Estimation of the fatigue life of the alloy steel 35NCD16 under random loading

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ABSTRACT. *The paper concerns predicting the fatigue life of the material 35NCD16 (36NiCrMo16) under random loading. High alloy steel 35NCD16 characterized by a lack of mutual parallelism of fatigue characteristics for extension and torsion. For such materials the fatigue life estimation, standard models shoul not be used, because they do not take into account the variability relative to the tangential and normal stress. The aim of the work is to compare the experimental results of the calculation using the proposed model obtaining satisfactory results.*

INTRODUCTION

35NCD16 is a high strength alloy steel that takes its name from the French industry designation. The combination of high strength, high fracture toughness and superior cleanliness identifies it as a good candidate for aerospace structural applications. The paper presents an algorithm for determination of the fatigue life of materials where there is no parallelism of fatigue characteristics for extension and pure torsion. Verification of the proposed algorithm has been done for the steel 35NCD16.

FATIGUE TESTS

The test results obtained for the steel 35NCD16 and presented in [1-3] were considered. Chemical composition of the material is presented in Table 1. Fig. 1 shows the fatigue graph for extension and two-sided torsion of the considered material. As for the steel 35NCD16, fatigue characteristics are not parallel (see Fig.1). Variable values of the ratio of normal and shear stresses coming from extension and torsion respectively cause that it is not possible to apply a constant value of this ratio in the fatigue criteria including that ratio. The latest review of multiaxial fatigue criteria presented in paper [4].

Table 1. Chemical composition of the high-steel [in %]

Material	C	Si	Mn	S	P	Ni	Cr	Mo	Fe
35NCD16	0.36	0.37	0.39	0.01	<0.003	3.81	17	0.28	rest

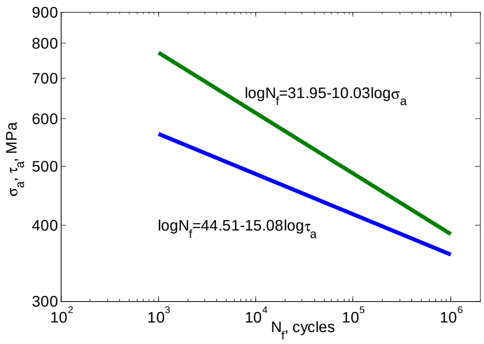

Figure 1. Fatigue graph for extension and two-sided torsion of steel 35NCD16.

The ratio of fatigue limits from extension σ_{af} and torsion τ_{af} is usually assumed for calculations

$$k = \sigma_{af} / \tau_{af} \quad . \tag{1}$$

Cylindrical specimens subjected to cyclic and random loadings were used for tests [1]. Cyclic and random tests were completed with proportional extension and torsion (τ_a=0.5σ_a). In the case of random loadings, the standard history CARLOS Car Loading Sequence-lateral [5] of 95180 cycles in the block was applied. After reduction of cycles of low amplitudes, two kinds of blocks were obtained: f1=46656 extrema and f2=13568 extrema.

MODEL OF THE FATIGUE LIFE ESTIMATION

Particular stages of the algorithm for fatigue life determination have been presented in Fig. 2. The previous models did not include variability of the parameter $k(N_f)$, including out-of-parallelism of fatigue characteristics for extension and pure torsion. A constant value of (1) has been usually assumed so far, for example in [6] constancy for 35NCD16 was assumed for $3 \cdot 10^5$ cycles. A similar algorithm for cyclic loadings was presented and used in [7].

The presented model is going to be used for analysis of fatigue tests for cyclic and random loadings under extension and torsion. The first block includes registration of the stress state components in the range of long-lasting fatigue strength.

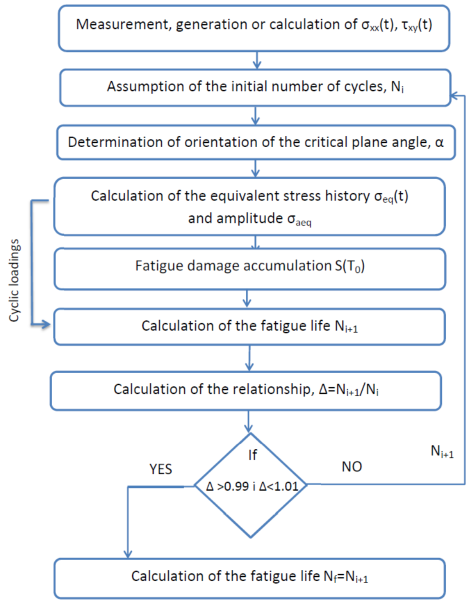

Figure 2. Algorithm for fatigue life determination for materials with no parallelism of fatigue characteristics.

At the next stage, the initial number of cycles necessary for calculation of the first cycle of the algorithm work, $N_i=10^6$ cycles, is assumed. The next block includes determination of the critical plane orientation angle, corresponding to the maximum effort of the material.

In this paper, the critical plane position was determined with the damage accumulation method, which consists in finding the angle of orientation of the critical plane at the maximum possible degree of damage (minimum durability) using shear stress. Expression for normal and shear stresses was completed with the correction function [8], using the fatigue limits for extension and torsion (1):

$$\sigma_\eta(t)=\sigma_{xx}(t)\cos^2\alpha+k(N_f)\cdot\tau_{xy}(t)\sin 2\alpha, \tag{2}$$

$$\tau_{\eta s}(t)=-\frac{1}{2}\sigma_{xx}(t)\sin 2\alpha+k(N_f)\cdot\tau_{xy}(t)\cos 2\alpha. \tag{3}$$

Let us notice that Eqs. (2) and (3) use parameter k, including out-of-parallelism of fatigue characteristics for extension and pure torsion.

The authors of this paper applied the criterion of maximum shear stresses [9]. It is strictly connected with orientation of the critical plane angle. History of the equivalent stress was written as

$$\sigma_{eq}(t)=B\tau_{\eta s}(t)+(2-B)\sigma_\eta(t). \tag{4}$$

In this paper assumed that B=1.

A damage degree should be found before calculations of the fatigue life. In the case of the considered material, assuming the hypothesis of fatigue damage accumulation according to Palmgren-Miner leads to incorrect estimation of the fatigue life.

Thus, for the damage accumulation process the Serensen-Kogayev hypothesis [10] was used. It is based on the Palmgren-Miner hypothesis [11,12] and the coefficient b characterizing the history:

$$S_{SK}(T_0)=\begin{cases}\sum\limits_{i=1}^{j}\dfrac{n_i}{b\cdot N_0\left(\dfrac{\sigma_{af}}{\sigma_{ai}}\right)^m} & for\quad \sigma_{ai}\geq a\cdot\sigma_{af}\\ 0 \quad for \quad \sigma_{ai}<a\cdot\sigma_{af}\end{cases} \tag{5}$$

where:

$$b=\frac{\sum\limits_{i=1}^{k}\sigma_{ai}t_i-a\cdot\sigma_{af}}{\sigma_{a1}-a\cdot\sigma_{af}},$$

$t_i=\dfrac{n_i}{\sum\limits_{i=1}^{k}n}$ - frequency of particular levels σ_{ai} in realization of $T_{0,}$

σ_{a1} – maximum stress amplitude from among σ_{ai}.

Fig. 3 presents comparison of calculation and experimental fatigue lives for different values of the coefficient a occurring in Eq. (5). Calculations were realized for the coefficient a = 0.5, 0.6, 0.8 and 1.

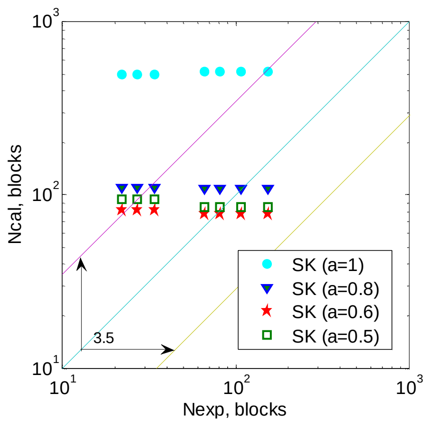

Figure 3. Comparison of the calculation fatigue life N_{cal} according to criterion on the plane of maximum shear stresses with the experimental fatigue life N_{exp} for uniaxial random loading.

In the case of steel 35NCD16, the coefficient a=0.6 was used for further analysis because it had given the best agreement of the compared calculation and experimental fatigue lives. The calculation life for analysis of the coefficient a was calculated with the method of modified amplitude [13]

$$\sigma_{md} = \frac{\sigma_{\sigma eqa}(\sigma)^{m_\sigma + 1}}{\sigma_{\sigma eqa}(\sigma)^{m_\sigma}}, \tag{6}$$

and the fatigue life was calculated from the transformated Basquin equation

$$N_f = 10^{A_\sigma - m_\sigma \log \sigma_{md}}. \tag{7}$$

Table 2 contains the mean relative errors of the calculation fatigue lives according to the following equation

$$R = \frac{N_{exp} - N_{cal}}{N_{exp}} \cdot 100\% . \tag{8}$$

Table 2. Mean relative errors for different values of the coefficient a

	a = 1	a = 0.8	a = 0.6	a = 0.5
R	1016%	151%	102%	123%

After determination of the damage degree $S(T_0)$ according to Eq.(5), the next stage of the algorithm includes calculation of the fatigue life:

$$N_f = \frac{T_0}{S(T_0)}. \tag{9}$$

In the case of fatigue tests of the considered material, observation time (T_0) is a single block, and the caculation life is a sum of the blocks. Under cyclic loadings, after calculation of the equivalent stress history it is necessary to calculate the fatigue life from the following equation similar to Eq.(7)

$$N_f = 10^{A_\sigma - m_\sigma \log \sigma_{eq}}. \tag{10}$$

The presented algorithm is based on the iteration method, so later it is necessary to calculate a ratio between the assumed and obtained lives

$$\Delta = \frac{N_{i+1}}{N_i} \quad . \tag{11}$$

This procedure is repeated for successive calculated lives up to the moment when the following condition is satisfied:

$$0.99 < \Delta < 1.01 \tag{12}$$

i.e. the assumed error is at the level of 1%, sufficient for fatigue calculations.
Let us remember that the life calculated from Eq. (9) is the life in one block. If condition (12) is satisfied, the obtained fatigue life is the searched quantity.

VERIFICATION OF THE PROPOSED CRITERION

The aim of the analysis is to check efficiency of the proposed criterion with special attention paid to variability of the parameter $k(N_f)$. Fig. 4 shows comparison of calculation and experimental lives under extension and pure torsion. Analysis was done for two cases: for k=const determined for the ratio of fatigue limits (k=0.86) and $k(N_f)$ in the scatter band of coefficient 3.5, characteristic for the considered steel.

Let us note that in the case when k = const, the obtained results are less conforming than those for $k(N_f)$. Fig. 5 presents comparison of the fatigue life with the experimental fatigue life for k = const, (a) and k(Nf), (b). In the case when k=const, the most results are not included into the scatter band of the coefficient 3.5 calculated for extension.

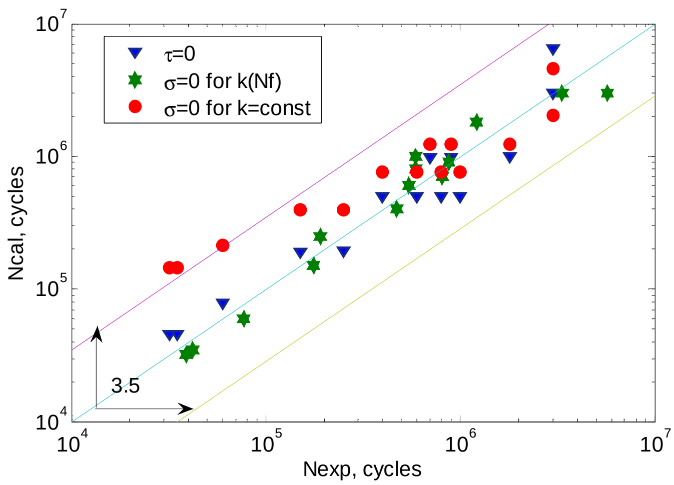

Figure 4. Comparison of the calculated life N_{cal} according to the criterion on maximum shear stresses with the experimental life N_{exp} for extension and torsion of steel 35NCD16 under cyclic loadings

a) b)

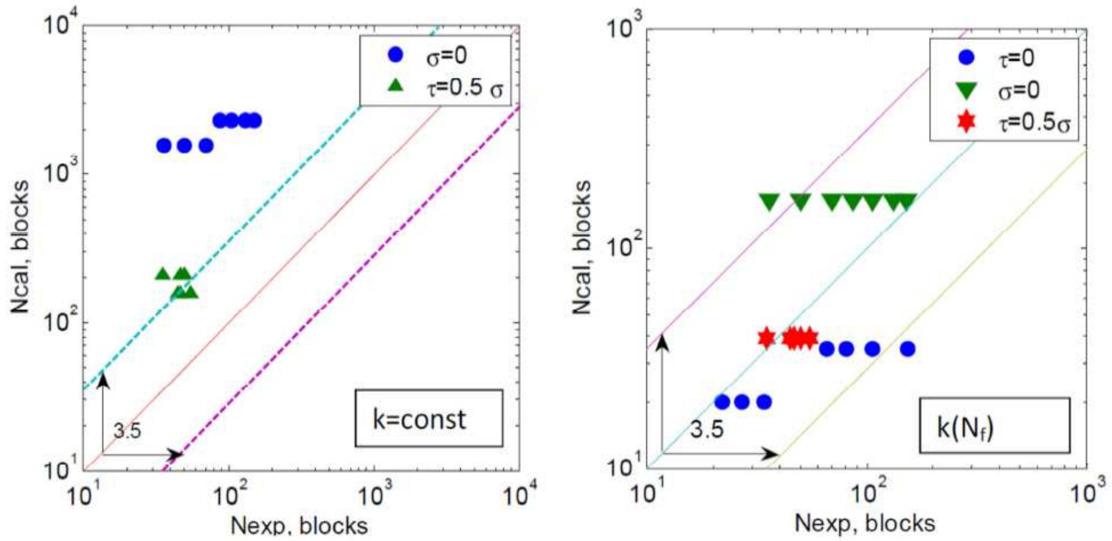

Figure 5. Comparison of the calculation life N_{cal} according to the criterion on the plane of maximum shear stresses with the experimental life N_{exp} for steel 35NCD16 under random loadings, when a) k=const. b) $k(N_f)$.

CONCLUSIONS

It is possible to draw the following conclusions from analysis of fatigue test results:

1. The proposed model can be applied for calculations of the fatigue life under cyclic and random loadings of materials with no parallelism of characteristics under extension and pure torsion. Verification of the model gave satisfactory results.
2. Analysis of the results of the calculations leads to the conclusion that the dependence of the coefficient k of the number of cycles to damage N_f gives better results than when k = const.
3. Further analysis of the proposed model for other materials and loadings seems to be necessary.

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