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) \cite{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) \cite{2}, except that the increase of load was concentrated in the range of $R_{0.2}$ 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 \cite{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 \(R_{pf} = 0.2\) to \(R_{pf} = 0.5\). 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 \(X_0\). 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):

\[
X_g = C \frac{1}{\sigma_0} \left( \sigma_{ij} - X_{ij} \right) \dot{\varepsilon}_{ij} \tag{1}
\]

\[
C = \frac{\sigma - \sigma^0}{\varepsilon^0}, \quad X_{ij} = \sum_{k=1}^{N} X_{ij(k)} \tag{2}
\]

where:
- \(C\) – the kinematic hardening modulus,
- \(\sigma^0\) – the flow stress determining the size of the plastic zone,
- \(\sigma\) – plastic deformation,
- \(\varepsilon^0_{ij}\) – the speed of plastic deformation,
- \(X_{ij}\) – the increment in back stress \(X_0\).

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:

\[
\sigma_\infty = K (\varepsilon_\infty)^n \tag{3}
\]

\[
\sigma_\infty = \sigma_\infty (2N)^b \tag{4}
\]

\[
\psi = \psi (2N)^c \tag{5}
\]

where:
- \(\sigma_\infty\) – the stress amplitude of the cycle,
- \(\sigma_\infty\) – the “fatigue strength coefficient” approximately equal to the tensile strength \(R_m\),
- \(\psi\) – the true plastic strain caused by the stress \(\sigma\),
- \(2N\) – the number of cycles to specimen failure,
- \(\psi\) – the true plastic strain caused by the 2N-load cycles,
- \(K, n, b, c\) – the cyclic stress, strain, and fatigue ductility exponents.

The \(Z_{\psi}\) 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 \(\psi_{\infty}\), 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: \(\ln 20, \ln R_0\) and \(\ln(2N), \ln(Z_{\psi})\) in the case of equation (4) and \(\ln20, \ln \psi\) and \(\ln(2N), \ln \psi\) in the case of equation (5),
- the rotating bending fatigue strength is evaluated according to Figure 1.
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 $R_{0.2}$, the apparent elastic limit $R_{0.02}$, the elastic modulus $E$, the rotating bending fatigue strength $Z_{go}$, the maximum total acceptable permanent deformation $\varepsilon_{\max}$, in this case for a $10^6$ 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

<table>
<thead>
<tr>
<th>$R_{0.02}$ [MPa]</th>
<th>$R_{0.2}$ [MPa]</th>
<th>$R_m$ [MPa]</th>
<th>$Z_{go}$ [MPa]</th>
<th>$E$ [MPa]</th>
<th>$A_5$ [%]</th>
<th>$\varepsilon_{\max}$ [mm/mm]</th>
<th>b</th>
<th>c</th>
</tr>
</thead>
<tbody>
<tr>
<td>970</td>
<td>1210</td>
<td>1446</td>
<td>528</td>
<td>185000</td>
<td>7.1</td>
<td>0.00385</td>
<td>-0.077</td>
<td>-0.182</td>
</tr>
</tbody>
</table>

### 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.](image)

The numerical model of the lock was designed in the Abaqus programme [1, 5-11]. Due to the symmetrical geometry of the lock-
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.
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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References


