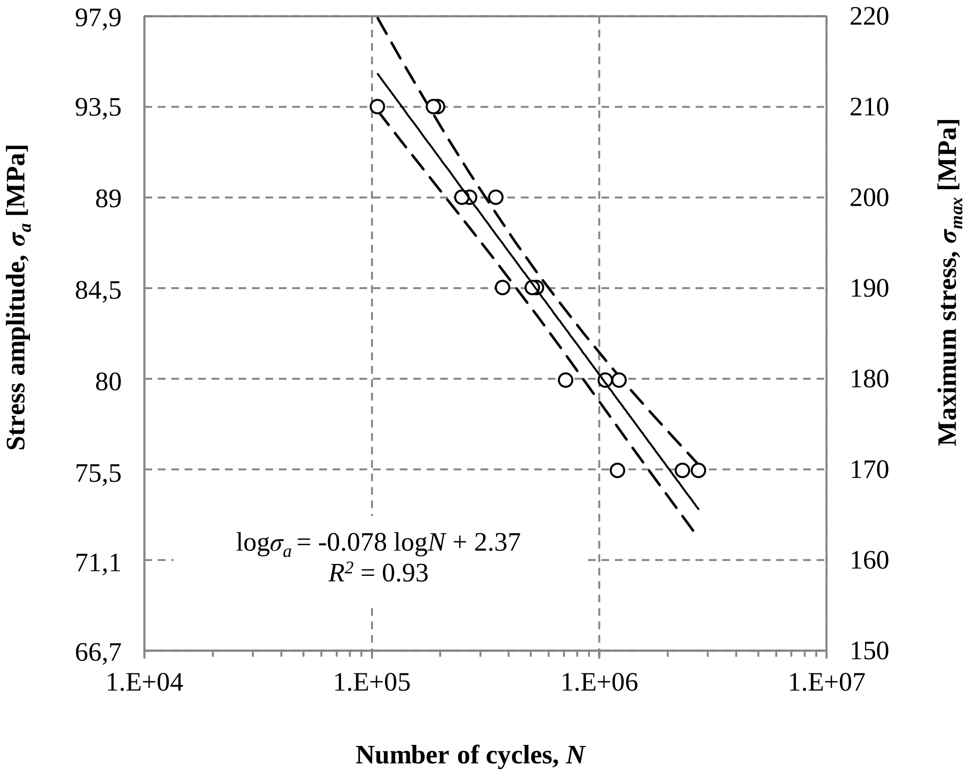

Fig. 2: Curve σ_a-N for a mini specimen made of EN AW-6063 aluminum alloy.

Fatigue strength was estimated within the lower (1.3x10^5 cycles) and the upper (2x10^6 cycles) high-cycle fatigue limits. The curves σ_a-N for R = -1 are shown in Fig. 3. The results were compared with a fatigue strength determined based on the coefficient ψ_σ as read from a Schütz curve (Fig. 3b) for EN AW-6063 (σ_u = 230 MPa, ψ_σ = 0.19).

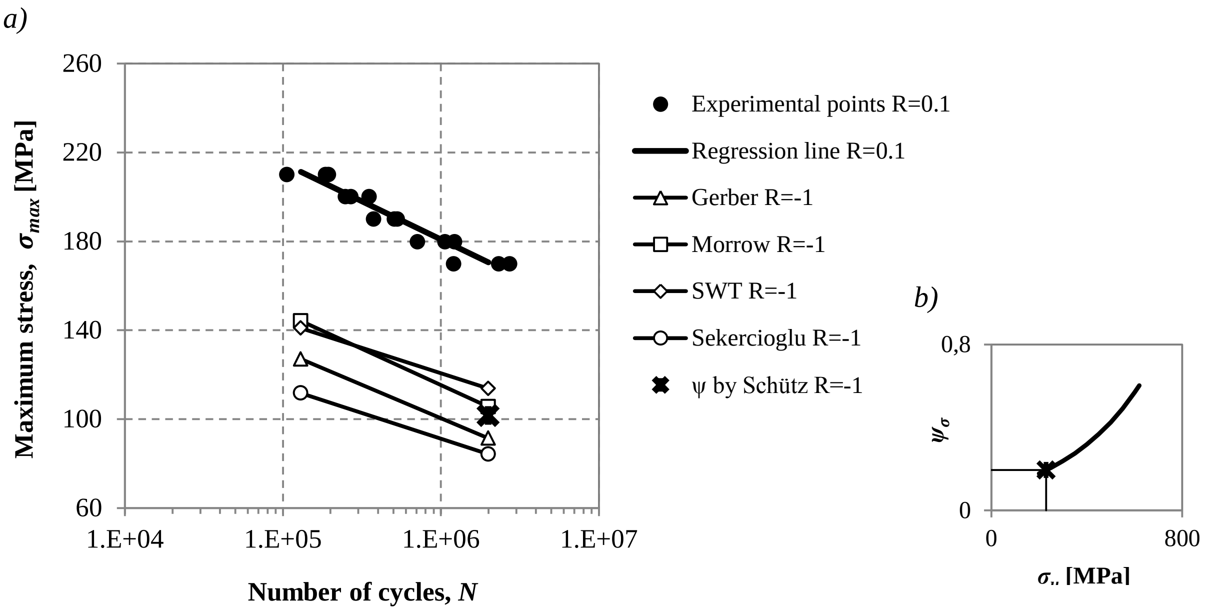

Fig. 3: Mean stress effect analysis: a) σ_a-N curve position;
b) Schütz curve for EN AW-6063 aluminum alloy.

4. Summary

One of the most significant limitations of using the mini specimens to determine the σ_a-N fatigue characteristics is the use of loads with a tensile component only (i.e. one-sided at $R > 0$). The analysis of selected analytical models of the effect of mean stress on fatigue strength was preformed. The scope of analysis included a verification of errors in estimation of the fatigue strength of aluminum alloys. The models used allowed the assessment of characteristics (R = -1) other than experimental (R = 0.1).

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