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AN APPROACH FOR LOW CYCLE FATIGUE LIFE PREDICTION OF VARIOUS METALLIC MATERIALS SUBJECTED TO NON-PROPORTIONAL MULTIAXIAL LOADING CONDITIONS

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ABSTRACT

The safety and durability of structures is an important issue because the sudden failure of complex system such as nuclear power plants, automobiles, aircraft and pressure vessels may cause many injuries, much financial loss and even environmental damage. Since many of these systems are subjected to repeated multiaxial loading, evaluation of low-cycle fatigue (LCF) becomes one of the major considerations in the design structures.

An approach for estimating the multiaxial low cycle fatigue life under non-proportional loading using the non-proportional parameter by Itoh, Sakane, Ohnami and Socie has been developed. The non-proportional parameter includes the maximum principal strain range, non-proportional factor (it's a function of only strain path) and has a material constant which is defined as the sensitivity of the material to the non-proportional loading. The paper proposes the different versions of the non-proportional parameter and reports an investigation on the applicability of these versions to LCF life prediction.

The proposed parameter, which includes Pisarenko-Lebedev's equivalent strain (or equivalent strain of Coulomb-More type), has shown a very good correlation of multiaxial low-cycle fatigue lives for various non-proportional loading paths with different material fatigue data.

Keywords: Multiaxial low cycle fatigue; fatigue criteria; tension-torsion loading; non-proportional loading; fatigue life prediction

1. INTRODUCTION

The increase in operation factors of modern machinery, such as service loading, velocity, capacity, temperature, is a predetermined tendency in modern engineering. In its turn it predetermines the increase in requirements to existing structure analysis, particularly to analysis of low-cycle fatigue. One of the important trends of the development of low-cycle fatigue analysis is an account of stress/strain state type and loading path type influence.

The multiaxial loading can be proportional or non-proportional. The directing stress tensor is steady during proportional loading. In the homogeneous stress state this condition is fulfilled if the loads increase or decrease proportionally to one parameter. In other cases the loading is non-proportional.

In last years a big number of low-cycle fatigue researches were carried on, and they discovered some deviations of metal alloy behavior under proportional and non-proportional low-cycle fatigue loading. Particularly, the effect of "additional cyclic hardening" was found, that is while complex cycle elasto-plastic loading the material becomes much more hardening than at proportional loading. The experimental investigation results are the evidence of the existence of direct relations between decreasing in low-cycle fatigue lives under non-proportional loading conditions and increasing in additional cyclic hardening of metal alloys. It was also shown that the level of additional hardening under non-proportional loading depends on type of material, i.e. the materials can be classified according to their sensitivity to non-proportional loading.

Under non-proportional loading when direction of the principal stresses change, it is very difficult to predict fatigue behavior of materials and structures. Many multiaxial fatigue theories have been developed by this time. There are stress-, strain- and energy-based fatigue failure criteria but there is no one universal criterion for different loading condition. As the majority of known criteria of multiaxial low-cycle fatigue don't consider the abovementioned effects, so the application of these criteria for the estimating of material critical state under the non-proportional loading is problematical.

In this work the authors propose a multiaxial fatigue damage parameter, which considers non-proportional loading effects and may be applied for the estimation of low-cycle fatigue lives both under proportional and non-proportional loading.

2. MATERIALS

With the aim to check this multiaxial fatigue damage parameter, the analysis results are compared to experimental investigation results, obtained on the specimens made of Type SNCM630 stainless steel (Han, Chen, Kim, 2002), Type 08X18H10T stainless steel (Mojarovsky, Shukayev, 1988), BT9 titanium alloy (Shukayev, 2001) and Inconel 718 (Sosie, Kurath and Koch, 1989).

The mechanical properties of the materials are given in Table 1.

Table 1. The mechanical properties of materials used in this work

Materials and mechanical data	SNCM630	08X18H10T	BT9	Inconel 718
Yung modulus *E,* GPa	196	203	118	208,5
Yield stress $\sigma_{0.2}$, MPa	951	320	865	1160
Ultimate stress σ_b , MPa	1103	690	973	1420
Elongation δ , %	19	40	17	33
Reduction of area ψ , %	49	55	45	28
Poisson's ratio ν	0,273	0,29	0,32	0,34

3. PROPOSED PARAMETR AND ANALYSIS

In general, critical multiaxial state criterion of low-cycle fatigue can be given as

$$\Delta\varepsilon_{NP} \le \varepsilon_f \,, \tag{1}$$

where ε_f is a material limit constant. The value of ε_f comes from the uniaxial strain-life curve.

Basing on experimental investigation results, strain equivalent range under non-proportional loading $\Delta\varepsilon_{NP}$ can be represented as a function of three parameters:

$$\Delta\varepsilon_{NP} = f\left(\Delta\varepsilon, \alpha, f_{NP}\right), \tag{2}$$

where $\Delta\varepsilon$ is maximum strain equivalent range; α is coefficient of metal sensitivity to non-proportional loading; f_{NP} is a non-proportional factor, which expresses the severity of non-proportional straining and is described by only the strain history.

Such approach was realized in the work by Itoh, Sakane, Ohnami and Socie (1995), where the following determination of strain equivalent range under non-proportional loading was proposed

$$\Delta\varepsilon_{NP} = \left(1 + \alpha \cdot f_{NP}\right) \cdot \Delta\varepsilon_I \,, \tag{3}$$

where $\Delta\varepsilon_I$ is the maximum principal strain range; α is coefficient of metal sensitivity to non-proportional loading related to the additional cyclic hardening. The value of α is defined as the ratio of stress amplitude under

90-degree out-of-phase loading (circular strain path in $\gamma/\sqrt{3}-\varepsilon$ plot, f_{NP} =1) to amplitude under proportional loading (f_{NP} =0). The 90-degree out-of-phase loading shows the maximum additional hardening among all the non-proportional histories. For 08X18H10T stainless steel, the stress amplitude under the 90-degree out-of-phase loading was increased up to 95% in comparison with the proportional loading, so the value of α is 0.95. For BT9 titanium alloy, the difference between the equivalent stress amplitudes of proportional and non-proportional loadings is equal to 5% that coincides with the inaccuracy of the experiment.

The application of the Eq. 3 gives the satisfactory results in the cases when a material has large additional cyclic hardening.

The materials which have a small additional cyclic hardening or don't have it at all (for example, titanium alloy BT9, nickel alloy Inconel 718, stainless steel SNCM630) also have decreasing low-cycle fatigue lives under non-proportional loading. At the same time material constant α according to the work by Itoh, Sakane, Ohnami and Socie (1995) must be equal to zero, i.e. $\Delta\varepsilon_{NP}=\Delta\varepsilon_I$. In such case the influence of non-proportional loading on low-cycle lives isn't taken to consideration.

For similar alloys the coefficient of material sensitivity to non-proportional loading can be calculated as value considering decrease in the lives under non-proportional loading, as it is shown in the work by Borodii, (2001). And the strain equivalent range under non-proportional loading can be expressed by the following equation:

$$\Delta\varepsilon_{NP}=\left(1+\eta\cdot f_{NP}\right)\cdot\Delta\varepsilon_I\ , \tag{4}$$

where η is coefficient of metal sensitivity to non-proportional loading, calculated by the procedure described in the work by Borodii (2001). This enables to expand the application area of non-proportional parameter of Eq. 3.

In the work by Shukayev (1997), the analysis of critical multiaxial state criteria under proportional loading was carried out, showing that the two-parameter criteria, such as Pisarenko-Lebedev and Coulomb-More, were the most suitable for this type of loading.

Consequently on developing of low-cycle fatigue criterion it is proposed to calculate the maximum strain equivalent range under non-proportional loading as

$$\Delta\varepsilon_{NP}=\left(1+\eta\cdot f_{NP}\right)\cdot\Delta\varepsilon_{eq}\ , \tag{5}$$

where $\Delta\varepsilon_{eq}=\max\left|\varepsilon_{eq}^{\max}-\varepsilon_{eq}(t)\cos\xi(t)\right|$ is a maximum strain equivalent range. According to the two-parameter criterion of Pisarenko-Lebedev type:

$$\varepsilon_{eq}=\varepsilon_{eqPL}=\chi_\varepsilon\cdot\frac{\sqrt{(\varepsilon_1-\varepsilon_2)^2+(\varepsilon_2-\varepsilon_3)^2+(\varepsilon_3-\varepsilon_2)^2}}{\sqrt{2}\cdot(1+\nu)}+(1-\chi_\varepsilon)\cdot\left[\frac{\varepsilon_1+\frac{\nu}{1-2\cdot\nu}\cdot(\varepsilon_1+\varepsilon_2+\varepsilon_3)}{1+\nu}\right], \tag{6}$$

where $\chi_\varepsilon=\frac{1}{\sqrt{3}-1}\cdot\left[2(1+\nu^*)\left(\frac{\varepsilon_{np}}{\gamma_{np}}\right)-1\right]$.

According to the criterion of Coulomb-More type:

$$\varepsilon_{eq}=\varepsilon_{eqKM}=\frac{\varepsilon_{pr}}{\gamma_{pr}}\cdot\gamma_{\max}+\frac{2}{1-\nu^*}\cdot\left[1-(1+\nu^*)\cdot\frac{\varepsilon_{pr}}{\gamma_{pr}}\right]\cdot\varepsilon_n\ , \tag{7}$$

where $\frac{\gamma_{\max}}{2}$ - the maximum shear strain amplitude, ε_n - amplitude of the normal strain acting on the γ_{max} plane, γ_{pr} is shear strain amplitude under conditions of pure torsion for given number of cycles N, ε_{pr} is strain amplitude of uniaxial fatigue for the same fatigue life. Note, that Eq. 6 and Eq. 7 have been derived for the case of fully reversed strain controlled cycling.

The Poisson's ratio can be approximately obtained in the elastic-plastic range from the following equation:

$$\nu^*=0.5-0.2\frac{\sigma_{0.2}}{E\varepsilon_{eq}}\ , \tag{8}$$

where ε_{eq} is equivalent strain of the corresponding criterion.

The procedure of determining maximum strain equivalent range is shown in figure 1.

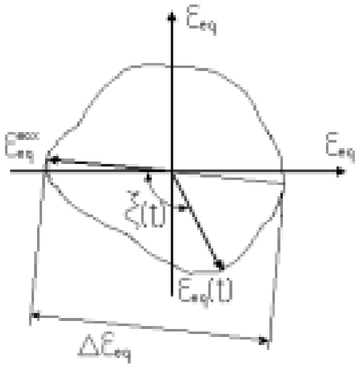

Fig.1. Determination of maximum strain equivalent range.

The fatigue properties of the materials used in this work are given in Table 2.

Table 2. Fatigue properties of materials used in this work

Materials and fatigue data	SNCM630	08X18H10T	BT9	Inconel718
Coefficient of sensitivity material to non-proportional loading				
η	0,974	0,787	0,25	0,87
α	–	0,95	0	0
Constants of LCF lives equation $N_f = A \cdot (\Delta\varepsilon)^n$				
A	4632,34	616,74	809,28	13807
n	-2,7108	-3,6062	-2,0602	-3,4341

4. CORRELATION OF FATIGUE DATA USING THE PROPOSED PARAMETER

The calculation results carried out using equivalent strain of Pisarenko-Lebedev or Coulomb-More type are compared to experimental data and calculation data by Eq. 3 and Eq.4.

The comparisons of calculation results by Eq. 2, Eq. 3 and Eq. 4 with experimental data are given in Fig. 2. Low-cycle multiaxial fatigue life N_f is calculated by equation $N_f = A \cdot (\Delta\varepsilon_{NP})^n$ where A and n are the material constants of uniaxial fatigue (Table 2).

The results demonstrate that the versions of the non-proportional parameter which include Pisarenko-Lebedev's equivalent strain and Coulomb-More equivalent strain successfully correlated multiaxial fatigue lives within a factor that varied with materials from 1.5 to 2.0 for various non-proportional loading paths.

According to Fig. 2, calculations by both versions of Eq. 5 are much closer to the presented experimental results than calculations by Eq. 3 and Eq. 4.

Both these versions of multiaxial fatigue damage parameter are applicable to materials with small and large additional hardening.

5. CONCLUSIONS

The paper deals with a multiaxial fatigue parameter that can be represented as function of three parameters: the equivalent strain of Pisarenko-Lebedev or Coulomb-More type; the coefficient of material sensitivity to the non-proportional loading; the non-proportional parameter, depending only on the kind of strain history.

The proposed multiaxial fatigue damage parameter has shown a very good correlation of multiaxial low-cycle fatigue lives for various proportional and non-proportional loading paths with different fatigue data of small and large additional cyclic hardening materials.

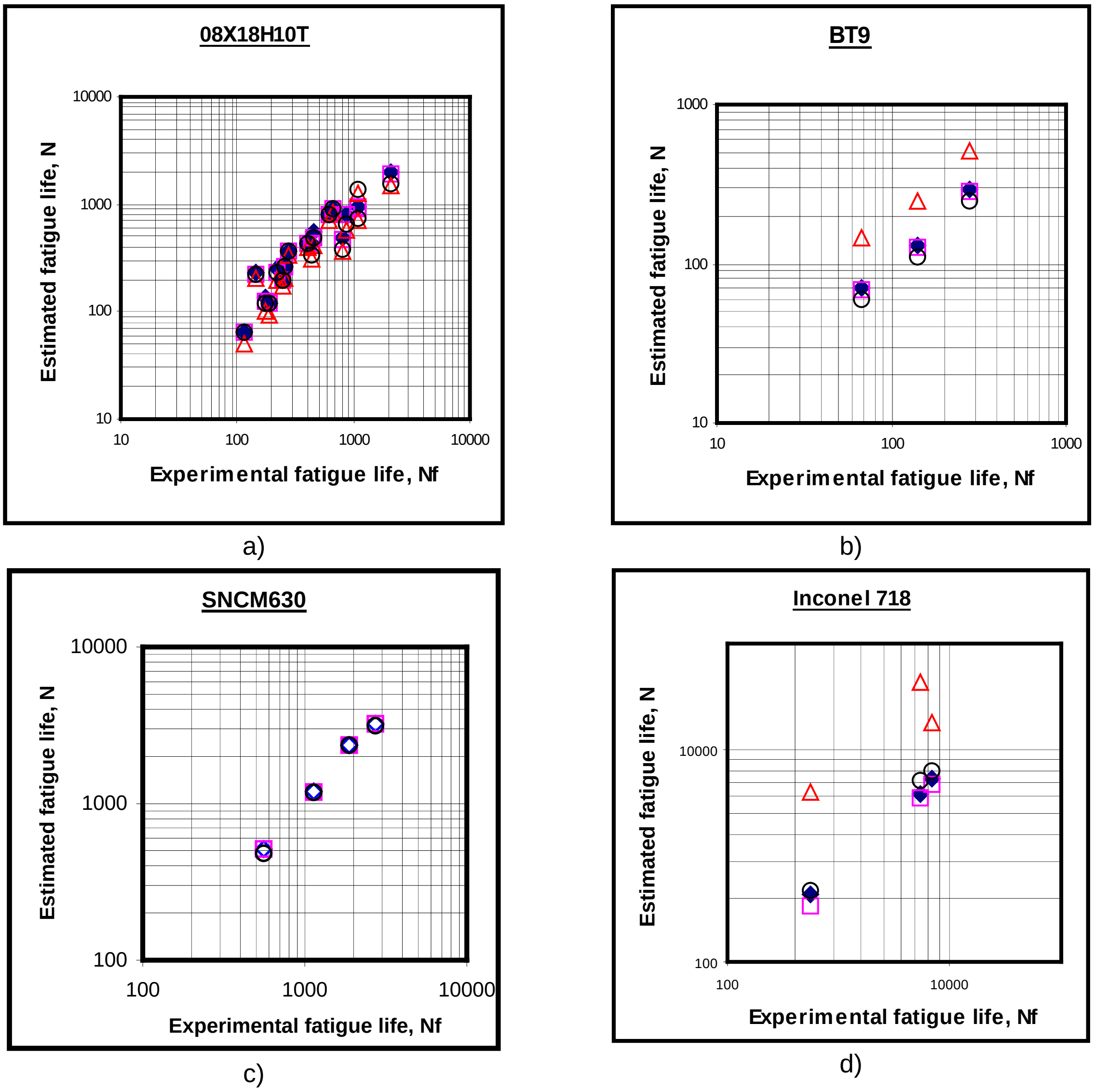

Fig. 2. Non-proportional fatigue life correlation for four different materialsi: a) – 08X18H10T steel; b) – titanium alloy BT9; c) – SNCM630 steel; d) Inconel718 (♦ – Proposed parameter with equivalent strain of Pisarenko-Lebedev type; ■ – Proposed parameter with equivalent strain of Coulomb-More type; ▲ – non-proportional parameter by Itoh, Sakane, Ohnami and Socie (Eq. 3); ● – modified parameter by Itoh, Sakane, Ohnami and Socie (Eq. 4)).

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