Methodological conditionings of a modified low cycle fatigue method of tempered 41Cr4 steel in comparison to some other materials

M. Maj a*, W. Moćko b, K. Pietrzak b, A. Klasik b,

a AGH University of Science and Technology Faculty of Foundry, 27 Reymonta St., 30-059 Kraków, POLAND
b Motor Transport Institute, Jagiellońska 80, 03-301 Warsaw, POLAND

*Corresponding author. E-mail address: mmaj@agh.edu.pl

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Abstract

In the research work results of the application of modified LCF method in the assessment of fatigue parameters of various materials were discussed. The new software algorithm was proposed in the determination of fatigue parameters. A comparative verification of the new procedure with bibliographical data confirmed the possibility of the replacement of classical LCF by proposed original MLCF method as especially suitable test in the case of heterogeneous materials microstructure, particularly when it is hard to design Wöhler’s diagrams as well as to carry on research according to the classical LCF method.

Keywords: Cast aluminum; Cast iron; Steel; Material fatigue; LCF parameters; Microstructure

1. Introduction

A basic problem in the fabrication of final products, which are made from various kinds of materials, is to obtain their high, but also repeatable quality, consequential from the set of required functional properties of materials, used in this production. The aim formulated this way requires permanent improvement of assessment methods, also in the range of fatigue characteristics. There are also many results concerning the new fatigue models and criterions (in the area of HCF and LCF methods) as a proposed basis for life prediction of various materials and products operating under the uniaxial and multiaxial mechanical loads [1 - 6] in ambient or elevated temperature. The typical fatigue parameters for selected materials such as forged steel, cast aluminum, cast iron and powder metal based on bibliographical data are presented in the Table 1.

This research work is concentrated on the another original modified LCF method making possible to predict the fatigue characteristics basing on test results determined for the one sample only. This procedure, described in detail in another publication [10], was practically used, among others, in research works [10 - 12]. Table 2 shows the comparison of selected fatigue parameters obtained by means of classical LCF [7] and modified MLCF (own earlier results – [10]) methods, for three types of cast iron with spherical, vermicular and flake graphite.
### Table 1.
Comparison of selected fatigue parameters for some various materials, based on literature data

<table>
<thead>
<tr>
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</tr>
</thead>
<tbody>
<tr>
<td>Fatigue strength exponent (b)</td>
<td>-0,082</td>
<td>-0,117</td>
<td>-0,095</td>
<td>-0,076</td>
<td>-0,103</td>
</tr>
<tr>
<td>Fatigue ductility exponent (c)</td>
<td>-0,791</td>
<td>-0,610</td>
<td>-0,690</td>
<td>-0,771</td>
<td>-0,530</td>
</tr>
<tr>
<td>Cyclic strength coefficient (K')</td>
<td>1269,500</td>
<td>430,300</td>
<td>940,200</td>
<td>649,100</td>
<td>2,005</td>
</tr>
<tr>
<td>Cyclic strain hardening exponent (n')</td>
<td>0,137</td>
<td>0,063</td>
<td>0,110</td>
<td>0,075</td>
<td>0,192</td>
</tr>
<tr>
<td>Fatigue ductility coefficient (εf')</td>
<td>3,032</td>
<td>0,094</td>
<td>0,350</td>
<td>0,864</td>
<td>0,198</td>
</tr>
</tbody>
</table>

### Table 2.
Comparison of selected fatigue parameters obtained by means of classical LCF and modified MLCF methods for three types of cast iron

<table>
<thead>
<tr>
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</tr>
</thead>
<tbody>
<tr>
<td>Fatigue strength exponent (b)</td>
<td>-0,076</td>
<td>-0,076</td>
<td>-0,060</td>
<td>-0,050</td>
</tr>
<tr>
<td>Fatigue ductility exponent (c)</td>
<td>-0,771</td>
<td>-0,708</td>
<td>-0,516</td>
<td>-0,264</td>
</tr>
<tr>
<td>Cyclic strength coefficient (K'-[MPa])</td>
<td>649,100</td>
<td>1206,00</td>
<td>1372,00</td>
<td>3590,00</td>
</tr>
<tr>
<td>Cyclic strain hardening exponent (n')</td>
<td>-0,075</td>
<td>0,264</td>
<td>0,300</td>
<td>0,504</td>
</tr>
<tr>
<td>Fatigue ductility coefficient (εf')</td>
<td>0,864</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Max. strain (εmax⋅10^6)</td>
<td>lack of data</td>
<td>832,00</td>
<td>1372,00</td>
<td>1358,00</td>
</tr>
</tbody>
</table>
2. Materials, methods and results


41Cr4 steel was tested by means of classical LCF method and original MLCF method [10, 11]. The chemical composition of the investigated steel is presented in Table 2.

<table>
<thead>
<tr>
<th>Material</th>
<th>Chemical composition [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>C</td>
</tr>
<tr>
<td>41Cr4</td>
<td>0.44</td>
</tr>
</tbody>
</table>

2.2. Mechanical tests

The analysis of mechanical properties in a range of low-cycle changing loads is well-known in literature in the approach proposed by Manson; Coffin and Morrow [10, 13 - 15]. It is also included in one of the Polish standards [16]. The Low Cycle Fatigue (LCF) test is carried out under the conditions of symmetrical loads. The loading cycle consists of the application of tensile and compressive forces to a specimen within the range of “hypercritical” stresses, i.e. above the fatigue limit, starting usually with the stress amplitude that results in permanent set of at least 0.2%. Testing under such conditions restricts the number of cycles that cause failure of the specimen, while the test results obtained on one specimen mark one point on the low-cycle fatigue curve. Hence a conclusion follows that the results are the more precise, the larger number of the specimens is used in the test. The application of LCF test is confined to materials characterized by high plastic properties, since the whole measuring cycle is lying well above the proof stress [10, 14]. As described by relevant standard [16], the test consists of subjecting the specimen to the effect of uniaxial changing loads (tensile-compressive) until its failure occurs, recording simultaneously the number of cycles during the test and plotting the stress-strain curve (or force-displacement curve) in the form of hysteresis loop. The test is carried out under control of stress (force referred to the initial specimen cross-section), strain (measurement base of the specimen), or displacement (the load-applying system).

It is important to note that the operating parameters of a low-cycle fatigue test (LCF) require the use of 6-10 specimens, which may create problems when testing materials of a heterogeneous structure. Of some importance is also the duration of the test, in many cases taking the time of several days even, as well as the fact that the results obtained in the test are limited to the parameters strictly related with the material fatigue behaviour (b, c, n’, K and \(\varepsilon_{\text{max}}\)).

In its original form, the computerized program was first used by A. Karamara [14] and M. Maj [10]; later it has been adapted to the use with an MTS Test Star IIs machine, equipped with modern control system [17]. In this study, the most important elements of the system will be described. Quite naturally, they all require further improvements to raise the versatility of the whole application.

The program enables the modulus of elasticity to be determined in its general form, within the range of different stresses for stable mechanical hysteresis:

\[
E = \frac{\sigma_2 - \sigma_1}{\varepsilon_2 - \varepsilon_1}
\]  

where:

- \(\sigma_1, \varepsilon_1\) - the stress and strain for the lower vertex of a mechanical hysteresis loop,
- \(\sigma_2, \varepsilon_2\) - the stress and strain for the upper vertex of the loop.

As a next step, the following parameters are determined: the apparent elastic limit – \(R_{0.02}\); the apparent limits \(R_{0.05}\) and \(R_{0.1}\); the yield strength \(R_{0.2}\); the accommodation limit \(-R_a\); the estimated value of the rotary bending fatigue strength \(-Z_{\text{go}}\); the values of material constants determined from a low-cycle fatigue test: b, c, n’, the true stress \(-K\); the maximum total admissible strain \(-\varepsilon_{\text{max}}\), and the tensile strength \(-R_m\).

The fatigue strength \(Z_{\text{go}}\), necessary for computation of the parameters used in MLCF test, is determined from the test curve plotted for different material families, starting with pure metals and ending in ferrous and non-ferrous metal alloys (Fig.1. – [14])

![Fig.1. The curve for fatigue strength determination [14]](image)

The most important quantity determined in the MLCF test is the maximum admissible total strain for the number of cycles corresponding to a fatigue limit of the examined material.

\[
\varepsilon_c = \varepsilon_e + \varepsilon_p = \frac{\sigma_f}{E} (2N_f)^b + \varepsilon_f (2N_f)^c
\]

where:

- \(\varepsilon_c\) – the maximum total admissible strain,
- \(\varepsilon_e\) – the elastic (reversible) strain,
- \(\varepsilon_p\) – the permanent (true) strain after 2Nf load cycles,
- \(\varepsilon_f\) – the permanent (true) strain induced by the stress \(\sigma_f\),
σ₉ – the stress approaching the tensile strength (in materials with distinct plastic properties this is the stress preceding the formation of a „neck”),
b – the fatigue strength coefficient (Basquin’s coefficient),
c – the fatigue deformability exponent.

All of the above mentioned values are obtained during the research of only one specimen and this is the most precious in the new method, as that all static mechanical values and those which are responsible for the low-cycle fatigue strength permit to characterize very exactly analyzed material irrespective of how heterogeneous its structure may be. In the case of determination of fatigue values based on classical LCF method, to obtain information on the maximum total admissible strain, it is necessary to have at least a dozen or so specimens.

### 2.3 Heat treatment

The tested steel was conducted to a heat treatment consisted of austenitizing at 850°C and tempering at 650°C. The aim of this treatment was to obtain the same hardness (mean value was 20.5 HRC, min. – 19.00 HRC; max. – 21.8 HRC), the same tensile strength (mean value – 891 MPa, min. – 879 MPa, max. – 897 MPa) and the same microstructure (Fig. 2). It was connected with a necessity to ascertain that the classical LCF method may be (or may be not) replaced by a proposed MLCF method. The microstructure, as sorbite mixture, visible in Fig. 2, is characteristic for the tempered state and it is the same for all observed samples. Additionally, for comparative purposes, the microstructures of earlier tested steels are also shown (Fig. 2a, b).

![Microstructures of three kinds of steels](image)

**Fig. 2.** Microstructures of three kinds of steels; conventional light, magn. 500x, etched state

Results of own mechanical investigations carried out by means of proposed MLCF method in comparison to results obtained by classical LCF method (bibliographical data) are presented in Table 4.
Table 4. Comparison of selected fatigue parameters obtained by means of classical LCF and modified MLCF methods for various kinds of steels

<table>
<thead>
<tr>
<th>Cyclic properties</th>
<th>LCF classical (literature data for typical steel) [7]</th>
<th>MLCF (Modified LCF – own results – C45E steel) [12]</th>
<th>MLCF (Modified LCF – own results – 100Cr6 steel) [12]</th>
<th>MLCF (Modified LCF – own results – 41Cr4 steel)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fatigue strength exponent (b)</td>
<td>-0.082</td>
<td>-0.078</td>
<td>-0.076</td>
<td>-0.07</td>
</tr>
<tr>
<td>Fatigue ductility exponent (c)</td>
<td>-0.791</td>
<td>-0.780</td>
<td>-0.748</td>
<td>-0.66</td>
</tr>
<tr>
<td>Cyclic strength coefficient (K')</td>
<td>1269.50</td>
<td>1227.00</td>
<td>1266.00</td>
<td>808.00</td>
</tr>
<tr>
<td>Cyclic strain hardening exponent (n')</td>
<td>0.137</td>
<td>0.263</td>
<td>0.254</td>
<td>0.017</td>
</tr>
<tr>
<td>Fatigue ductility coefficient (ε’f)</td>
<td>3.032</td>
<td>lack of data</td>
<td>lack of data</td>
<td>3.500</td>
</tr>
<tr>
<td>Max. strain max (εmax⋅10^6)</td>
<td>1500</td>
<td>746</td>
<td>761</td>
<td>1600</td>
</tr>
</tbody>
</table>

3. Concluding remarks

Results of research allow to ascertain that:
- it is a good conformity between the fatigue parameters of spheroidal cast iron determined by means of LCF (bibliographical data) and assessed by means of MLCF method – own results (Table 2),
- the variability of Basquin’s fatigue strength exponent (b) depends on the graphite shape and it is the highest for spherical graphite and lowest for flake graphite (Table 2),
- it is a good conformity between the fatigue parameters of typical forged steel determined by means of LCF (bibliographical data) and MLCF method – own results (Table 3),
- the original software algorithm has been positively verified by carried out experiments,
- basing on results and comparisons with bibliographical data, it is possible to conclude that classical LCF method may be replaced by proposed MLCF method. This fact is especially significant in the case of heterogeneous material microstructure when is difficult to design Wöhler’s diagrams.

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[17] Projekt badawczy 4T08B 006 25 pt.: Zastosowanie zmodyfikowanej, niskocyklowej próby zmęczeniowej do wyznaczania właściwości mechanicznych żeliwa ADI w temperaturze pokojowej i podwyższonej, kierownik projektu – dr inż. Maria Maj, Kraków 2005