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FATIGUE BEHAVIOR OF PURE COPPER IN NON-PROPORTIONAL LOAD CONDITIONS

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Abstract

This paper deals with fatigue behavior of pure copper in different load conditions, including complex proportional and non-proportional loads. The material has been chosen due to its potential high sensitivity for non-proportional loads. The aim of this paper is search for relationship between the fatigue life of pure copper and shear stress vector paths in non-proportional load conditions.

Keywords: *multiaxial fatigue, non-proportional load, copper*

1. Introduction

For many materials an influence of non-proportional load on fatigue life and strength can be observed [1, 2]. This influence is manifested by decrease of fatigue life and fatigue limit. It can be shown on S-N curves diagram for equivalent stresses calculated using the common fatigue criteria (Fig .1).

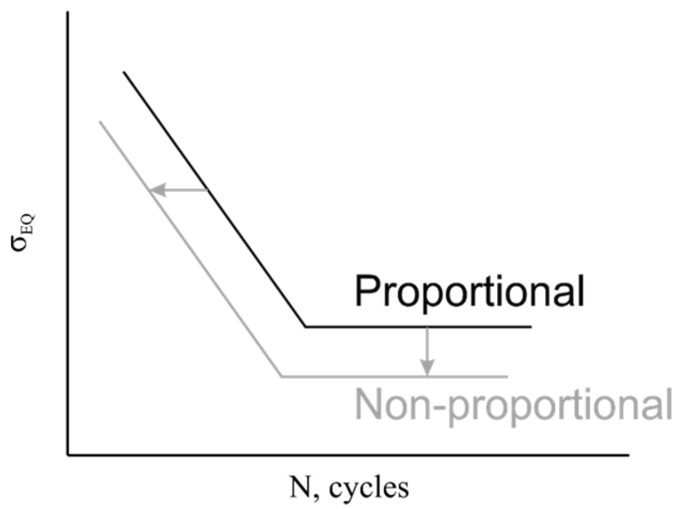

Fig. 1 – Influence of non-proportional load on fatigue life and fatigue limit.

An example of non-proportional load is out-of-phase tension-compression with torsion. In this case, non-proportionality of load is caused by phase shift between sine signals of axial and torsional load. From the point of view of signals, the highest non-proportionality of load takes place when the phase shift angle is $\delta = 90°$ [3, 4] (Fig. 2).

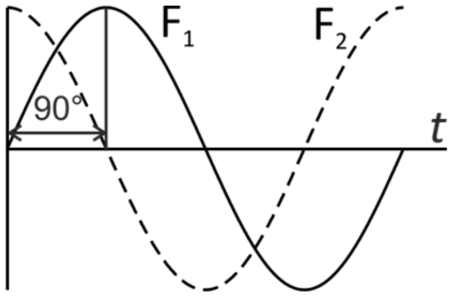

Fig.2 – Highest non-proportionality of load in out-of-phase load type.

Another factor that affects the level of non-proportionality of load is axial amplitude $\sigma_{TC,a}$ and torsional amplitude $\sigma_{T,a}$ ratio, denoted as λ, which can be written as follows:

$$\lambda = \frac{\sigma_{TC,a}}{\sigma_{T,a}}. \qquad (1)$$

A characteristic feature of non-proportional load is a change of shear stress vector direction, acting on a sectional plane Δ. In case of uniaxial and proportional load the shear stress vector path is straight line, because, the vector changes only its magnitude. But when load components changes non-proportionally also the direction of the shear stress vectors changes. The result is path, different than straight line. In case of out-of-phase load it is always an ellipse (Fig. 3.). The shape of this ellipse depends on phase shift and λ ratio.

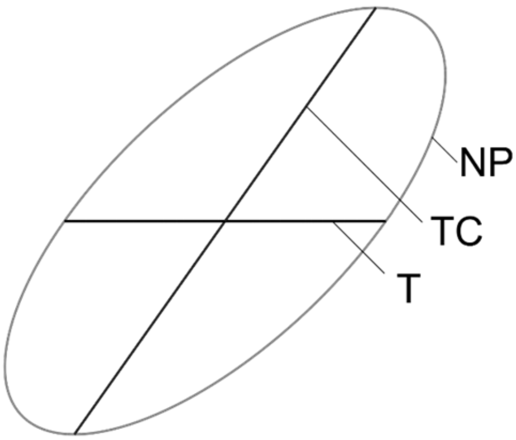

Fig. 3 – Shear stress vector paths for tension-compression TC, torsion T and non-proportional out-of-phase load NP.

The objective of this paper is to find relationship between the shape of shear stress vector's path for out-of-phase load and fatigue life of pure copper Cu-ETP.

2. Testing methods and conditions

Hourglass shape specimens for fatigue tests have been made of pure copper Cu-ETP (EN: CW004A, DIN: E-Cu58, ASTM: C11000) by machining. Basic monotonic and cyclic properties of the material are given in Tab1. The geometry of specimen has been shown on Fig. 4.

Tab. 1. Monotonic and cyclic properties of Cu-ETP copper

$R_{p,02}$, MPa	R_m, MPa	A, %	E, GPa	Z_{so}, MPa [5]	Z_{rc}, MPa [5]
360	367	36,16	131	28	50

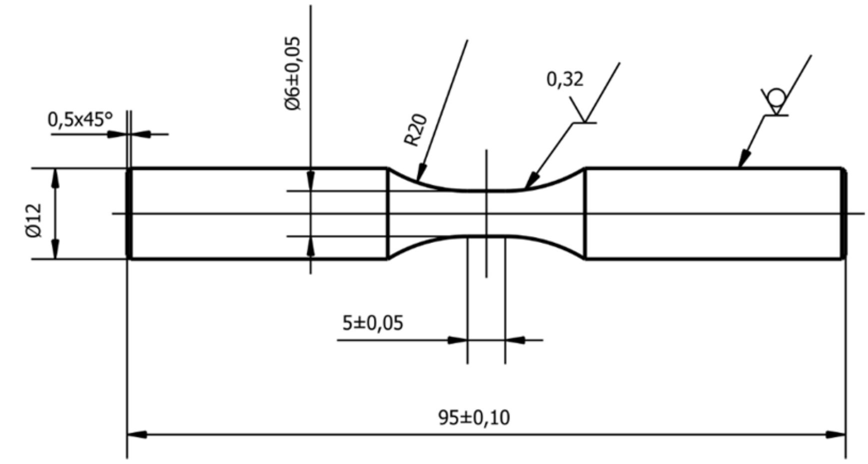

Fig. 4 – Tested specimen's geometry.

Specimens has been tested on INSTRON 8874 multi-axial testing system, using different fully reversed load types: tension-compression, torsion, combined proportional tension-compression with torsion ($\lambda = 0.5$, $\delta = 0°$) and combined out-of-phase tension-compression with torsion ($\lambda = 0.3$ to 0.8, $\delta = 90°$).

Amplitudes of load components were chosen in the way that gives the same maximum value of equivalent stress calculated with use of Zenner and Liu criterion [5] during the load's cycle (Fig. 5). For loads with no mean values this criterion can be written as follows:

$$\sigma_Z = \sqrt{\frac{15}{8\pi} \int_{\gamma=0}^{\pi} \int_{\varphi=0}^{2\pi} \left(a\tau_{\gamma\varphi,a}{}^2 + b\sigma_{\gamma\varphi,a}{}^2\right) \sin\gamma \, d\gamma d\varphi} \leq Z_{rc}, \tag{2}$$

where *a* and *b* are coefficients calculated from fatigue limit for tension-compression and torsion:

$$a = \frac{1}{5}\left(3\left(\frac{Z_{rc}}{Z_{so}}\right)^2 - 4\right), \quad b = \frac{2}{5}\left(3 - \left(\frac{Z_{rc}}{Z_{so}}\right)^2\right), \tag{3}$$

$\tau_{\gamma\varphi,a}$ and $\sigma_{\gamma\varphi,a}$ are the amplitudes of nominal shear stress $\tau_{\gamma\varphi}$ and normal stress $\sigma_{\gamma\varphi}$ acting on a sectional plane Δ [3, 7]:

$$\sigma_{\gamma\varphi} = \boldsymbol{n} \cdot \boldsymbol{\sigma} \cdot \boldsymbol{n}, \quad \tau_{\gamma\varphi} = \boldsymbol{\sigma} \cdot \boldsymbol{n} - (\boldsymbol{n} \cdot \boldsymbol{\sigma} \cdot \boldsymbol{n})\boldsymbol{n}, \tag{4}$$

where the unit vector normal to Δ plane is denoted as **n**.

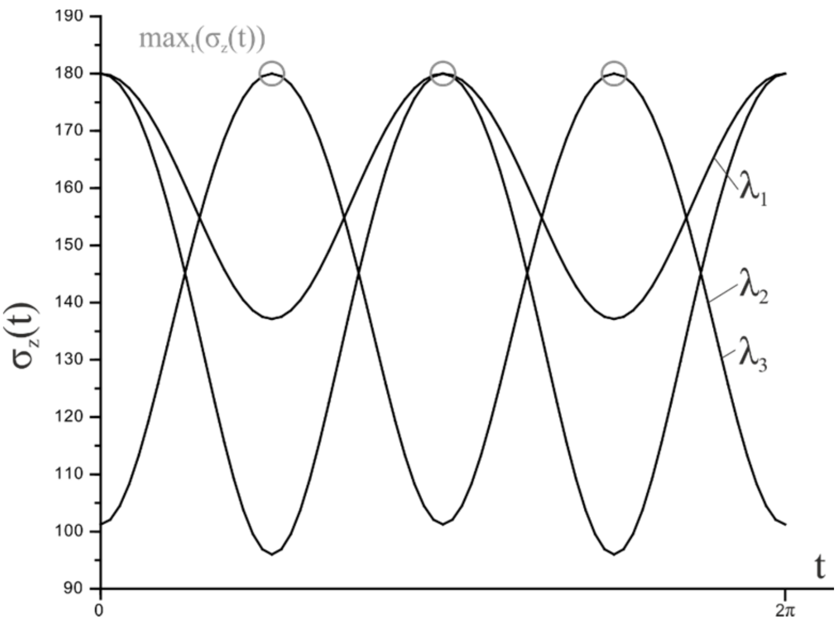

Fig. 5 – Result of equivalent stress calculation for each moment of the non-proportional load cycle with different values of λ ratio.

Non-proportional load cycles that gives the same value of equivalent stress but has different values of λ ratio, also gives different shapes of shear stress vector path. On the Figure 6 shear stress vector paths for λ ratio range from 0.3 to 0.8 has been shown. One can notice that the path with the greatest area occurs for $\lambda = 0.5$, which is approximately equal to quotient of fatigue limit for torsion Z_{so} and fatigue limit for tension-compression Z_{rc} [5].

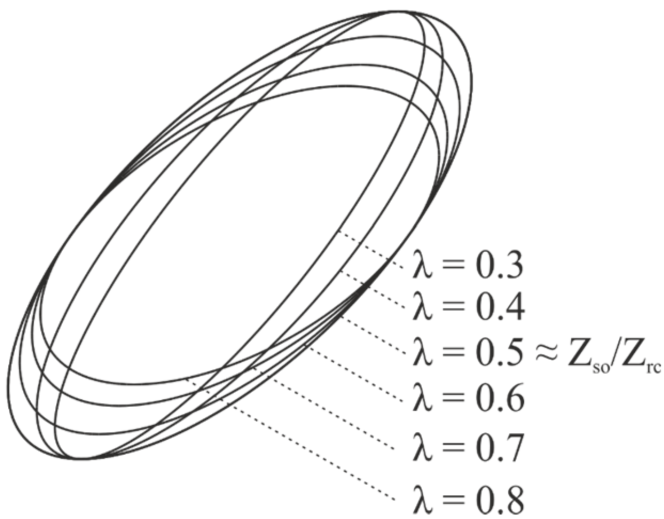

Fig. 6 – Shear stress vector paths for λ ratio range from 0.3 to 0.8.

3. Results

The results are shown on the S-N curves diagram, made for equivalent stresses calculated with use of Zenner and Liu criterion, in the way described above (Fig. 7). Curves are depicted by the Basquin equation [8]:

$$\sigma_{eq} = AN^B. \quad (5)$$

Coefficients A and be are given in Tab. 3. For torsion and proportional load curves approximately overlaps with tension-compression curve, which means that equivalent stresses are calculated properly. Difference occurs for non-proportional loads. One can observe decrease of fatigue strength. It can be also interpreted as an underestimation of fatigue life. The maximum decrease appears for λ ratio equal to 0.5.

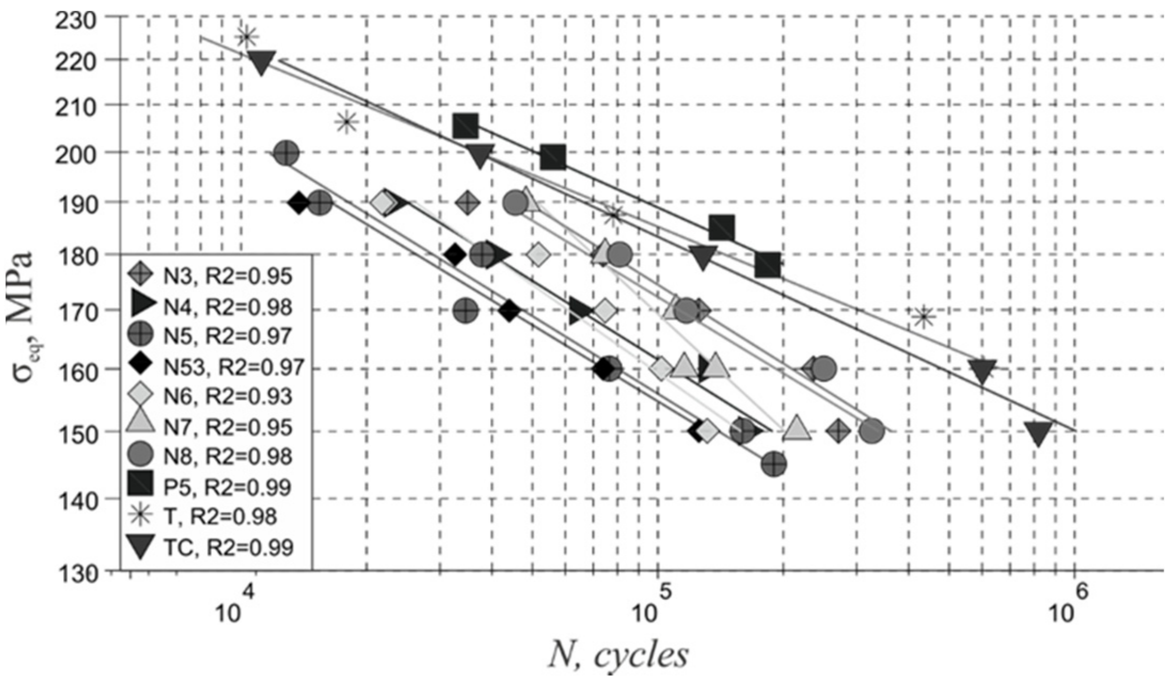

Fig. 7 – S-N curves diagram made for different types of load: TC – tension-compression, T – torsion, P – proportional load, N – non-proportional load. Numbers next to the letters are values of λ ratio times 10. Coefficient of determination was denoted as R2.

Tab. 3. Basquin equation coefficients for different types of load

Load type	Test frequency, HZ	A	B	λ	δ, degrees
TC	5	496.69	-0.087	0	0
T	2	450.74	-0.077	∞	0
P5	2	496.15	-0.084	0,5	0
N3	2	635.18	-0.113	0,3	90
N4	2	619.67	-0.117	0,4	90
N5	2	588.27	-0.115	0,5	90
N53	2	570.47	-0.113	0,53	90
N6	2	718.43	-0.131	0,6	90
N7	2	1228.70	-0.172	0,7	90
N8	2	671.12	-0.117	0,8	90

4. Conclusions

The material that has been tested has shown high sensitivity for non-proportional loads. For the most damaging non-proportional load, which for this material is the one with λ ratio equal to 0.5, fatigue strength calculated with frequently used Zenner and Liu criterion is approximately 15% lower than for tension-compression. Values of λ above and below 0.5 are gradually less damaging for material

The λ ratio value equal to 0.5 gives also the shear stress vector path with the largest area which also encloses other paths. The size of these paths seems to be related to λ value and fatigue life and strength. The larger the area of the path is, the higher level of fatigue strength decrease and shorter life occurs.

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