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Mechanical Characteristics of Ductile Iron Determined in an Original Modified Low Cycle test

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Abstract

The results presented in this article are part of the research on fatigue life of various foundry alloys carried out in recent years in the Lukasiewicz Research Network – Institute of Precision Mechanics and AGH University of Science and Technology, Faculty of Foundry Engineering. The article discusses the test results obtained for the EN-GJS-600-3 cast iron in an original modified low-cycle fatigue test (MLCF), which seems to be a beneficial research tool allowing its users to evaluate the mechanical properties of materials with microstructural heterogeneities under both static and dynamic loads. For a comprehensive analysis of the mechanical behaviour with a focus on fatigue life of alloys, an original modified low cycle fatigue method (MLCF) adapted to the actually available test machine was used. The results of metallographic examinations carried out by light microscopy were also presented. From the analysis of the results of the conducted mechanical tests and structural examinations it follows that the MLCF method is fully applicable in a quick and economically justified assessment of the quality of ductile iron after normalizing treatment.

Keywords: Iron, Mechanical properties, Microstructure

1. Introduction

Ductile iron is undoubtedly one of the leading construction materials. Normalizing and ferritizing annealing are the two basic types of heat treatment during which the structure of this cast iron is formed in a eutectoid transformation. Therefore any additional information about the impact of cooling speed in the range of eutectoid transformation on the structure formation in heat-treated cast iron is of fundamental practical importance. The aim of the normalizing treatment is to obtain the maximum possible content of pearlite ensuring high tensile strength (R_m up to 900 MPa) at an elongation AC of at least 2%, while the aim of the ferritizing annealing is to obtain a purely ferritic matrix, which gives the highest ductility (AC up to 22%) [1-2]. In this study, the focus was primarily on the possibilities of making a comprehensive evaluation of the mechanical characteristics based on the results of a modified low-cycle fatigue test (MLCF). The aim of the procedure described below and of the test results obtained using this procedure was to determine how homogeneous the mechanical characteristics of the tested normalized ductile iron are.

To assess the fatigue life, an original modified low-cycle fatigue test [10, 11, 12] (hereinafter referred to as MLCF) was used. As claimed by the authors of the study, this method may also serve as a tool for the quick estimation of other fatigue parameters. The microstructure was determined quantitatively based on a set of geometric parameters of its individual constituents.

2. Low cycle fatigue test (LCF) vs modified low cycle fatigue test MLCF)

When searching for data on fatigue strength, in particular on the fatigue strength of ductile iron, a lot of information can be found in the technical literature [3-10]. Various mechanisms related to the fatigue phenomenon, including microstructural conditions, are described [3-5], and the onset and propagation of fatigue cracks are related to the microstructure of cast iron metal matrix and morphological features of graphite precipitates [6-8]. Some of the studies also include the developed theoretical models predicting fatigue life at different temperatures [9-10]. Generally speaking, however, fatigue tests performed by the conventional low-cycle fatigue (LCF) method [11]) require at least 10 samples for testing, since the measurement data obtained from a single sample give only one point on the fatigue curve. This means that the accuracy of the method increases with the increasing number of samples. Additional complications arise when the examined material has any microstructural heterogeneities, as then even more samples are needed for a reliable analysis.

Considering all these drawbacks, a modified version of the low cycle fatigue test (MLCF) was developed. The MLCF method gives comprehensive information on numerous static and dynamic mechanical properties based on the measurements which are always taken on one sample only [12]. The fatigue limit (Z_{go}), necessary to calculate the test parameters, is determined from a test curve developed for different types of materials [13].

3. Test materials and methods

Tests were carried out on the EN-GJS-600-3 ductile iron after normalizing treatment, applying the annealing temperature of about 900-925ºC and rapid air cooling. In this way, a fully pearlitic microstructure was obtained.

The ductile iron was subjected to mechanical tests and to qualitative and quantitative microstructure examinations.

3.1. Microstructure examinations

The microstructure of cast iron was examined by light microscopy using a NIKON ECLIPSE LV150 microscope with image analyzer. Geometric parameters of the cast iron microstructure were determined by the combinatorial method described in detail in [14, 15]

3.2. Mechanical properties

To estimate the parameters typical of low cycle tests, a modified low cycle fatigue test (MLCF) was applied [12,13], and the following relationships known from the conventional low cycle fatigue test (LCF) were used:

$$\sigma_a = K^{'} (\varepsilon_p)^{n'} \tag{1}$$

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

$$\varepsilon_p = \varepsilon^{'}_f (2N_f)^c \tag{3}$$

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

The fatigue limit Z_{go} necessary for the calculation of sample parameters was evaluated from an experimental curve (Fig. 1) plotted for a variety of materials ranging from pure metals to iron alloys and non-ferrous metal alloys [12, 13, 16].

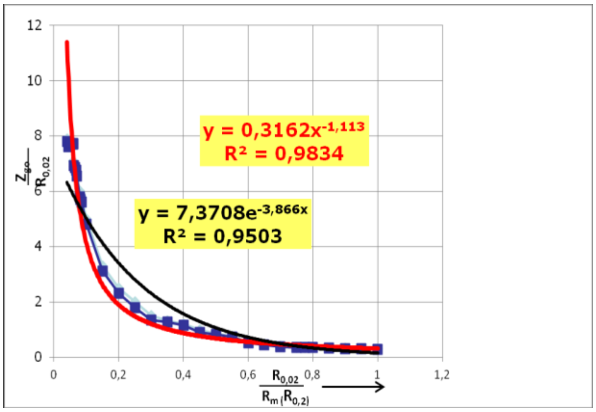


Fig. 1. Curve for fatigue strength evaluation [12, 13, 16].

To determine the values of *b, c, n', K* and ε_{max}, the following assumptions were adopted [12, 13, 16]:

- the disorders in a uniaxial stress field under compression are eliminated by application of one-sided cycles during tension in the fatigue test,
- the relationship between permanent set, induced by the adopted low number of cycles, and cycle amplitude is the same as in the case of the strain after sample failure [12, 13],
- the mechanical properties mentioned at the beginning of this chapter are determined on one sample only,

- the straight waveforms in a double logarithmic scale according to equations (2) and (3) are determined from the position of points with coordinates:
  [ln 20, ln R_m] and [ln ($2N_f$), ln (Z_{go})]: equation (2) and [ln20, ln ε_f] and [ln ($2N_f$), ln ε_z]: equation (3),
- the evaluation of fatigue strength under rotational bending is carried out in accordance with [12, 13].

Figures 2a and 2b show graphical interpretation of the Basquin's exponent *b* based on the results obtained in the conventional low cycle fatigue test (LCF) and its modified version (MLCF), respectively.

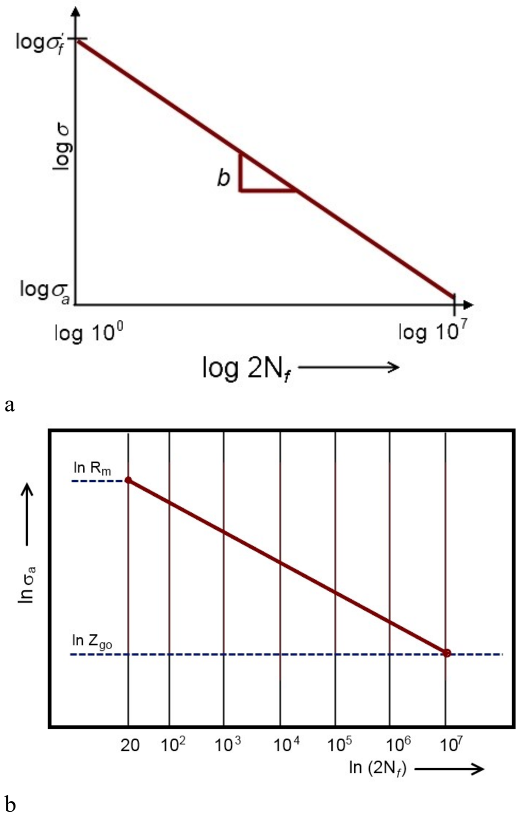


Fig. 2. Graphical interpretation of the Basquin's exponent *b:* a - according to LCF, b - according to MLCF

Figures 3a and 3b show graphical interpretation of the fatigue ductility exponent *c* based on the results obtained in the conventional low cycle fatigue test (LCF) and its modified version (MLCF), respectively.

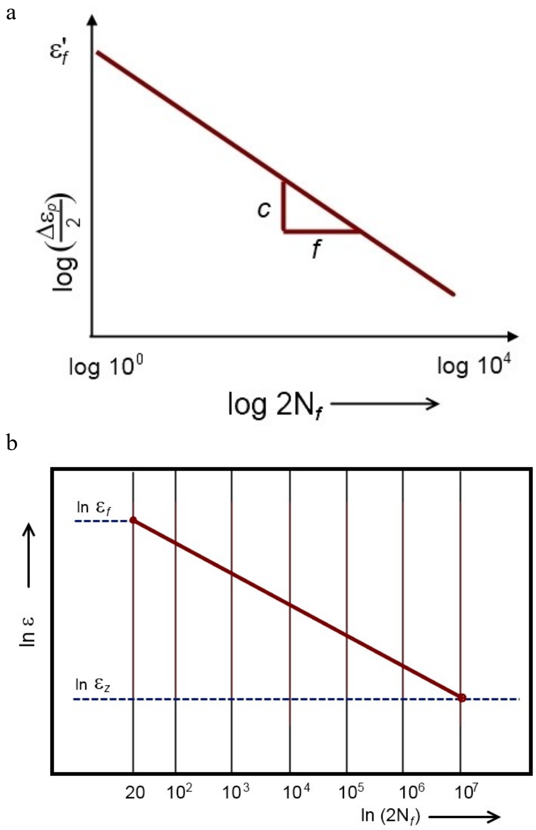


Fig. 3. Graphical interpretation of the fatigue ductility exponent *c:* a - according to LCF, b - according to MLCF

Figure 4 shows the essence of fatigue test in its two embodiments, i.e. conventional and modified (LCF and MLCF, respectively). The maximum permanent set is here a criterion value which, determined for a given material, should not be exceeded during operation, as it is the permissible limit value. This value is comparable with a dangerous state of deformation, which can be determined from performance hypotheses (e.g. Huber-Mises-Hencky) expressed in strains [17].

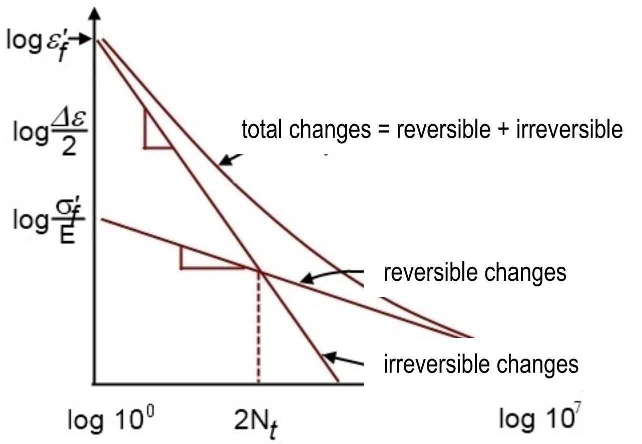


Fig. 4. Fatigue life graph in logarithmic coordinates ($\varepsilon_{max.} \cdot 10^6$)

4. Research results

The following subsections discuss the results of the mechanical tests and microstructure examinations.

4.1. Mechanical properties

The mechanical properties of EN-GJS-600-3 cast iron were determined from the results of fatigue tests carried out in accordance with the MLCF procedure [10, 11]. The results of the measurements are presented in Tables 1 and 2.

Table 1.
Mechanical parameters of EN-GJS-600-3 cast iron - MLCF method

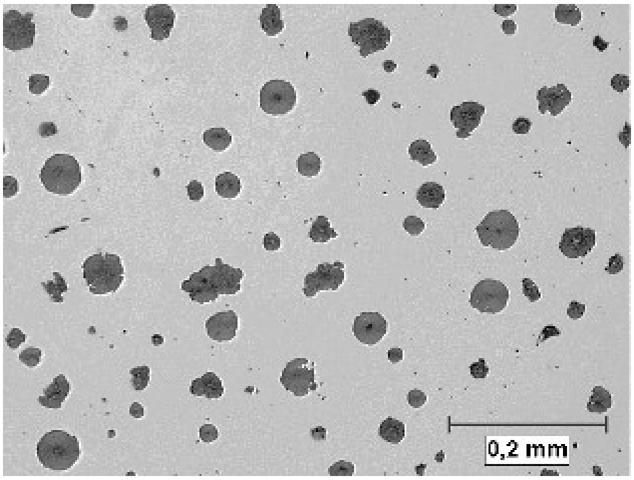
No.	E	UTS	$R_{0.02}$	$R_{0.2}$	Z_{go}	R_a
	GPa	MPa				
1	198	569	339	479	189	534
2	194	557	341	469	186	533
3	179	533	343	487	191	492
4	199	601	348	486	192	573
5	193	493	308	484	183	492
6	180	533	344	488	192	492
7	180	492	431	446	182	452
8	190	573	411	489	226	532
Avg	189	544	358	479	193	513
S	8	39	41	15	14	38
Coefficient of Variation (CV) [%]	4	7	11	3	7	7

Table 2.
Mechanical parameters of EN-GJS-600-3 cast iron - MLCF method

No.	b	c	n’	K’ MPa	$\varepsilon_{max}\cdot 10^6$
1	-0.096	-0.446	0.106	933	1069
2	-0.095	-0.535	0.091	849	899
3	-0.089	-0.343	0.171	1461	1156
4	-0,099	-0,525	0,104	939	1001
5	-0,086	-0,364	0,15	1267	1005
6	-0,089	-0,333	0,155	1345	1116
7	-0,087	-0,360	0,16	1318	977
8	-0,081	-0,569	0,092	873	1141
Avg	-0.090	-0.434	0.129	1123	1046
S	0.006	0.097	0.033	248	90
Coefficient of Variation (CV) [%]	7	22	26	22	9

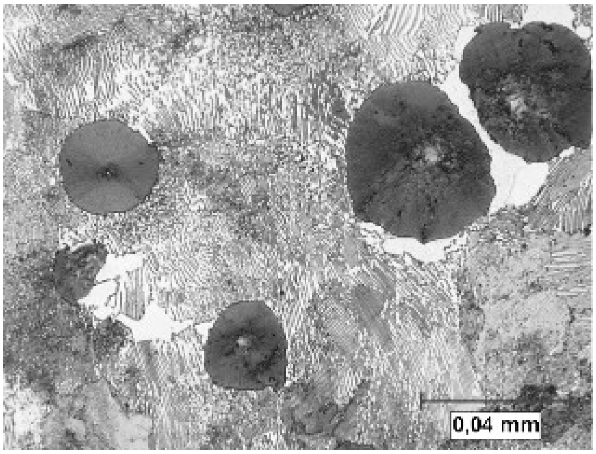
4.2. Microstructure characteristics

Figure 5 shows the microstructure of ductile iron as seen under a light microscope. This is the microstructure typical of cast iron after normalizing treatment. It consists of graphite precipitates in the unetched state (Fig. 5a) and a pearlitic matrix in the etched state with scarce precipitates of ferrite distributed mainly around the graphite precipitates (Fig. 5b).



a)

Fig. 5. Microstructure of EN-GJS-600-3 cast iron: a) unetched state, 100x, b) etched state, 500x



b)

Fig. 5. Microstructure of EN-GJS-600-3 cast iron: a) unetched state, 100x, b) etched state, 500x.

Due to small differences observed in the pearlitic matrix, quantitative studies of cast iron microstructure were limited to graphite precipitates. The following geometric parameters were determined: $A_A = V_A$ [%] - volume fraction, N_L - relative surface estimators, Ω - coefficient of microstructural anisotropy, l_{avg}- average chord, F_{avg} - average Feret's diameter (Table 3).

Table 3.
Geometric parameters of graphite in EN-GJS-600-3 cast iron

No.	A_A	N_L	N_A	Ω_{avg}	F_{avg}	l_{avg}
	%	1/mm	1/mm^2		µm	µm
1	10	65	682	1	9	16
2	10	61	687	1	9	17
3	10	67	829	1	8	15
4	10	64	670	1	9	16
5	11	65	845	1	9	15
6	10	61	695	1	9	17
7	10	68	820	1	8	15
8	11	62	636	1	9	14
Avg	10	64	733	1	9	16
S	1	3	84	0	1	1
Coefficient of Variation (CV) [%]	5	5	11	0	11	6

The data shows that most of the measured geometric parameters of graphite precipitates have remained nearly unchanged, as the coefficients of variation are less than 10%. Only coefficients of variation of the geometric parameters N_A and F take a higher value equal to 11% (Table 3). For the determined mechanical parameters $R_{0.02}$, c, n', K (Table 2), the coefficients of variation also take values higher than 10% (11%, 22%, 26% and 22% respectively). It can therefore be concluded that the mechanical parameters mentioned above are much more structure-sensitive than other parameters.

5. Conclusions

1. The results of the tests and analyses carried out have demonstrated that most of the determined mechanical parameters and geometric parameters of the microstructure show little variation, as evidenced by the values of the measured coefficients of variation.
2. In terms of the static and dynamic mechanical behaviour, four mechanical parameters have turned out to be the most structure-sensitive, i.e. $R_{0.02}$, c, n' and K.
3. Larger variations in the parameters $R_{0.02}$, c, n' and K are the result of variations in the size of graphite precipitates in cast iron (parameters N_A and F).
4. The MLCF method can serve as an efficient tool for quick and economically justified determination of the cast iron quality after normalizing treatment, depicting its mechanical characteristics and microstructure.
5. The results obtained suggest that similar results can be expected when testing other materials.

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