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MODIFIED LOW-CYCLE FATIGUE (LCF) TEST

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Preliminary Note – Prethodno priopćenje

The fatigue test results obtained by the common low-cycle fatigue test (LCF) and its modified MLCF counterpart were presented. A satisfactory agreement of results was achieved for the two selected materials. With the MLCF method it is possible to examine from ten to twenty parameters using one single sample only. These parameters characterise the tested material in terms of its mechanical properties under the conditions of mechanical loads. Simultaneously, the study shows the implementation of the modified low-cycle fatigue test in practice.

Key words: steel, aluminium, fatigue life, microstructure

INTRODUCTION

A major problem of modern automotive industry and technique in general is the process of fatigue developing in engineering materials under long-term cyclic loading. Cyclically varying stresses shorten the service life of structural components, since their destruction can occur at stresses well below the value of the static strength of the material [1]. Fatigue is a common cause of premature failure of the structure and, therefore, this term means in practice a finite number of cycles of loading that the material / product is able to withstand. There are many factors that directly affect the limit cycles. These include, among others, the nature of the loads, their sequence and duration.

Up to now, most commonly, the data on fatigue characteristics have been derived from the well-known fatigue tests carried out in a high- or low-cycle regime (HCF and LCF, respectively) [2, 3]. As a result of those tests, complete Wöhler diagrams were obtained such as, for example, the diagram illustrated schematically in Figure 1 [1-3].

Very often, the fatigue life of materials is evaluated from a low-cycle fatigue test (LCF). Then the analysis of the mechanical properties for the low-cycle variable loads in Manson-Coffin and Morrow's approach [3-6] is based on tests conducted under the conditions of balanced loads (tension and compression) within the range of "hypercritical" strain, i.e. higher than the fatigue strength, generally starting from the stress amplitude causing plastic strain of usually not less than 0,2 %. The adoption of such conditions limits the number of cycles which cause failure of the sample and the results of tests made on one sample correspond to one point on the curve characteristic of the low-cycle fatigue strength.

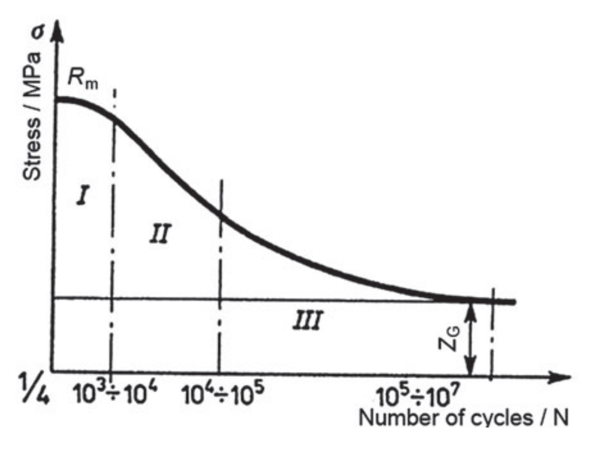

Figure 1 A complete Wöhler diagram with areas of: I – quasi-static strength, II – low-cycle strength, III – high-cycle strength [1-3]

However, for both HCF and LCF, the measurements are the more accurate, the greater is the number of the samples available. Moreover, the LCF applicability is limited to materials which have good plastic properties, since the entire measuring range is substantially above the yield strength [3], [5]. In this study, the fatigue life was examined using the author's own original modified low cycle test (hereinafter referred to as MLCF), described in detail in [4].

TEST MATERIALS AND METHODS

The following test materials were used: 40H (41Cr4) steel and Al 6082 (AlSi1MgMn). alloy. Both materials have undergone an appropriate heat treatment ensuring their stable microstructure. The 40H (41Cr4) steel was subjected to a toughening treatment (quenching in oil at 850 °C and tempering for 2 h at 450 °C), while the Al 6082 alloy was heat treated to T6 condition, which consisted in solution treatment and aging at 190 °C for 6 h.

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METHODOLOGY AND DISCUSSION OF RESULTS

Tensile Test

Studies of fatigue life were preceded by an evaluation of basic mechanical properties determined from the results of static tensile test (Instron 8874). Table 1 shows the values of Young's modulus (*E*), apparent elastic limit and yield strength ($R_{0,02}$ and $R_{0,2}$ respectively), tensile strength (R_m) and elongation (A_5) obtained for the 40H steel and Al 6082 alloy.

Table 1 **The results of the tensile test**

Material		*E* /MPa	$R_{0,02}$ /MPa	$R_{0,2}$ /MPa	R_m /MPa	A_5 /%
40H	1	151 000	666	754	1 091	22
	2	154 000	587	675	1 005	22
Al 6082	1	56 000	389	394	553	15
	2	46 000	383	388	544	16

LCF vs MLCF – a comparison of the test results

To demonstrate the reliability of the results obtained by MLCF, a comparative study was conducted on the fatigue life of 40H (41Cr4) steel and 6082 aluminium alloy tested by two methods, i.e. the common LCF method (Tables 2 and 3) and its modified MLCF counterpart (Tables 4 and 5).

Table 2 **The results of LCF test (40H steel)**

b	*c*	ε_{max}	*K'* / MPa	*n'*
- 0,06216	- 0,86625	0,05432	1 077	0,04296

Table 3 **The results of LCF test (Al 6082 alloy)**

b	*c*	ε_{max}	*K'*/ MPa	n'
- 0,09241	- 0,81850	0,01905	591	0,13113

where:

b – Basquin's exponent,
c – fatigue ductility exponent
K' – cyclic strength coefficient
n' – cyclic strain hardening exponent
ε_{max} – maximum strain

In the stress-controlled MLCF method, samples were subjected to positive loading cycles. To avoid sample distortion due to the effect of compressive loads, in the first step, the sample was loaded with an extra load of s_{Min} = 10 MPa. The research programme consisted of N_p "packages", with stress increased in each successive "package". Each "package" contained N_c = 20 cycles of the tensile stress of the same amplitude. The run of MLCF tests is shown in Figure 2.

Examples of the waveforms obtained by MLCF are shown in Figure 3, where Figures 3a and 3b illustrate the process of loading in a stress-controlled mode and strain-controlled mode, respectively.

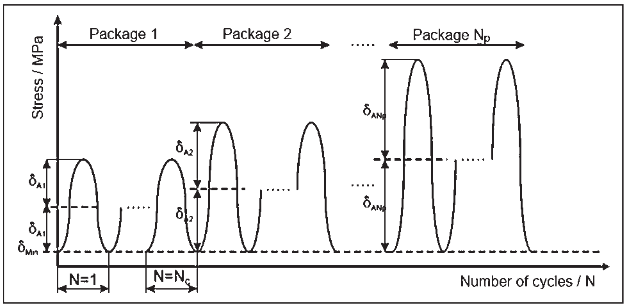

Figure 2 The run of a test programme

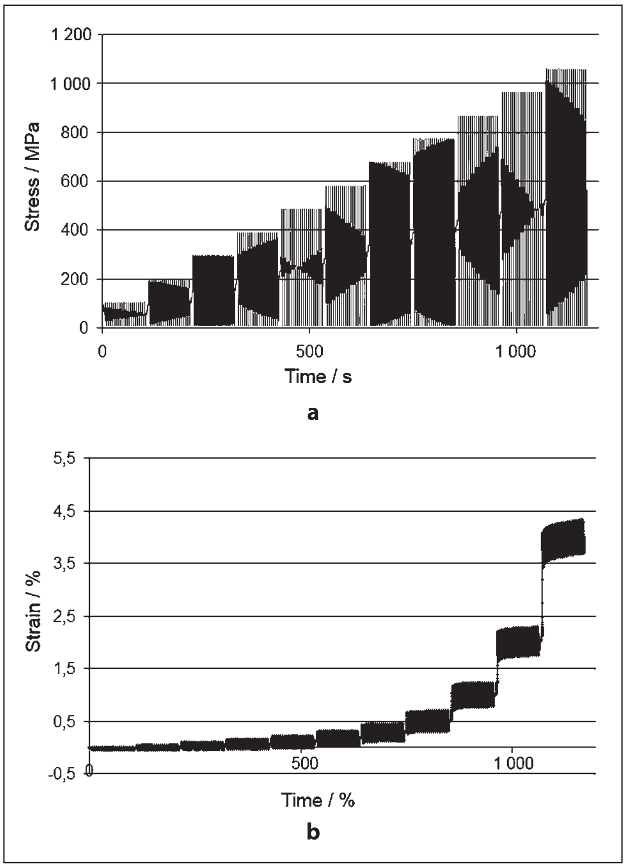

Figure 3 Examples of waveforms obtained by the MLCF test: a) the stress curve obtained for all „packages", b) the strain curve obtained for all „packages"

Table 4 **The results of MLCF test (40H steel)**

Sample No.	*E* /MPa	R_m /MPa	$R_{0,02}$ /MPa	$R_{0,2}$ /MPa	Z_{go} /MPa	R_a /MPa
St 21	103 000	1 032	909	-	500	1 012
St 22	106 000	1 032	923	-	508	1 028
Sample No.	*b*	*c*	ε max	*K'* /MPa	*n'*	
St 21	-0,06292	-0,51694	0,04972	1 710	0,14650	
St 22	-0,06157	-0,52272	0,04998	1 560	0,12909	

The numerical values of the mechanical parameters obtained are compared in Tables 4 and 5 for the 40H steel and Al 6082 alloy, respectively.

The selected fatigue parameters obtained by LCF and MLCF methods are compared with the data given in literature in Tables 6 and 7 for the 40H steel and Al 6082 alloy, respectively.

Table 5 **The results of MLCF test (Al 6082 alloy)**

Sample No.	E /MPa	R_m /MPa	$R_{0,02}$ /MPa	$R_{0,2}$ /MPa	Z_{go} /MPa	R_a /MPa
Al 21	52 000	494	253	259	139	469
Al 22	54 000	494	256	267	141	470
Al 36	78 000	547	348	372	192	544
Al 37	80 000	555	346	371	190	544

Sample No.	b	c	ε_{max}	K' /MPa	n'
Al 21	-0,11019	-0,60230	0,03800	579	0,09982
Al 22	-0,10878	-0,64658	0,03449	579	0,09802
Al 36	-0,09119	-0,76851	0,01885	742	0,13644
Al 37	-0.09306	-0,79649	0,01819	723	0,13006

Table 6 **Selected fatigue parameters for 40H steel in comparison with the literature data**

Fatigue parameters	Own results		Literature data	
	LCF	MLCF	LCF [11]	MLCF [4]
b	- 0,062	- 0,062	- 0,082	- 0,07
c	- 0,866	- 0,523	- 0,791	- 0,66
K'	1 077	1 560	1 269	808
n'	0,043	0,129	0,137	0,017

Table 7 **Selected fatigue parameters for Al 6082 alloy in comparison with the literature data**

Fatigue parameters	Own results		Literature data	
	LCF	MLCF	LCF* [12]	MLCF [4]
b	- 0,09241	- 0,09306	- 0,095	- 0,08650
c	- 0,8185	- 0,79649	- 0,690	- 0,68818
K'	591	723	940	639
n'	0,13113	0,13006	0,110	0,02671

The obtained results of the fatigue life tests carried out in accordance with the MLCF methodology described in detail in [4] give rise to a conclusion that there is a satisfactory agreement between fatigue parameters determined by the LCF method (literature data and own studies) and MLCF method (also literature data and own studies). Therefore, it can also be concluded that the MLCF method has been implemented correctly in the ITS Material Research Centre.

Microstructure of the tested 40H steel and Al 6082 alloy

Microstructure of the materials tested was examined by light microscopy. Based on the results of these examinations, it was found that the microstructure of the 40H steel included highly tempered fine-grain martensite (formerly sorbite) (Figure 4).

The microstructure of 40H steel is homogeneous in nature, does not exhibit the anisotropic properties, and non-metallic inclusions are below the reference standard No. 3 according to PN-84/H 04507-01.

The microstructure of Al 6082 alloy consists of a solid solution with different grain size and well-visible precipitates of the secondary phases of complex chemical composition, including fine precipitates of the a-Al (FeMn)Si phase of a globular shape shown in Figure 5. The observed differences in grain size had no appreciable effect on the resulting mechanical properties as determined by MLCF.

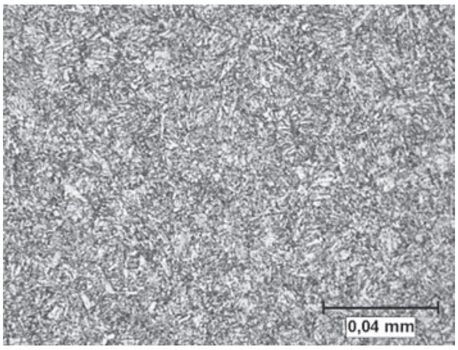

Figure 4 The microstructure of heat-treated 40H steel, etched, mang. 500 x

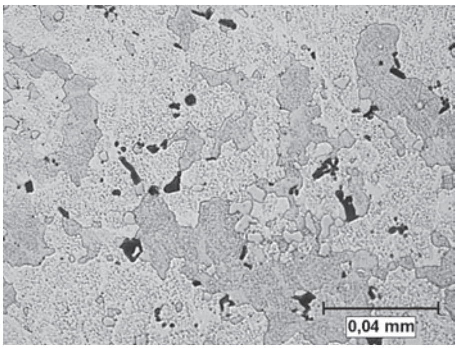

Figure 5 The microstructure of Al 6082 alloy, etched, mang. 500 x

CONCLUSIONS

Based on the results obtained and their comparison with data given in the literature it can be concluded that it is fully justified to implement in practical use the modified version of low-cycle fatigue test (MLCF). With regard to the 40H steel and Al 6082 alloy, a good agreement was achieved between fatigue parameters obtained in own research made by the common LCF test and its modified MLCF counterpart and data given in the literature for both LCF and MLCF testing techniques [4, 7, 8].

Attention deserves the fact that in the case of the common LCF method, a large number of samples is required to ensure the repeatability of the test results obtained. This condition can be satisfied only in the case of materials characterised by homogeneous structure (e.g. steel after the toughening treatment which shows a uniform dispersion of phases/constituents occurring in its structure).

The problem becomes much more complicated when fatigue testing is conducted on materials made by casting techniques, including composites. Then the presence of large microstructural heterogeneities can be expected that may affect the level and scatter of the values of the mechanical properties obtained.

The MLCF test requires the use of one sample only to simultaneously assess several mechanical parameters. This eliminates the negative impact of possible microstructural inhomogeneities on the reliability of the test results, and significantly reduces the time necessary for the test to be conducted. To carry out in a proper way the testing by MLCF, which requires the determination of threshold stresses at which the loading cycles are applied, the fatigue test is always preceded by static tensile test.

As already mentioned, owing to the use of MLCF, it becomes possible to obtain from a single measurement taken on a single sample, a set of several mechanical parameters, including the modulus of elasticity for different stress ranges (E_0, E_{10}, E_{80}, E_{180}), the apparent limits ($R_{0,02}$ and $R_{0,05}$, $R_{0,1}$, $R_{0,2}$), the tensile strength R_m, the fatigue strength at rotary bending Z_{go} and parameters characteristic of the low-cycle fatigue test (b, c, ε_{max}).

The application of MLCF method is thus very advantageous in all those cases in which the mere process of fabrication of a material or product is technologically difficult and/or expensive (e.g. composites). At the initial stage of the development of new manufacturing technologies it is very difficult to achieve the required reproducibility of the results and, if this is the case, the acquisition of data on several mechanical characteristics based on the measurements taken on a single sample only can be very valuable. Information obtained from such studies can provide important clues for further technological developments.

From the statements made above, a conclusion follows that it is recommended and advisable to continue the task of further intensive dissemination of the presented method for fatigue life assessment in the materials with an arbitrarily heterogeneous microstructure.

Acknowledgements

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Note: The responsible translator for English language is Krystyna Kowalska-Bany, Krakow, Poland