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Evaluation of Multiaxial Fatigue Criteria on LCF Data of SS316L

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Abstract. The paper (study) deals with the evaluation of 10 low cycle fatigue criteria (critical plane) for stainless steel SS316L under 7 different loading paths. Best results were obtained based on the Socie at all criterion. The criterion of Jiang´s provided slightly more conservative prediction. The advantage of Jiang´s criterion is its possibility to be used for general case of multiaxial loading including variable amplitude loading without use of rain flow method.

Introduction

Most machine parts are loaded in a combined mode. In the field of low cycle fatigue, stress-strain behavior plays a significant role, which is also influenced by the level of non-proportionality of loading. The effect of additional hardening due to non-proportional loading for stainless steels is well known. Within the project of the Grant Agency of the Czech Republic [1], the advanced concept of prediction of fatigue failure under general multiaxial loading was implemented according to Jiang [2]. Other aims of the project were to apply parallel algorithms to increase the speed of fatigue calculations, to evaluate available approaches for the elastoplastic correction at the root of the notch and to develop models of cyclic plasticity for selected metallic materials.

In this paper, we focused on the evaluation of selected low cycle fatigue criteria in the case of constant amplitude of strain. Ten selected criteria proposed for multiaxial fatigue according to various authors were evaluated. As an experimental set, the own data obtained for the 316L stainless steel under seven different strain paths served for evaluation.

Evaluation study description

Known algorithms have been implemented to determine the amplitude of normal and shear stress / strain. The algorithm of the circumscribed circle identification was used in presented calculations. In all cases, it is the criterion of the critical plane. Following lifecycle algorithms are presented:

- Jiang´s criterion [2],
- Socie et all [3],
- Fatemi-Socie [6],

- Brown-Miller [7],
- Kandil-Brown-Miller [8],
- Wang-Brown [9].

The Jiang's criterion includes the concept of the critical plane, the influence of the plastic deformation energy and the principle of the material memory from the mathematical modeling of cyclic plasticity. The combination of the energy approach with the material memory concept has the following form

$$dD = \langle \sigma_{mr} - \sigma_0 \rangle^m \left(1 + \frac{\sigma}{\sigma_f} \right) dY \,, \tag{1}$$

$$dY = a\sigma\, d\varepsilon^p + \frac{1-a}{2} \tau\, d\gamma^p \,. \tag{2}$$

Socie et all is the criterion of stress-strain models where the control parameter is deformation and the secondary parameter is stress. The effect of the mean normal stress $\sigma_{n,m}$is included as follows

$$\gamma_{amax} + \varepsilon_{an} + \frac{\sigma_{n,mean}}{E} = \frac{\tau_f'}{G}\left(2N_f\right)^{b_\gamma} + \gamma_f'\left(2N_f\right)^{c_\gamma}. \tag{3}$$

Fatemi-Socie is a stress-strain criterion as well.

$$\frac{\Delta\gamma}{2}\left(1 + k\frac{\sigma_{n,max}}{R_e}\right) = f(N_f). \tag{4}$$

Brown-Miller is a deformation criterion. The deformation is the damage critical parameter. The critical plane is defined as the plane where the shear deformation reaches the maximum value of

$$\frac{\Delta\gamma_{max}}{2} = \frac{\tau_f'}{G}\left(2N_f\right)^{b_\gamma} + \gamma_f'\left(2N_f\right)^{c_\gamma}. \tag{5}$$

Unlike the previous criterion, the effect of both normal and shear deformation is assumed in case of Kandil-Brown-Miller criterion.

$$\frac{\Delta\bar{\gamma}}{2} = \left(\frac{\Delta\gamma_{max}^{\alpha}}{2} + S\Delta\varepsilon_n^{\alpha}\right)^{\frac{1}{\alpha}} = f(N_f). \tag{6}$$

Wang-Brown is a modification of the Kandil-Brown-Miller criterion, including the influence of mean stress, $\alpha = 1$

$$\frac{\Delta\bar{\gamma}}{2} = \frac{\Delta\gamma_{max}}{2} + S\Delta\varepsilon_n = f(N_f). \tag{7}$$

a, m - material constant,
b_γ - fatigue shear strength exponent,

c_γ – fatigue ductility exponent,

dD - infinitesimal increment od fatigue damage,
D - fatigue damage,
E – Young´s modulus,

G - shear modulus,

k – material constant,
N_f - number of cycles to failure,

R_e - yield strength,
S – material constant,
Y - plastic strain energy on a material plane,
γ_{amax} – maximum plastic shear strain range,

γ'_f - fatigue shear ductility coefficient,

γ^p - plastic shear strain corresponding to the shear stress on a material plane,
$\Delta\gamma$ – maximum shear strain range,
$\Delta\bar{\gamma}$- ekvivalent of maximum shear strain range,

ε_{an} – elastic-plastic notch tip strain,

ε^p - plastic strain corresponding to the normal stress on a material plane,
$\Delta\varepsilon_n$ - normal strain range on the plane of maximum shear strain,

σ - normal stress on a material plane,
σ_f - true fracture stress,
σ_{mr} - memory stress,
$\sigma_{n,max}$ – maximum normal stress on the plain of maximum shear strain

$\sigma_{n,mean}$ – mean normal stress on the plane of maximum shear strain,,

σ_0 - endurance limit,
τ - shear stress on a material plane,
τ'_f - torsional fatigue strength coefficient,

<> - MacCauley bracket.

Uniaxial fatigue parameters of the SS316L steel were determined by both conventional and 3D method. Six fatigue constants is usually determined by the conventional method based on the linear approximation of experimentally obtained data (three independent linear regressions). The main advantage of the new3D method is that it ensures the compatibility of six fatigue constants. The method is based on the linear approximation in space. The complete description of the 3D method is in [4].

Details about multiaxial experiments are listed in article [5]. The following loading spectre were considered:

- uniaxial (case A),
- torsional (B),
- proportional (C),
- square (D),
- rhombic (E),
- two blocks (F),
- circular (G),
- elliptical (H).

The elliptical path shape corresponds to the 45° out of phase fatigue test. Case (A) was used only to determine material parameters by the 3D method.

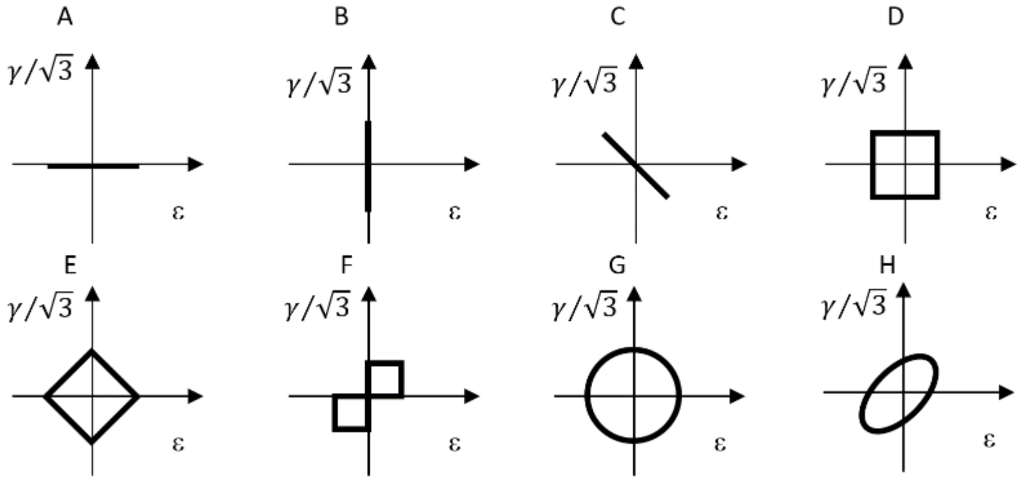

Fig.1 Strain path shapes in particular cases

The best results are obtained from theories according to Jiang [2] and Socie at all [3]. In order to evaluate the agreement between experimental measurements and results obtained from the predictions using individual criteria, charts were created in logarithmic coordinates, where values obtained from the experimental measurements N_{exp} are plotted on the horizontal axis and values obtained using individual criteria N_{pred} are plotted on the vertical axis. In the ideal case, points obtained should lie on a straight line that passes through the origin and is inclined at an angle of 45 degrees. Additionally, the Logarithmic Lifetime Ratio (LLR) criterion was selected to evaluate the agreement of individual criteria with experimental data, defined by the following expression

$$LLR = \log\left(\frac{N_{exp}}{N_{pred}}\right). \quad (8)$$

In the case of an ideal state - when the value obtained from the experiment and the value obtained using the criterion are the same, the value of LLR = 0. If values differ from one another, two cases may occur. If LLR is <0, the criterion predicts non-conservative results. On the other hand, if the value of LLR> 0, the criterion predicts conservative results. The value of the criterion (without considering the sign) shows then the quantitative match between results obtained by experiments and calculations.

Results presenting the comparison of the number of cycles predicted by criteria mentioned above with experimentally determined number of cycles are presented in Fig. 2.

Conclusions

Best results were obtained by the Socie at all criterion (see Figure 1). Jiang´s criterion gives slightly more conservative prediction. Despite this fact, the prediction capability of the Jiang´s criterion can be considered as very good too, compared to other eight criteria. Its advantage is the possibility of the application on the general multiaxial loading including the variable amplitude loading without the use the rainflow method.

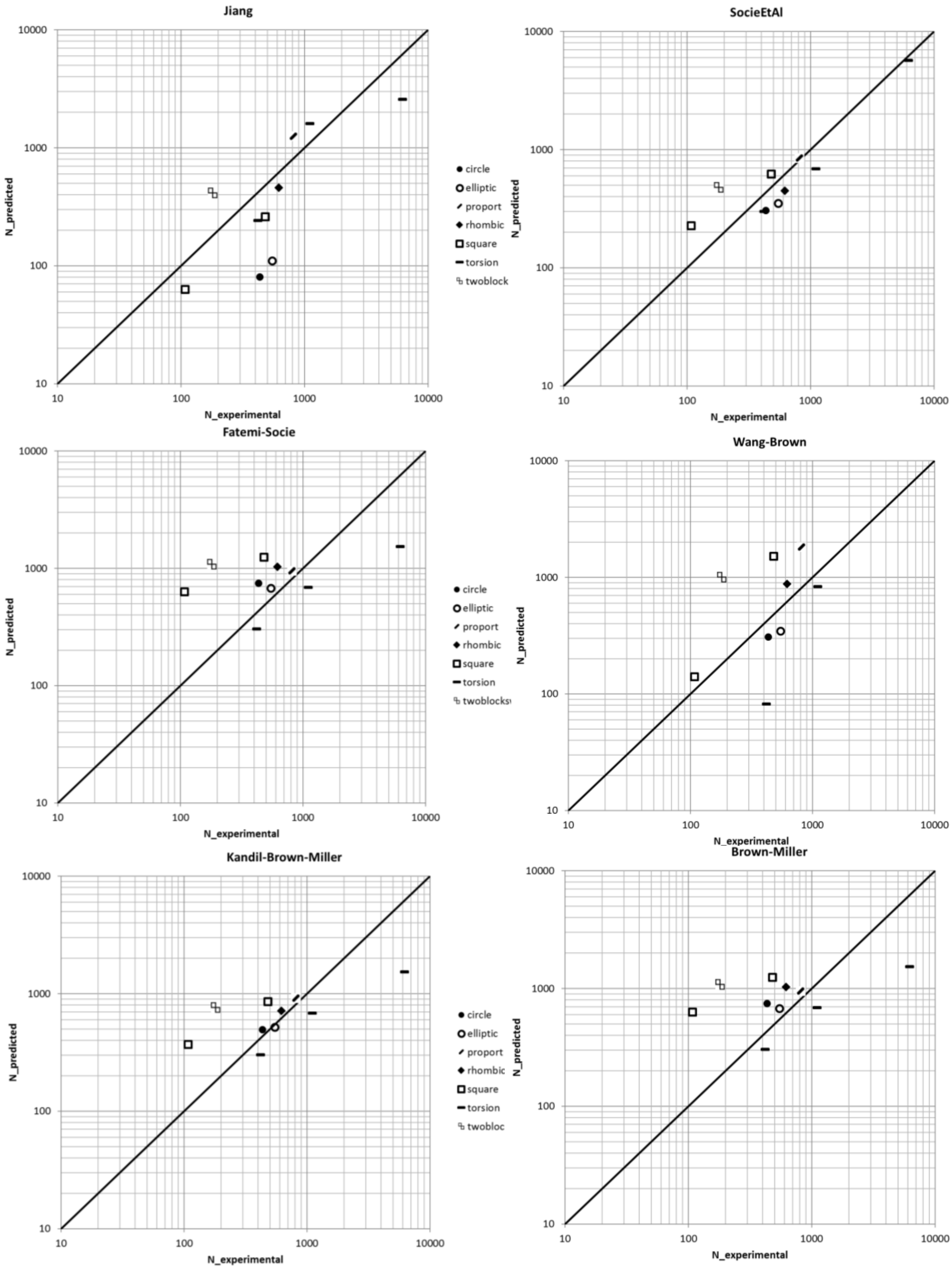

Fig.2 Comparison of predictions of multiaxial criteria with experiment

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