# ESTIMATION OF FATIGUE LIFE OF ALLOY STEEL 35NCD16 UNDER RANDOM LOADING

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The paper deals with the prediction of the fatigue life of 35NCD16 (36NiCrMo16) steel under random loading. The 35NCD16 material is a high strength alloy steel, characterised by a lack of mutual parallelism of fatigue characteristics for extension and torsion. It has been established that fatigue life estimation by standard models should not be used, because they do not take into account the variability relative to tangential and normal stress. The comparison of experimental results and calculations using the proposed model obtained satisfactory results.

**Keywords:** *fatigue life, random loading, 35NCD16 alloy steel.*

The 35NCD16 material 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 [1, 2]. 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 35NCD16 steel.

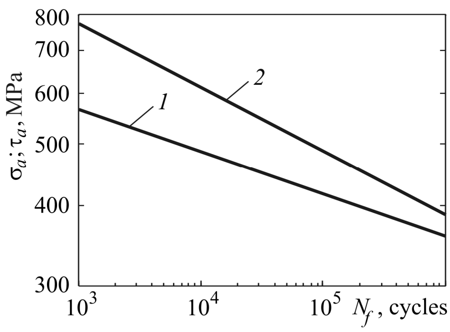


Fig. 1. Fatigue graph for extension and two-sided torsion of 35NCD16 steel:
*1* – $\log N_f = 31.95 - 10.03 \log\sigma_a$;
*2* – $\log N_f = 44.51 - 15.08 \log\tau_a$.

**Materials and fatigue tests.** Test results obtained for 35NCD16 steel and presented in [3–5] are considered. Chemical composition of the material is as follows (%): C – 0.36; Si – 0.37; Mn – 0.39; S – 0.01; P – <0.003; Ni – 3.81; Cr – 17.0; Mo – 0.28; Fe – rest. Fig. 1 shows the fatigue graph for extension and two-sided torsion of the considered material. As for 35NCD16 steel, fatigue characteristics are not parallel (see Fig. 1). Variable values of the ratio of normal and shear stresses coming from extension and torsion respectively make it impossible to apply a constant value of this ratio in fatigue criteria including this ratio. The latest review of multiaxial fatigue criteria is presented in [6, 7].

The ratio of fatigue limits from extension $\sigma_{af}$ and torsion $\tau_{af}$ is usually assumed for the calculation

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

Cylindrical specimens subjected to cyclic and random loadings were used for the tests [3]. Cyclic and random tests were completed with proportional extension and torsion ($\tau_a = 0.5\sigma_a$). In the case of random loading, the standard course CARLOS Car

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Loading Sequence-lateral [8] of 95180 cycles in the block was applied. After reduction of low amplitude cycles, two kinds of blocks were obtained: $f_1$ = 46656 extrema and $f_2$ = 13568 extrema.

**Model of fatigue life estimation.** Particular stages of the algorithm for fatigue life determination are presented in Fig. 2. The previous models did not include the variability of the parameter $k(N_f)$, which took into account the out-of-parallelism fatigue characteristics for extension and pure torsion. A constant value of Eq. (1) has been usually assumed so far, e.g. in [9], the constancy for 35NCD16 steel has been assumed to be $3{\cdot}10^5$ cycles. A similar algorithm for cyclic loading was presented and used in [10]. In this paper the authors included variability of parameter $k(N_f)$ according to:

$$k(N_f) = \frac{\sigma_a(N_f)}{\tau_a(N_f)}, \qquad (2)$$

where $\sigma_a$ – amplitude of the normal stress under bending; $\tau_a$ – amplitude of the shear stress under torsion.

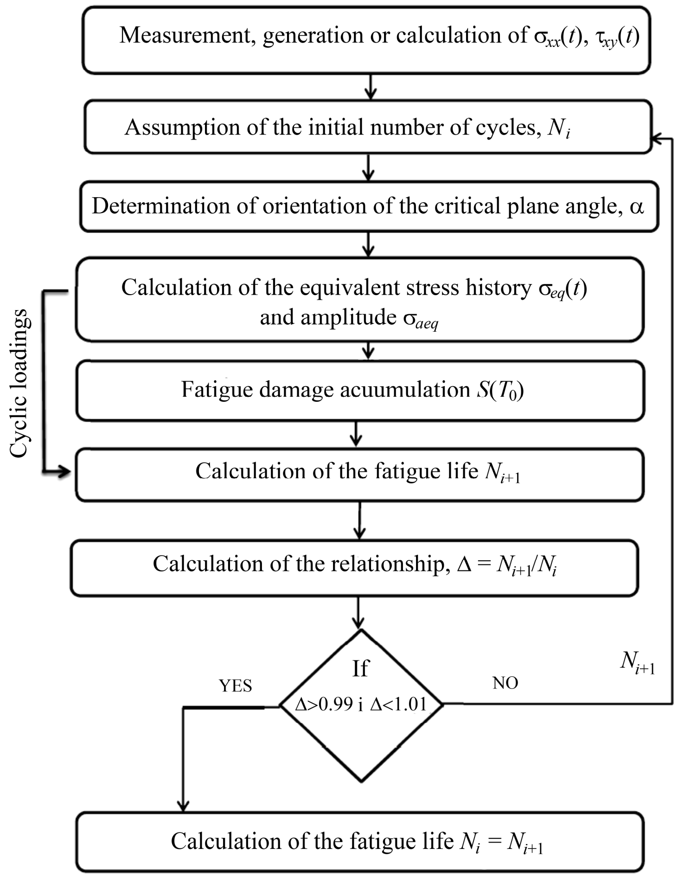


Fig. 2. Algorithm for fatigue life determination for materials with no parallelism of fatigue characteristics.

The presented model can be used for the 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.

In the next stage, the initial number of cycles necessary for calculation of the first cycle of the algorithm work, is assumed to be $N_i = 10^6$ cycles. 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 is determined with the damage accumulation method which consists in finding the orientation angle of the critical plane at the maximum possible degree of damage (minimum durability), using shear stress. The expression for normal and shear stresses was completed with the correction function, using the fatigue limits for extension and torsion Eq. (2):

$$\sigma_{\eta}(t) = \sigma_{xx}(t)\cos^2\alpha + k(N_f)\cdot\tau_{xy}(t)\sin 2\alpha\,, \tag{3}$$

$$\tau_{\eta s}(t) = -\frac{1}{2}\sigma_{xx}(t)\sin 2\alpha + k(N_f)\cdot\tau_{xy}(t)\cos 2\alpha\,, \tag{4}$$

where $\sigma_{xx}(t)$ – stresses coming from bending; $\tau_{xy}(t)$ – stresses coming from torsion; $\alpha$ – critical plane orientation angle.

Let us note that Eqs. (3) and (4) use parameter $k$, taking into account the out-of-parallelism fatigue characteristics for extension and pure torsion.

The authors of this paper applied the criterion of maximum shear stresses [11]. In [12] they demonstrated that the expression of the equivalent stress value should be a linear function including normal and shear stresses. Based on this, the criteria were formulated and verified for cyclic [13–15] and random loading [16–18]. The authors applied the criterion of maximum shear stresses [11]. This is strictly connected with the orientation of the critical plane angle. The history of the equivalent stress was written as

$$\sigma_{eq}(t) = k(N_f)\tau_{\eta s}(t) + (2 - k(N_f))\sigma_{\eta}(t)\,. \tag{5}$$

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

Thus, for the damage accumulation process, the Serensen–Kogayev hypothesis [19] was used. This is based on the Palmgren–Miner hypothesis [20, 21] and the coefficient $b$, characterising the history:

$$S_{SK}(T_0) = \begin{cases} \sum_{i=1}^{j} \dfrac{n_i}{b\cdot N_0\left(\dfrac{\sigma_{af}}{\sigma_{ai}}\right)^m} & \text{for} \quad \sigma_{ai} \geq a\cdot\sigma_{af}\,, \\ 0 & \text{for} \quad \sigma_{ai} < a\cdot\sigma_{af}\,, \end{cases} \tag{6}$$

where $b = \dfrac{\sum_{i=1}^{k}\sigma_{ai}t_i - a\cdot\sigma_{af}}{\sigma_{a1} - a\cdot\sigma_{af}}$, $t_i = \dfrac{n_i}{\sum_{i=1}^{k} n}$ – frequency of particular levels $\sigma_{ai}$ in realization of $T_0$; $\sigma_{a1}$ – maximum stress amplitude.

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

In the case of 35NCD16 steel, coefficient $a$ = 0.6 was used for further analysis, because this had provided the best agreement of the compared calculation and experimental fatigue lives. The calculation life for analysis of the method of modified amplitude [22]

$$\sigma_{md} = \frac{\sigma_{\sigma eqa}(\sigma)^{m_\sigma + 1}}{\sigma_{\sigma eqa}(\sigma)^{m_\sigma}}, \quad (7)$$

and the fatigue life was calculated from the transformated Basquin equation

$$N_f = 10^{A_\sigma - m_\sigma \log \sigma_{md}}. \quad (8)$$

The mean relative errors of the calculation fatigue lives for different values of coefficient $a$ are obtained according to the following equation

$$R = \frac{N_{\text{exp}} - N_{\text{cal}}}{N_{\text{exp}}} \cdot 100\%, \quad (9)$$

where $R$ for $a$ = 1 is 1016%; $a$ = 0.8 is 151%; $a$ = 0.6 is 102%; $a$ = 0.5 is 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:

$$N_f = \frac{T_0}{S(T_0)}. \quad (10)$$

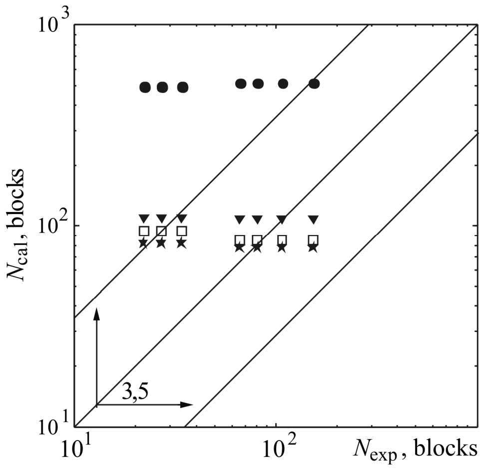


Fig. 3. Comparison of the calculation fatigue life $N_{cal}$ according to criterion on the plane of maximum shear stresses with the experimental fatigue life $N_{exp}$ for uniaxial random loading:
● – SK ($a$ =1); ▼ – SK ($a$ = 0.8);
★ – SK ($a$ = 0.6); □ – SK ($a$ = 0.5).

In the case of fatigue tests of the considered material, observation time ($T_0$) is a single block and the calculation life is a sum of the blocks. Under cyclic loadings, after calculation of the equivalent stress history, it is necessary to calculate fatigue life from the following equation, which is similar to Eq. (8)

$$N_f = 10^{A_\sigma - m_\sigma \log \sigma_{eq}}. \quad (11)$$

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

$$\Delta = \frac{N_{i+1}}{N_i}. \quad (12)$$

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

$$0.99 < \Delta < 1.01 \quad (13)$$

i.e. the assumed error is at a level of 1%, which is sufficient for fatigue calculations.

Let us remember that the life calculated from Eq. (9) is the life in one block. If condition (13) is satisfied, the obtained fatigue life is the sought after quantity.

**Verification of the proposed criterion.** The aim of the analysis is to check the efficiency of the proposed criterion, not only for 35NCD16, but for similar materials [23, 24] with special attention paid to the variability of parameter $k(N_f)$. Fig. 4 shows a 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 a comparison of the fatigue life and the experimental fatigue life for $k$ = const ($a$) and $k(N_f)$ ($b$).

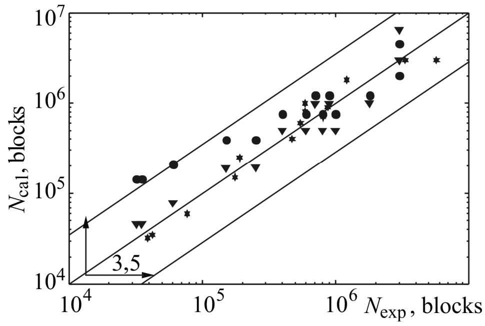


Fig. 4. Comparison of the calculated life $N_{cal}$ according to the criterion of the maximum shear stresses plane and the experimental life $N_{exp}$ for extension and torsion of 35NCD16 steel under cyclic loadings: ▼ – $\tau = 0$; ● – $\sigma = 0$ for $k(N_f)$; ✱ – $\sigma = 0$ for $k$ = const.

In the case when $k$ = const, most of the results are not included into the scatter band of the coefficient 3.5, which is calculated for extension.

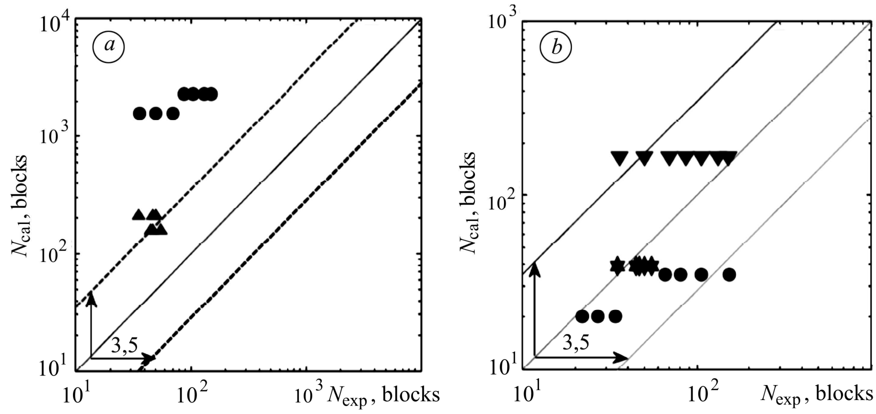


Fig. 5. Comparison of the calculation life $N_{cal}$ according to the criterion of the maximum shear stresses plane and the experimental life $N_{exp}$ for 35NCD16 steel under random loadings. *a*: $k$ = const, ● – $\sigma = 0$; ▲ – $\tau = 0.5\sigma$; *b*: $k(N_f)$, ● – $\tau = 0$; ▼ – $\sigma = 0$; ✱ – $\tau = 0.5\sigma$.

**CONCLUSIONS**

It is possible to draw the following conclusions from the analysis of the fatigue test results. 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 has provided satisfactory results. Analysis of the calculations results leads to the conclusion that the dependence of coefficient $k$ on the number of cycles to damage $N_f$ provides better results than for $k$ = const. Further analysis of the proposed model for other materials and loadings seems to be necessary.


*РЕЗЮМЕ*. Проаналізовано втомну довговічність високоміцної сталі 35NCD16 (36NiCrMo16) за випадкового навантаження. Сталь відрізняється відсутністю відповідності характеристик втоми за розтягу і закруту. Порівняно експериментальні результати з даними прогнозування довговічності на основі запропонованої моделі. Встановлено, що оцінка втомної довговічності таких матеріалів не може ґрунтуватися на стандартних моделях, оскільки вони не враховують зміни тангенціальних і нормальних напружень.

*РЕЗЮМЕ*. Проанализирована усталостная долговечность высокопрочной стали 35NCD16 (36NiCrMo16) при случайном нагружении. Сталь отличается отсутствием соответствия характеристик усталости при растяжении и кручении. Сравнены экспериментальные результаты с данными прогнозирования долговечности на основе предложенной модели. Установлено, что оценка усталостной долговечности таких материалов не может быть основана на стандартных моделях, так как они не учитывают изменение тангенциальных и нормальных напряжений.



***Acknowledgments. "The project is financed from the funds of the National Centre of Science – decision number 2011/01/B/ST8/06850" Estimation of the fatigue life of the alloy steel 35NCD16 under random loading.***

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*Received 10.02.2014*