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Evaluation of Casting Fatigue Life Based on Numerical Model and Fatigue Tests

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Abstract

The article presents the results of experimental and numerical analysis carried out on a variable in time state of stress and strain using the proposed algorithm. Calculations were performed on a model of the scraper conveyor lock used in mining transportation equipment; fatigue tests were performed on samples of the cast L20HGSNM steel.

Keywords: Fatigue testing, numerical calculations, mining equipment.

1. Introduction

Estimation of the fatigue life of a construction requires, on the one hand, the experimental determination of material characteristics, while, on the other hand, it requires our knowledge of the components of the state of stress and strain in the examined element. Fatigue tests are usually carried out under uniaxial loads, which makes their use in the analysis of the structure stability, in most cases subjected to multiaxial loads, quite difficult. The criteria of multiaxial fatigue enable reducing the spatial state of stress to a uniaxial tension, which is used in the determination of fatigue life based on standard tests. The reduction is usually done through the use of a relationship linking the components of the state of stress and strain; often, however, the applied criterion is also based on the measured strain energy. Among the numerous multiaxial fatigue criteria, attention deserve those that have been formulated basing on the concept of the, so-called, critical plane, assuming that the fatigue crack is triggered by the effect of stress or strain operating in this plane. Critical plane defines the place of crack initiation; thus, initially, it has been applied to the high-cycle fatigue test (HCF) only, but - as confirmed by numerous studies - it operates equally well also in the low-cycle fatigue tests (LCF) [1]. Determination of the components of stress and strain in the examined structure is usually performed with programmes based on numerical methods, e.g. FEM, where the description of the material includes its linear characteristics, optionally the stress-strain relationship above the yield point. In the case of the examined lock of the scraper conveyor, the numerical model, besides typical material characteristics obtained in the static tensile test, also included fatigue characteristics of the cast L20HGSNM steel obtained in the fatigue tests with increasing force amplitude, such as the modified low cycle fatigue test (MLCF) [2], except that the increase of load was concentrated in the range of $R_{p0.2}$ and R_m, due to a small difference between the respective values. As a sample structure examined in this way, the lock of the scraper conveyor has been selected [3]. Its shape and dimensions as well as the method of assembly are presented later in this article. Static tensile and fatigue tests were performed on samples of the cast abrasion resistant L20HGSNM steel, considered as possible substitute for the alloy 25HGNMA steel used, among others, in the production of chains and forged locks for mining conveyors of this type. The article focuses on the analysis of the results of fatigue tests of the alloy based on numerical modelling and real experiments.

2. Description of the applied research methodology

The successive steps accompanying the performance of a numerical model, the calculation of stress and strain and the determination of fatigue life involved:

1. Conducting the static tensile test.
2. Conducting fatigue tests by the LCF and MLCF method.
3. Interpretation of the obtained results and their incorporation into the numerical model of a sample subjected to cyclic loading to test the validity of the "virtual properties".
4. Building a numerical model of the lock with description of material allowing for the effect of load on the fatigue behaviour (mixed kinematic and isotropic hardening).
5. Determination of components of the spatial stress-strain state in the lock.
6. Selection of multiaxial fatigue criterion based on the interpretation of the results of calculations made by FEM.
7. Prediction of the fatigue life of the lock based on the numerically determined value of deformation and fatigue life curve plotted for the cast 25HGNMA steel.

In further part of the article, some of the above mentioned items, more important in terms of the applied methodology, will be developed.

3. Fatigue testing by LCF and MLCF

LCF fatigue tests were performed on 6.5 mm diameter samples applying a symmetric loading cycle with different strain amplitudes corresponding to the stress interval from $R_{p0.2}$ to R_m. Based on the results of the tests, the kinematic hardening was defined. It describes a rigid shift in stress-space of the centre of the original yield surface under the effect of the back stress X_{ij}. The size of the yield surface does not change during the shift and, contrary to isotropic hardening, depends on the stress trajectory. On the other hand, isotropic hardening is responsible for changes in the flow stress determining the size of the yield surface as a function of plastic deformation [12-16]. The simplest description of the isotropic hardening is in the form of a table with plastic strain-flow stress pairs of values. The kinematic hardening for a half-cycle is also expressed in the form of the stress-strain pairs of values, or in the case of the entire hysteresis loop, using the relationships given below, Ziegler hypothesis included (1):

$$X_{ij}^{'} = C\frac{1}{\sigma^{o}}\left(\sigma_{ij} - X_{ij}\right)\dot{\varepsilon}_{ij}^{vp} \qquad (1)$$

$$C = \frac{\sigma - \sigma^{o}}{\varepsilon^{p}}, \quad X_{ij}^{'} = \sum_{k=1}^{N} X_{ij(k)} \qquad (2)$$

where:

C – the kinematic hardening modulus,
σ^{o} – the flow stress determining the size of the plastic zone,
ε^{p} – plastic deformation,
ε^{vp}_{ij} – the speed of plastic deformation,
$X^{'}_{ij}$ – the increment in back stress X_{ij}.

To determine the range of mechanical properties, a modified low cycle fatigue test (MLCF) [2, 4] was applied. It allows specifying the parameters resulting from the Manson-Coffin-Morrow relationship:

$$\sigma_a = K^{'} (\varepsilon_p)^{n'} \qquad (3)$$

$$\sigma_a = \sigma^{'}_f (2N_f)^{b} \qquad (4)$$

$$\varepsilon_p = \varepsilon^{'}_f (2N_f)^{c} \qquad (5)$$

where:

σ_a – the stress amplitude of the cycle,
$\sigma^{'}_f$ – the „fatigue strength coefficient” approximately equal to the tensile strength R_m,
ε_f – the true plastic strain caused by the stress $\sigma^{'}$,
$2N_f$ – the number of cycles to specimen failure,
ε_p – the true plastic strain caused by the $2N_f$ load cycles, where: $\varepsilon_p = \ln(1 + \varepsilon_k)$, and where, in turn, $\varepsilon_k = \Delta l_{trwałe} / l_0$,
$K^{'}$ – the cyclic strength coefficient,
$n^{'}$ – the cyclic strain hardening exponent,
c – the fatigue ductility exponent.

The Z_{go} fatigue strength necessary for the calculation of test parameters was evaluated from the experimental graph (Fig. 1) plotted for a diverse group of materials, starting from pure metals and ending in iron alloys and alloys of non-ferrous metals [4].

To determine the values of b, c, n', K and ε_{max}, the following assumptions were adopted [2, 4]:

- disorders in a uniaxial field of compressive stresses are effectively eliminated by the use of one-sided loading cycles during tension in fatigue test,
- the dependence of permanent deformation caused by the preset small number of cycles (e.g. twenty load-unload cycles) on the amplitude of the cycle is similar to the dependence of deformation occurring upon the specimen failure, the more that the permanent deformation after 20 cycles either shows a very insignificant change with the growing number of cycles or does not change at all [2, 4],
- the mechanical properties mentioned above are determined on one sample only,
- simple waveforms according to equations (4) and (5) in a double logarithmic scale are determined from the position of points with coordinates: /ln 20, ln R_m/ and /ln($2N_f$), ln(Z_{go}/ in the case of equation (4) and /ln20, ln ε_f/ and /ln($2N_f$), ln ε_z/ in the case of equation (5),
- the rotating bending fatigue strength is evaluated according to Figure 1.

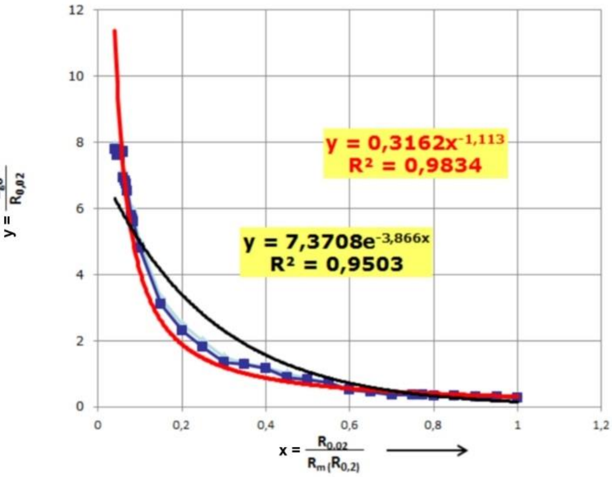

Fig. 1. Curve for the evaluation of fatigue strength [4]

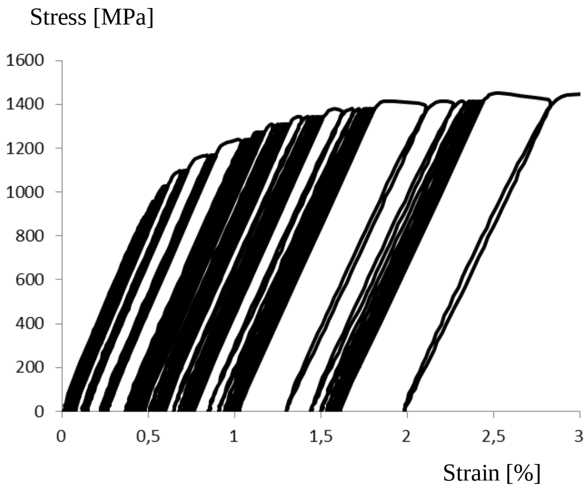

Fig. 2. The increase in permanent deformation due to load increment recorded in the MLCF test

MLCF tests were also performed on 6.5 mm diameter samples in the positive pulsating cycle with increasing stress amplitude, introducing, as mentioned in the introduction, small loading force increments in a range above $R_{0.2}$. A typical course of deformation changes recorded as a function of the increasing force converted to stress is shown in Figure 2.

Based on these results, the following average values listed in Table 1 were calculated: the tensile strength R_m, the yield strength $R_{p0.2}$, the apparent elastic limit $R_{0.02}$, the elastic modulus E, the rotating bending fatigue strength Z_{go}, the maximum total acceptable permanent deformation ε_{max}, in this case for a $10 \bullet 10^6$ number of cycles, the fatigue strength exponent b and the fatigue ductility exponent c.

Table 1.
The results of MLCF test and static tensile test made on the cast 25HGNMA steel

$R_{p0,02}$ [MPa]	$R_{p0,2}$ [MPa]	R_m [MPa]	Z_{go} [MPa]	E [MPa]	A_5 [%]	ε_{max} [mm/mm]	b	c
970	1210	1446	528	185000	7,1	0,00385	-0,077	-0,182

4. Numerical model of conveyor lock

Conveyors are important elements of equipment during the coal transport in longwall excavations and drift mining, where they form an integral part of the cutting and loading machines and of the wall casing [5]. Typically, parts of conveyors are forgings made of the low-alloy structural steel - 25HGNM (Figs. 3a, 3b).

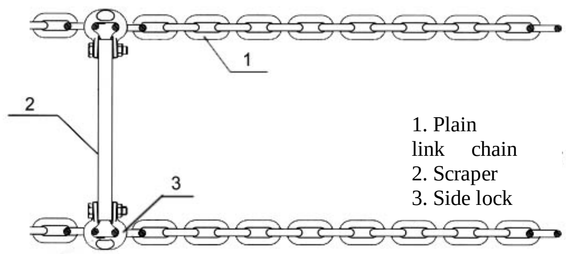

Fig. 3a. Fixing of scraper in a conveyor.

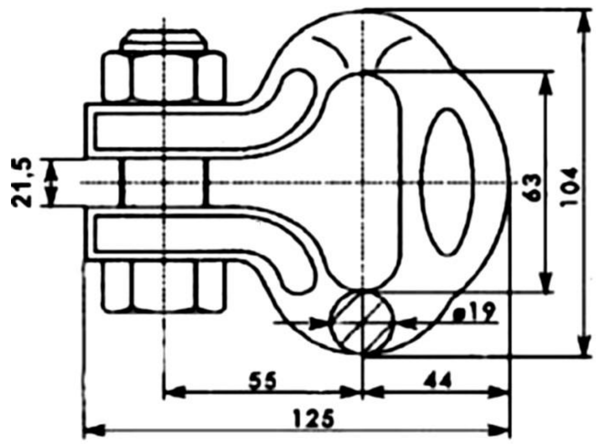

Fig. 3b. Sample solution of lock design

The numerical model of the lock was designed in the Abaqus programme [1, 5-11]. Due to the symmetrical geometry of the lock-chain system and the assumed symmetry of load, for calculations, a half-object was used. The chain link had a mechanical type of contact with the surface of the lock. The force exerted by the chain link varied in a large range of values, in extreme cases causing reduced stress in the lock, close to the boundary tensile strength R_m of cast steel. From the area of the model where the calculated stress values were the highest, and where usually cracks in the conveyor locks are observed to occur, a few elements were selected, and in those elements changes in the components of the state of stress and strain were recorded and depicted in the form of graphs showing the "virtual fatigue" of the examined material (Fig. 4).

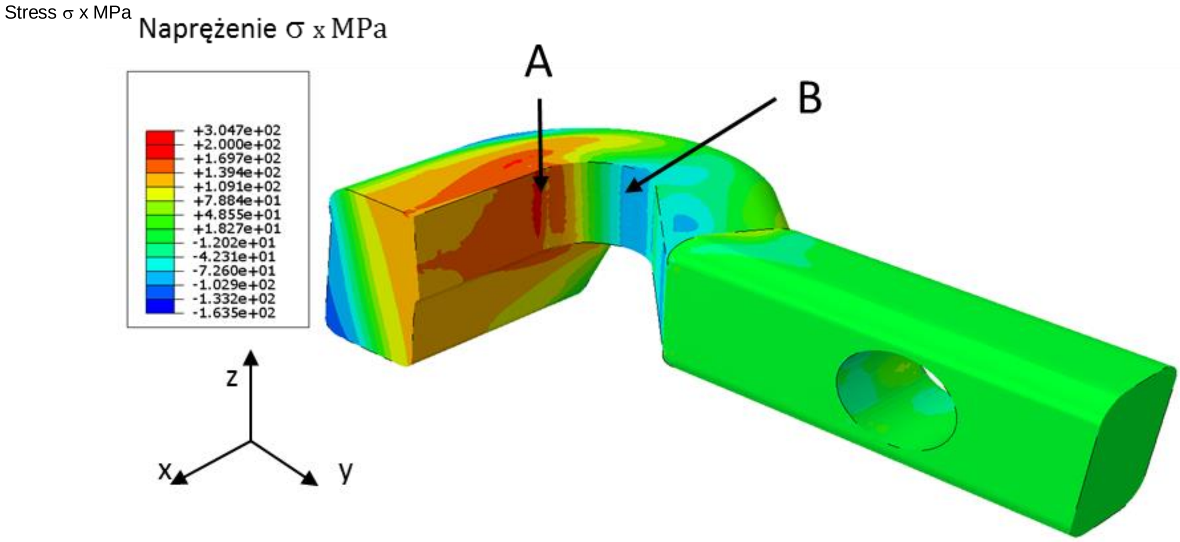

Fig. 4. Image of stresses σ_x in the lock model induced by impact force of the chain;
A - the area of occurrence of the largest tensile stresses σ_x possibly causing cracks,
B - the area of contact with the chain link, where compressive stresses coloured in blue are visible

5. Estimation of the lock fatigue life

Estimation of fatigue life is done by comparing the state of strain in selected finite elements of a representative area with the fatigue life curve. The state of strain in the selected elements is subjected to analysis and is reduced to equivalent strain following one of the hypotheses, or in the case of one dominant component is considered identical with this component. The high-cycle fatigue life curve plotted for the cast 25HGNMA steel is shown in Figure 5.

As a representative area, the place marked in Figure 4 with the letter A was selected. In this place, the calculations showed the highest values of stress and strain. The lock was subjected to a virtual cyclic fatigue, whose run was the same as in experimental studies. The load was caused by the pulling force of the chain link, which varied from zero to a maximum value increasing in successive cycles. The chart of the virtual fatigue for area A is shown in Figure 6.

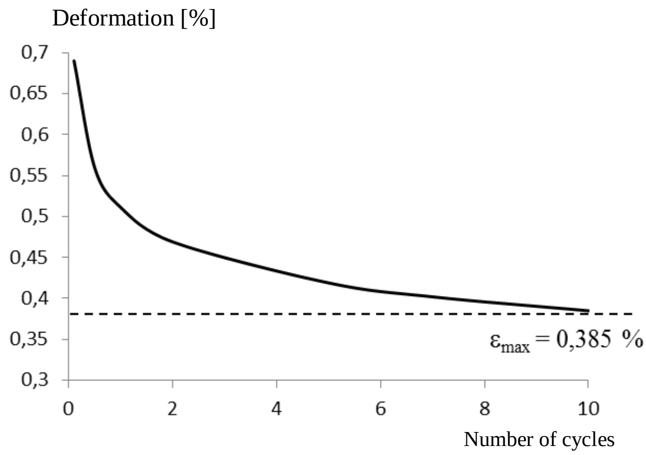

Fig. 5. Fatigue life curve plotted for the cast 25HGNMA steel with maximum allowable strain marked for the limit number of cycles amounting to 10^7

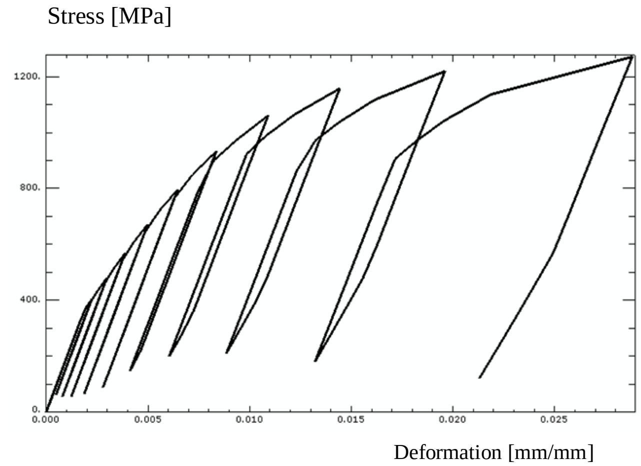

Fig. 6. The course of virtual fatigue in the area marked with letter "A" in Figure 4

Special attention deserve the differences in the fatigue curves plotted in Figures 2 and 6. The cycle in Figure 2 can be compared to changes in force or tension occurring on the contact surface between the chain link and the lock. As has already been mentioned, it is a growing positive pulsating cycle, while the response of area "A" in the lock is conditioned by the state of stress and strain in this location, and also by a virtual model of the material, which allows for the kinematic and isotropic hardening. Hence the decline in the exciting force to zero does not cause loss of the stress state in area "A" - Figure 6, due to the appearance of permanent deformation in this and other areas of the model of the lock. By further analysis of the fatigue behaviour of the lock it is possible to estimate, for the specified constant values of the traction force, changes in fatigue life basing on the stabilised hysteresis loop. For example, Figure 7 shows its course in the case of structure overloading, which will result in maximum stresses of approximately 800 MPa formed in the dangerous area.

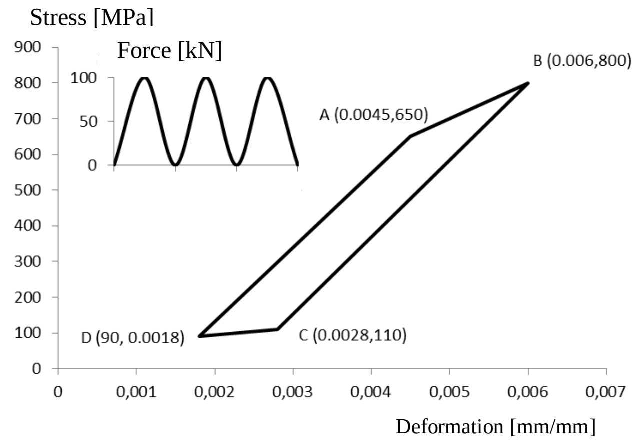

Fig. 7. The shape of stabilised hysteresis loop in area "A" of the lock caused by positive pulsating load of the chain link contact force of a maximum value of 10 kN

6. Summary

The methodology proposed in this article, combining experiments with numerical calculations, allows us to estimate the fatigue life using maximum allowable strain determined for the maximum number of cycles corresponding to a fatigue limit and deformation as a function of the predetermined number of cycles operating in a high and low range of values. The values determined experimentally are compared with the values of the deformation calculated numerically for the most loaded areas of the examined structural element. In the case under discussion, in the tensor of the state of strain, only one component was dominant, and therefore the determination of equilibrium strain was relatively easy - simply the value of this component was adopted. Considering the fact that the crack initiation usually occurs on the surface of the element, the above case of the determination of equivalent strain will occur quite frequently, but when the shape of the structure is more complex, appropriate deformation criteria will be necessary. If numerical calculations are carried out to determine the value of the equivalent strain for vastly different loading ranges of the structural element, the LCF experimental studies should be conducted for several ranges of the deformation, to properly define the material properties in a calculation model.

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