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APPLICATION OF THE STRAIN ENERGY DENSITY PARAMETER FOR ESTIMATION OF MULTIAXIAL FATIGUE LIFE OF SINTERED STEELS WITH STRESS CONCENTRATORS

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This paper presents fatigue test results of a Fe-Cu sintered alloy (1.5% Cu) and three types of Fe-Cu-Ni sintered alloys (2% Cu, 2.5% Ni). Fe-Cu-Ni sintered alloys were produced under different compaction pressures and sintering temperatures. Round specimens with fillet notches were subjected to a constant amplitude pure bending, pure torsion and a combined in-phase and out-of-phase ($\delta = 90°$) bending with torsion. All results have been described by the criterion of the strain energy density parameter on the critical plane. It was assumed that the fatigue life is influenced by a linear combination of normal and strain energy density parameters with the coefficients that refer to the calculated plane. In particular, it allowed one to compute fatigue lives sufficiently comparable to the experimental ones.

Key words: energy models, cyclic loading, fatigue lifetime, sintered steel

Notations

b_k	–	fatigue strength exponent for notched elements
C	–	coefficient determining values of stresses in circumferential direction depending on stress concentration
E	–	Young's modulus
$\boldsymbol{i}, \boldsymbol{j}, \boldsymbol{k}$	–	unit vectors in Cartesian coordinate system

K_t	–	theoretical stress concentration factor
$\widehat{l}_\eta, \widehat{m}_\eta, \widehat{n}_\eta$	–	direction cosines of unit vector $\boldsymbol{\eta}$
$\widehat{l}_s, \widehat{m}_s, \widehat{n}_s$	–	direction cosines of unit vector $\boldsymbol{s}$
N_f	–	number of cycles to failure
$R_{e0.2}$	–	yield stress
R_m	–	ultimate tensile strength
$\operatorname{sgn}[i,j]$	–	binary logical function *sgn* with variables i, j
t	–	time
W	–	strain energy density parameter
x, y, z	–	spatial coordinates
β, κ	–	coefficients indicating criterion form, obtained from uniaxial fatigue tests
ε	–	strain
ν	–	Poisson's ratio
γ	–	engineering shear strain
σ	–	normal stress
σ'_{fk}	–	fatigue strength coefficient for notched elements
τ	–	shear stress

Subscripts:

a	–	amplitude
b	–	bending
eq	–	equivalent
s	–	shear
t	–	torsion
η	–	normal

1. Introduction

Notch problems occur in the case of component section discontinuity, which causes local stress concentrations that are higher than the nominal calculated ones. Their quantity depends, among others, on the notch geometry, properties of the material, and the loading path. The notch occurrence leads to reduction in fatigue strength of a material. Thus, an efficient method for fatigue life determination under stress concentration should be searched for.

For fatigue life determination under stress concentration, it is necessary to determine local stresses and elastic-plastic strains in the notch root at first. In the case of cyclic loading, the Neuber method (Neuber, 1961), or the strain energy density method (SEDM) (Molski and Glinka, 1981) are usually applied.

Both methods have been generalized to the multiaxial loading state (Moftakhar *et al.*, 1995). These methods differ only in the procedure of determination of the plastic strain energy density. The values of strains and stresses in the notch root obtained according to the Neuber method are overestimated, and those obtained according to SEDM are lowered as compared with the true results. The calculated results included between those obtained according to the Neuber and Molski-Glinka models are presented in Łagoda and Macha (1998). In the literature, one can also found other energy models formulated by Inoue *et al.* (1996) and Ye *et al.* (2004), and the empirical model proposed by Sonsino (1993). Determination of local stresses and strains at the notch root requires also application of the Hencky constitutive equations and complex numerical calculations. Under a non-proportional loading, the calculations become even more complicated, because the chosen method should be expressed in an incremental notation, as the loading path influence must be taken into account. Moreover, a plasticity model (for example, the model proposed by Mróz (1967) or Chu (1984)) has to be applied in order to determine the relation between stresses and plastic strains. Thus, pseudoelastic stresses and strains are often used for fatigue calculations. In Sumsel (2004), a criterion assuming the elastic stress state near the notch was presented. Fatigue life was determined on the basis of normal and shear stresses on the plane of the maximum normal stresses.

Also the criterion proposed in Grubisic and Simbürger (1976) for ductile steels was based on elastic stresses. In that case, the maximum shear stress was assumed to be as the equivalent stress amplitude.

In Łagoda and Ogonowski (2005), the criterion of strain energy density parameter on the critical plane was proposed. This criterion is based on pseudoelastic stresses and strains and it is valid under stress concentration. It was verified for 42CrMo4V steel. Next, similar criteria performed in stress and strain notations were presented (Ogonowski *et al.*, 2004). Moreover, the efficiency of particular criteria was analysed according to the test results obtained for 10HNAP steel. From the analysis, it appears that the energy notation that includes variation of both strains and stresses gives calculated fatigue lives closest to the experimental ones.

The aim of this paper is to verify the energy criterion for Fe-Cu and Fe-Cu-Ni sintered steels with stress concentrators, using the test results obtained by Sonsino (1983), Sonsino and Grubisic (1989). In Sonsino (1983), Sonsino and Grubisic (1989), the criterion of the maximum normal elastic stress amplitude, which occurs in the critical plane, is applied.

2. Application of the strain energy density parameter in the presence of stress concentration in a component

2.1. The case of uniaxial loading

Under a uniaxial loading, the strain energy density parameter (SEDP) (Grubisic and Simbürger, 1976) is defined as

$$W_{xx}(t) = \frac{1}{2}\sigma_{xx}(t)\varepsilon_{xx}(t)\,\mathrm{sgn}\,[\sigma_{xx}(t), \varepsilon_{xx}(t)] \tag{2.1}$$

where

$$\mathrm{sgn}\,[i,j] = \frac{\mathrm{sgn}\,[i] + \mathrm{sgn}\,[j]}{2} \tag{2.2}$$

For a constant amplitude loading, we have the following amplitude of SEDP

$$W_{xx,a} = \frac{1}{2}\sigma_{xx,a}\varepsilon_{xx,a} \tag{2.3}$$

Let us note (Kluger *et al.*, 2007) that the strain energy density parameter is of a vectorial character, whereas the strain energy density applied in mechanics is a scalar.

When stress concentration occurs, stress histories in particular directions can be expressed for axial stresses (under bending)

$$\sigma_{xx}(t) = K_{tb}\sigma_{xx,\eta}(t) \tag{2.4}$$

and for circumferential stresses

$$\sigma_{yy}(t) = C\sigma_{xx}(t) \tag{2.5}$$

where $0 \leqslant C \leqslant \nu$. Changes of the coefficient C depending on K_t factor are shown in Fig. 1. Its approximate value, found from numerical calculation and extrapolated, can be determined from

$$C = \frac{1.84\nu}{K_t}(K_t - 1)^{1-\nu} \tag{2.6}$$

The relation given by Eq. (2.6) was based on calculations with the use of the finite element method for different notch geometries, $K_t = K_{ta}$ for axial loading and $K_t = K_{tb}$ for bending. At the bottom of the notch root (surface),

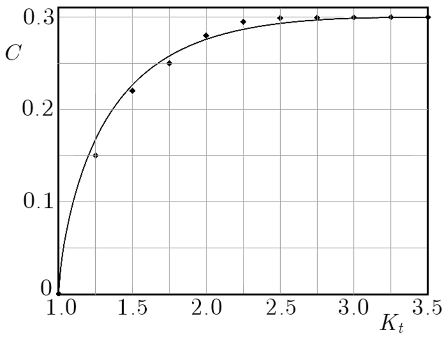

Fig. 1. Changes of coefficient C values against stress concentration factor K_t

the radial stresses equal zero ($\sigma_{zz}(t) = 0$). Thus, assuming an elastic body model, the following strain histories are obtained

$$\begin{aligned} &\varepsilon_{xx}(t) = (1 - C\nu)K_{tb}\frac{\sigma_{xx,\eta}(t)}{E} \qquad\qquad \varepsilon_{yy}(t) = (C - \nu)K_{tb}\frac{\sigma_{xx,\eta}(t)}{E} \\ &\varepsilon_{zz}(t) = -(C + \nu)K_{tb}\frac{\sigma_{xx,\eta}(t)}{E} \end{aligned} \tag{2.7}$$

Taking into consideration Eqs (2.3), (2.4) and $(2.7)_1$, the following formula is valid for the elastic material

$$W_{xx,a} = \frac{\sigma^2_{xx,a\eta}}{2E}(1 - \nu C) = \frac{\sigma^2_{xx,a\eta}K^2_{tb}}{2E}(1 - \nu C) \tag{2.8}$$

Using Eq. (2.8), we can propose a new fatigue characteristic S-N that is based on the strain energy density parameter and involves the stress concentration field:

— under control of stress or strain energy density parameter (Będkowski *et al.*, 2004)

$$\log N_f = A_w - m_w \log W_{xx,a} \tag{2.9}$$

where A_W and m_W are coefficients determining the fatigue curve W_a-N_f, like for the standard Basquin curve σ_a-N_f

— or under strain control

$$W_a = \frac{\sigma'^2_{fk}K^2_{tb}}{2E}(1 - \nu C)(2N_f)^{2b_k} \tag{2.10}$$

2.2. The case of multiaxial loading

As in the case of criteria for smooth specimens or elements, it is assumed that fatigue damage is described by a linear combination of the parameters of normal and shear strain energy density parameters (W_n and $W_{\eta s}(t)$, respectively) on the critical plane. In Łagoda and Ogonowski (2005), two forms of the criterion dependent on the assumed critical plane (Fig. 2) have been presented. The calculations carried out for many materials have proved that the criterion based on the plane of maximum parameter of the normal strain energy density gives good results for cast irons only. For other materials, it is better to assume the critical plane where the shear strain energy density parameter reaches its maximum value. Thus, for calculations related to the discussed alloys, the following fatigue criterion on the plane of the maximum shear strain energy density parameter was assumed:

$$\beta \max_t\{W_{\eta s}(t)\} + \kappa W_\eta(t) = f(N_f) \tag{2.11}$$

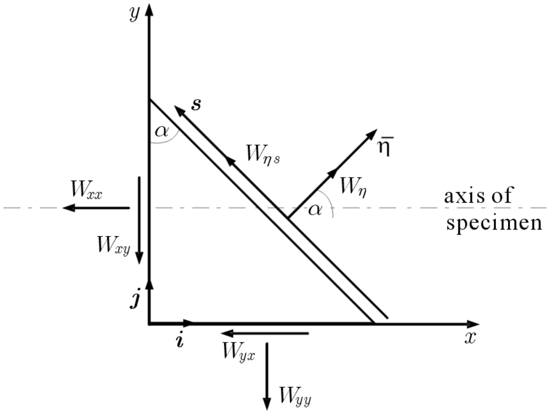

Fig. 2. Interpretation of the critical plane

The energy density parameters of normal and shear strains are determined as follows

$$\begin{aligned} W_\eta(t) &= \frac{1}{2}\sigma_\eta(t)\varepsilon_\eta(t)\,\mathrm{sgn}\,[\sigma_\eta(t),\varepsilon_\eta(t)] \\ W_{\eta s}(t) &= \frac{1}{2}\tau_{\eta s}(t)\varepsilon_{\eta s}(t)\,\mathrm{sgn}\,[\tau_{\eta s}(t),\varepsilon_{\eta s}(t)] \end{aligned} \tag{2.12}$$

The weight coefficients β and κ define contribution of the normal and shear strain energy density parameters during fatigue life determination. For a combined bending and torsion as well as stress concentration, the normal $\sigma_\eta(t)$ and shear $\tau_{\eta s}(t)$ stresses on the critical plane are defined as

$$
\begin{aligned}
\sigma_\eta(t) &= \widehat{l}_\eta^2\sigma_{xx}(t) + \widehat{m}_\eta^2\sigma_{yy}(t) + 2\widehat{l}_\eta\widehat{m}_\eta\sigma_{xy}(t) \\
\tau_{\eta s}(t) &= \widehat{l}_\eta\widehat{l}_s\sigma_{xx}(t) + \widehat{m}_\eta\widehat{m}_s\sigma_{yy}(t) + (\widehat{l}_\eta\widehat{m}_s + \widehat{l}_s\widehat{m}_\eta)\sigma_{xy}(t)
\end{aligned}
\tag{2.13}
$$

The normal $\varepsilon_\eta(t)$ and shear strains $\gamma_{\eta s}(t)$ being in the relation

$$
\varepsilon_{\eta s}(t) = \frac{1}{2}\gamma_{\eta s}(t) \tag{2.14}
$$

can be expressed as

$$
\begin{aligned}
\varepsilon_\eta(t) &= \widehat{l}_\eta^2\varepsilon_{xx}(t) + \widehat{m}_\eta^2\varepsilon_{yy}(t) + \widehat{n}_\eta^2\varepsilon_{zz}(t) + 2\widehat{l}_\eta\widehat{m}_\eta\varepsilon_{xy}(t) \\
\varepsilon_{\eta s}(t) &= \widehat{l}_\eta\widehat{l}_s\varepsilon_{xx}(t) + \widehat{m}_\eta\widehat{m}_s\varepsilon_{yy}(t) + \widehat{n}_\eta\widehat{n}_s\varepsilon_{zz}(t) + (\widehat{l}_\eta\widehat{m}_s + \widehat{l}_s\widehat{m}_\eta)\varepsilon_{xy}(t)
\end{aligned}
\tag{2.15}
$$

where $\sigma_{ij}(t)$, $\varepsilon_{ij}(t)$ are the components of stress and strain state tensors at the notch root, respectively.

For the plane stress state, the direction cosines $\widehat{l}_\eta$, $\widehat{m}_\eta$, $\widehat{l}_s$, $\widehat{m}_s$ of the vectors $\widehat{\eta}$ and $\widehat{s}$ refering to the normal strain (Eqs. $(2.13)_1$ and $(2.15)_1$) and shear strain energy density parameter (Egs. $(2.13)_2$ and $(2.15)_2$ are defined by one angle α in the following relationships

$$
\begin{aligned}
&\widehat{l}_\eta = \cos\alpha \qquad && \widehat{m}_\eta = \sin\alpha \qquad && \widehat{l}_s = -\sin\alpha \\
&\widehat{m}_s = \cos\alpha && \widehat{n}_\eta = \widehat{n}_s = 0 &&
\end{aligned}
\tag{2.16}
$$

where α is the angle determining the critical plane orientation.

After introducing

$$
\beta = \frac{k(1-\nu C)}{1+\nu} \tag{2.17}
$$

for the coefficient β and κ, according Łagoda and Ogonowski (2005), as in the following

$$
\kappa = \frac{[4-k(1-C)^2](1-\nu C)}{(1-\nu)(1+C)^2} \tag{2.18}
$$

for a given moment t, Eq. (2.10) can be written as

$$
\frac{k(1-\nu c)}{1+\nu}(W_{a,\eta s})_{max} + \frac{[4-k(1-C)^2](1-\nu C)}{(1-\nu)(1+C)^2}W_{a,\eta} = \frac{(\sigma'_{fk})^2}{2E}(2N_f)^{2b_k} \tag{2.19}
$$

In a general case, the weight coefficient k is defined with respect to a number of cycles to failure as

$$k = k(N_f) = \frac{\sigma_{xx,a}^2(N_f)}{\tau_{xy,a}^2(N_f)} \tag{2.20}$$

where

$\sigma_{xx,a}(N_f)$ – amplitude of local normal stress on the S-N curve for bending

$\tau_{xy,a}(N_f)$ – amplitude of local shear stress on the S-N curve for torsion.

Relationships (2.19) and (2.20) are the final form of the failure criterion under stress concentration on the plane of maximum shear strain energy density. The right-hand side of relationship (2.19) expresses the equation of the S-N curve for tension (alternating bending) rescaled to energy notation and written in an exponential form. Thus, the multiaxial stress state is reduced to an equivalent uniaxial one.

When the S-N fatigue curves for bending and torsion are parallel, then Eq. (2.20) can be written as

$$k = \frac{\sigma_{af}}{\tau_{af}} = \text{const} \tag{2.21}$$

3. Experimental verification

3.1. The experiments

The criterion of strain energy density parameter was verified for Fe-Cu and three Fe-Cu-Ni sintered steels; the verification was based on the tests made by Sonsino (1983), Sonsino and Grubisic (1989). Mechanical properties of the considered materials are presented in Table 1.

Various pressing pressures and temperatures of sintering as well as three types of gas mixtures were applied during production of the sintered alloys. Water atomized iron powder WPL 200 (base) was mixed with copper and nickel powders, and the whole mixture was then sintered (Table 2).

Round specimens with fillet notches as stress concentrators were tested (see Fig. 3). The theoretical notch factor for the given geometry was $K_{tb} = 1.49$ for bending, and $K_{tt} = 1.24$ for torsion. The assumed coefficient determining the values of circumferential stress according to Eq. (2.6) was $C = 0.215$ (Sonsino and Grubisic, 1989). A graphical interpretation and a method for the

Table 1. Mechanical properties of the considered sinters

Material	ρ [g/cm^3]	E [GPa]	$R_{p0.2}$ [MPa] Tension/Compression	R_m [MPa]	A_5 [%]	Z [%]
Fe-Cu	7.4	167	290/312	371	13	16
Fe-Cu-Ni$^{(1)}$	7.1	149	270/312	358	10	11
Fe-Cu-Ni$^{(2)}$	7.4	155	247/293	401	12	14
Fe-Cu-Ni$^{(3)}$	7.4	165	299/325	399	10	14

(1) $T_1 = 1280°$C
(2) $T_1 = 900°$C, $T_2 = 1120°$C
(3) $T_1 = 900°$C, $T_2 = 1280°$C
A_5 – elongation
Z – reduction of area

Table 2. Composition and manufacturing parameters of the considered sinters

<table>
<tr><th>Material</th><th>Compositions</th><th>p_1 [MPa]</th><th>T_1 [°C]</th><th>p_2 [MPa]</th><th>T_2 [°C]</th></tr>
<tr><td>Fe-Cu</td><td>WPL 200 +1.5%Cu</td><td>550</td><td>900 atmosphere 1</td><td>500</td><td>1280 atmosphere 3</td></tr>
<tr><td>Fe-Cu-Ni$^{(1)}$</td><td rowspan="3">WPL 200 +2%Cu +2.5%Ni</td><td>460</td><td>1280 atmosphere 3</td><td>–</td><td>–</td></tr>
<tr><td>Fe-Cu-Ni$^{(2)}$</td><td>500</td><td>900 atmosphere 1</td><td>550</td><td>1120 atmosphere 2</td></tr>
<tr><td>Fe-Cu-Ni$^{(3)}$</td><td>500</td><td>900 atmosphere 1</td><td>550</td><td>1280 atmosphere 3</td></tr>
</table>

Atmosphere 1: 36% H_2, 19% CO, 0.4% CO_2, 45% N_2
Atmosphere 2: 75% H_2, 25% N_2
Atmosphere 3: 70% N_2, 30% atmosphere 2

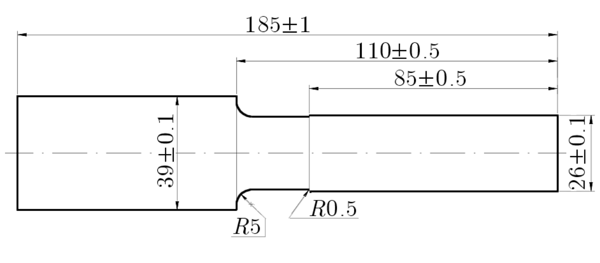

Fig. 3. Geometry of the round specimen

determination of the approximate value of the coefficient C were presented in Ogonowski *et al.* (2004).

Fatigue tests were conducted under a constant-amplitude pure bending, pure torsion, and combinations of proportional (in-phase, $\delta = 0°$) and non-proportional (out-of-phase, $\delta = 90°$) bending with torsion. For a combined loading, the selected ratio of the nominal shear stress amplitude and the nominal bending amplitude τ_{an}/σ_{an} was 0.58. The tests were performed under control of bending and torsional moments at the frequency 18.5 Hz.

For the considered materials, the multiaxial stress state was substituted by the equivalent stress state corresponding to a pure alternating bending. The S-N curves for the alternating equivalent bending and the obtained fatigue strengths at the knee point of the curves σ_{ak} for the tested alloys are shown in Fig. 4. From comparison of the data in Table 1 and Table 2, it appears that the sintering parameters strongly influence mechanical properties of the obtained materials. As the yield strength $R_{p0.2}$ and the ultimate tensile strength R_m increase, the fatigue life increases, too. Thus, the sintering parameters strongly influence the fatigue life (see also Fig. 4). Under loads with out-of-phase loading (90°), the obtained amplitudes for a given life level were greater than those obtained under the in-phase loading, i.e. the out-of-phase loading increases the fatigue life of the investigated alloys in contrast to the in-phase loading. This remark concerns all the sintered alloys considered in the paper.

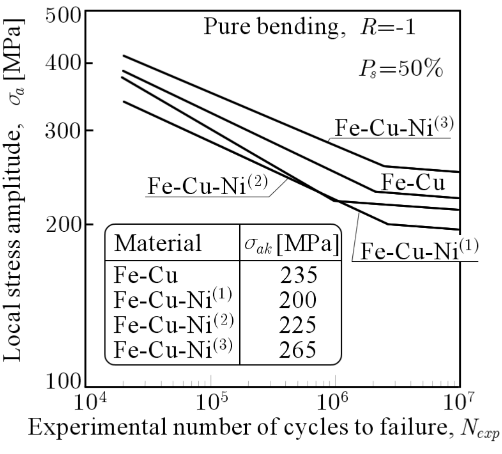

Fig. 4. S-N curves for alternating bending

3.2. Steps of the fatigue lifetime calculation procedure

The determination of fatigue life for known theoretical notch coefficients K_{tb} and K_{tt} as well as coefficient C according to the proposed criterion includes:

- determination of the histories of components of the stress tensor $\sigma_{ij}(t)$ and the strain tensor $\varepsilon_{ij}(t)$, including the influence of stress concentration,
- determination of the angle of critical plane position α,
- determination of histories of stresses, strains and normal and shear strain energy density parameters on the critical plane,
- determination of the equivalent history of the strain energy density parameter on the assumed plane,
- iterative computations of the fatigue life $N_{cal} = N_f$ calculated according to Eq. (2.17) including variations of the coefficient k (2.18).

The calculated fatigue lives N_{cal} obtained according to fatigue criterion (2.17) were compared with the experimental lives N_{exp} (see Figs. 5-8).

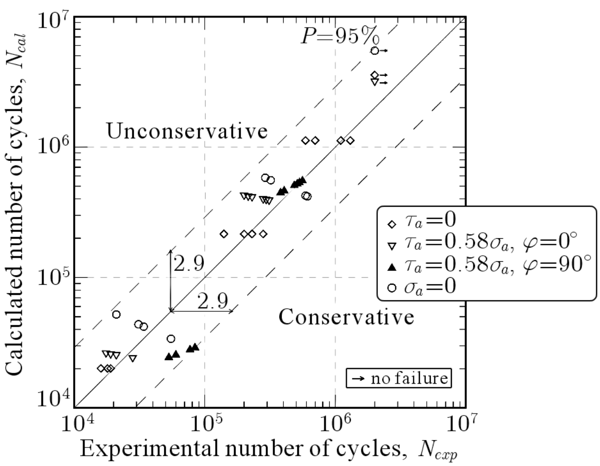

Fig. 5. Comparison of fatigue life N_{cal} calculated according to Eq. (2.17) and experimental fatigue life N_{exp} for Fe-Cu sintered steel

Correlation between the calculated and experimental fatigue lives seems to be satisfactory. They are included into a scatter band with the factor 3, like for the alternating bending. Only some results for the non-proportional combination of the Fe-Cu-Ni$^{(3)}$ alloy are located outside that band, but at the so-called safe side.

The taking into account of elastic-plastic stresses and strains at the notch root could give better correlation between N_{cal} and N_{exp}. However, in such a case, calculations of the fatigue life would be much more complicated.

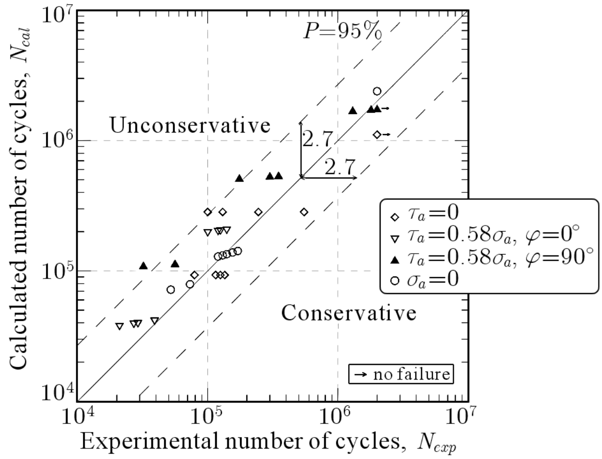

Fig. 6. Comparison of fatigue life N_{cal} calculated according to Eq. (2.17) and experimental fatigue life N_{exp} for Fe-Cu-Ni$^{(1)}$ sintered steel

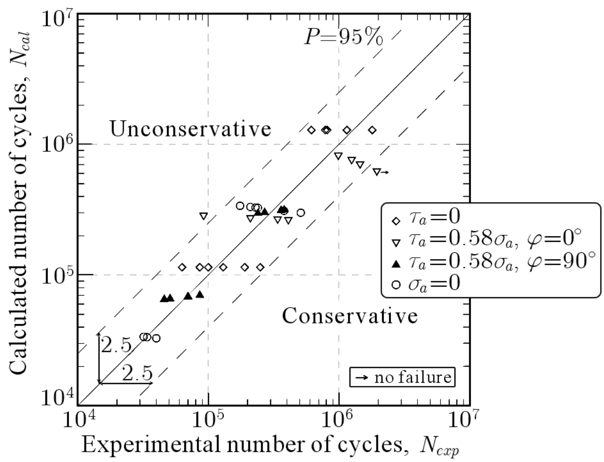

Fig. 7. Comparison of fatigue life N_{cal} calculated according to Eq. (2.17) and experimental fatigue life N_{exp} for Fe-Cu-Ni$^{(2)}$ sintered steel

4. Conclusions

The calculated fatigue lives correlate well with the experimental data. The results were found to be included within a scatter band with the factor 3 ($N_{cal}/N_{exp} = 3$ or $N_{cal}/N_{exp} = 1/3$), as in the case of alternating bending. Only some results for the non-proportional combination of Fe-Cu-Ni$^{(3)}$ sintered steels are located outside that band, but at the so-called safe side.

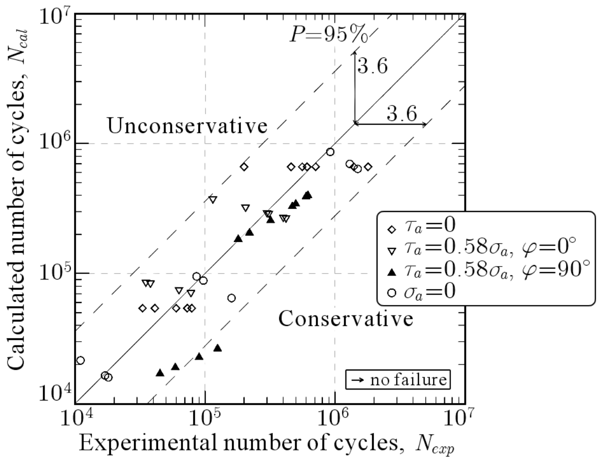

Fig. 8. Comparison of fatigue life N_{cal} calculated according to Eq. (2.17) and experimental fatigue life N_{exp} for Fe-Cu-Ni$^{(3)}$ sintered steel

A better correlation between the results should be expected if elastic-plastic stresses and strains at the notch root were taken into account. However, in such a case, the determination of the fatigue life might be much more complicated.

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Zastosowanie parametru gęstości energii odkształceń do oceny wieloosiowego zmęczenia stali spiekanych z koncentratorami naprężeń

Streszczenie

W pracy przedstawiono rezultaty badań zmęczeniowych spieku Fe-Cu o zawartości 1.5% miedzi oraz trzech rodzajów spieku Fe-Cu-Ni o zawartości 2% miedzi i 2.5% niklu. Do badań zastosowano próbki okrągłe z koncentratorami naprężeń w postaci odsadzenia. Zakres badań obejmował stałoampitudowe zginanie, skręcanie oraz kombinacje proporcjonalnego i nieproporcjonalnego zginania ze skręcaniem. Wyniki badań eksperymentalnych zostały opisane przy zastosowaniu kryterium parametru energetycznego, opartego na koncepcji płaszczyzny krytycznej. Trwałość zmęczeniowa została wyznaczona na podstawie liniowej kombinacji parametru gęstości energii odkształceń normalnych oraz stycznych z pewnymi współczynnikami w przyjętej płaszczyźnie krytycznej. W większości przypadków otrzymano zadowalającą zgodność trwałości obliczeniowych z eksperymentalnymi.

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