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Fatigue Life Assessment of Selected Engineering Materials Based on Modified Low-Cycle Fatigue Test

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Abstract

In this study, the mechanical tests were carried out on ductile iron of EN-GJS-600-3 grade and on grey cast iron of EN-GJL-250 grade. The fatigue life was evaluated in a modified low-cycle fatigue test (MLCF), which enables the determination of parameters resulting from the Manson-Coffin-Morrow relationship.

The qualitative and quantitative metallographic studies conducted by light microscopy on selected samples of ductile iron with spheroidal graphite and grey cast iron with lamellar graphite (showing only small variations in mechanical properties,) confirmed also small variations in the geometrical parameters of graphite related with its content and morphological features.

Keywords: Fatigue resistance, Low-cycle fatigue test (LCF), Material constants

1. Introduction

Fatigue characteristics of materials/products are always in the centre of interest of both science and engineering practice. This is due to at least two reasons. First, the dynamic development of modern manufacturing technology needs testing of the received materials for their optimal performance to enable their well-justified application in the manufacture of ready products recommended for a wide range of design solutions. Second, the dynamic technical development and constantly increasing opportunities for exchange of technical/scientific ideas that potentially might encourage the emergence of modern technologies also increase expectations regarding the applied research methods. Indeed, their effectiveness depends primarily on the proven reliability of the results obtained but also on the complexity of the obtained material characteristics (performance included) and the speed of obtaining them at the lowest possible cost. Hence, for example, follows the, observed for many years, trend in research procedures that tries to replace costly and time-consuming technical tests with non-destructive methods [1,2,3,4]. Unfortunately it is not always possible to use such methods, the obstacle may be, if nothing else, at least e.g. the lack of ferromagnetic properties in the tested materials. In such cases, the only solution is to continue searching for such methods of evaluation of the functional criteria, which can be regarded as competitive economically and technically compared to the ones used up to now.

Up to date, most data on the fatigue characteristics have been obtained from the well-known high- and low-cycle fatigue tests (HCF and LCF, respectively). Further part of this study gives examples of the results of such research when related to various structural materials.

In [5], the characteristics of cyclic stress, the resistance to deformation and fracture mechanism were examined in 2524 aluminium alloy. Alloy specimens were subjected to test cycles at ambient temperature and elevated temperature applying tensile-compressive load (with load factor equal to 1.0), under the conditions of total strain control, above the range of plastic strain, giving less than 104 cycles to rupture. The results of the study proved that the examined alloy in the form of a wrought plate showed a mixed hardening and softening behaviour in both directions, i.e. longitudinal and transverse.

Much attention has been paid to the alloys of magnesium used in the automotive industry, aerospace and electronics due to their low weight and high strength-to-weight ratio. For example, in [6] studies were carried out on the fatigue behaviour of AZ61 magnesium alloy produced by squeeze casting. Fatigue tests (based on low cycle fatigue test - LCF) were performed on smooth cylindrical specimens under completely controlled plastic strain. The standard tensile curve was compared with the cyclic stress-strain curve. A comparison made by the authors of [6] has indicated that the tested material exhibits cyclic hardening throughout the entire period of its operation. The resulting measurement data were used to evaluate the Manson-Coffin and Woehler-Basquin curves, and to fit them with the corresponding functions of regression, to determine the fatigue parameters next.

In [7], the fatigue properties of extruded AZ31B magnesium alloy were determined at room temperature, using strain-controlled tension-compression test for different amplitudes of total strain. The tested alloy exhibited an asymmetric sigmoidal-shaped (S-shaped) hysteresis loop due to twinning in compression during the unloading phase, and detwinning during the loading phase. The authors showed that the total strain amplitude, the asymmetry of hysteresis loop, the amplitude of plastic strain, mean stress and stress amplitude increased, while the ratcheting strain and pseudoelastic modulus decreased. The authors of [7] have found that the fatigue life of the tested alloy can be described with the Coffin-Manson and Basquin relationship.

On the other hand, studies disclosed in [8] summarise the results of extensive research conducted by the authors on the resistance to cyclic deformation, low-cycle fatigue life and fracture mechanism in three rapidly solidifying magnesium alloys. Magnesium alloy specimens were subjected to cyclic deformation with a fully reversible total strain amplitude, controlling deformation above the range of strain amplitudes, which gave less than 104 cycles to failure. The characteristics of cyclic stress response, strain resistance and low cycle fatigue behaviour of alloys have been discussed in terms of the alloy composition, and it has turned out that to all three alloys the Coffin-Manson and Basquin relationship shall apply.

The mechanism of low cycle fatigue behaviour in precipitation hardened nickel-based superalloy (720Li) with low concentration of the interstitial carbon and boron was studied at 25, 400 and 650°C [9]. Based on the results of the studies it was found that at all the three above mentioned temperatures, the corresponding cyclic stress was stable at a fully reversible constant amplitude of total strain ($\Delta\varepsilon/2$), where $\Delta\varepsilon / 2 \leq 0.6\%$. For $\Delta\varepsilon / 2 > 0.6\%$, cyclic hardening followed softening until fracture occurred at 25 and 650°C. However, it was also found that at 400°C, after initial hardening, the cyclic stress was stabilised. The results of some studies prove a classic approach to the determination of fatigue characteristics when based on HCF and LCF tests. In recent years, studies have also appeared that attempt a different approach to the determination of the fatigue life of materials/products [10,11], including those based on hardness testing [12] or applying the idea of neural networks [13,14].

In this paper, the fatigue life assessment was based on the author's modified low cycle fatigue test [15,16] (hereinafter referred to as MLCF), assuming that this method can be competitive to the ones used previously.

2. Test materials and methods.

In this study, the mechanical tests were carried out on ductile iron of EN-GJS-600-3 grade and on grey cast iron of EN-GJL-250 grade. The fatigue life was evaluated in a modified low-cycle fatigue test (MLCF) [15,16,17], which enables the determination of parameters resulting from the Manson-Coffin-Morrow relationship:

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

$$\sigma_a = \sigma'_f (2N_f)^b \quad (2)$$

$$\varepsilon_p = \varepsilon'_f (2N_f)^c \quad (3)$$

where:

σ_a – the stress amplitude,

σ'_f – the, so called, “fatigue strength coefficient” roughly equal to the tensile strength R_m,

ε_f – the fatigue ductility coefficient (the true strain caused by the stress σ'),

$2N_f$ – the number of loading cycles to specimen failure,

ε_p – the permanent (true) strain caused by the $2N_f$ loading cycles where: $\varepsilon_p = \ln(1 + \varepsilon_k)$, and where, in turn, $\varepsilon_k = \Delta l_{trwale} / l_0$,

K' – the cyclic strength coefficient,

n' – the cyclic strain hardening exponent,

c – the fatigue ductility exponent, after the adoption of assumptions discussed below.

The fatigue strength Z_{go}, necessary for the calculation of test parameters, is evaluated from the experimental diagram (Fig. 1) prepared for a diverse group of materials, ranging from pure metals to alloys of ferrous and non-ferrous metals [15].

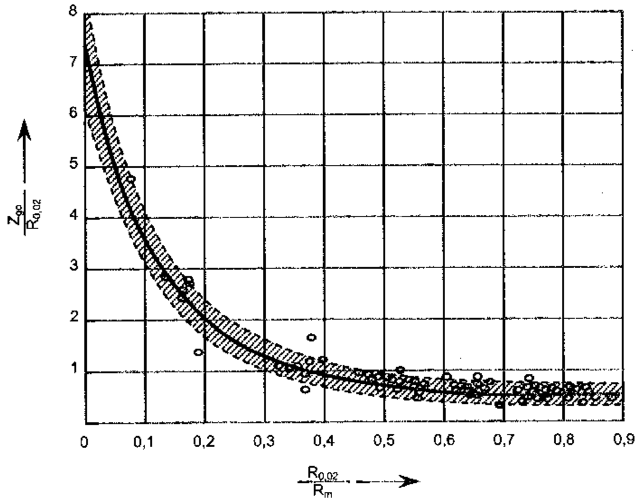


Fig. 1. Curve used in fatigue strength assessment [15]

To determine the value of b, c, n' and K, as well as ε_{max}, the following assumptions have been adopted [15,16]:

- disorders in the uniaxial compressive stress field are eliminated through the use of unilateral cycles (during tension) in the fatigue test,
- the permanent strain caused by the adopted low number of cycles (e.g. twenty load-unload cycles) shows the same dependence on cycle amplitude as the strain after the specimen failure, the more that the permanent strain after 20 cycles shows with the increasing number of cycles either an insignificant change only or does not change at all [15,16],
- the mechanical properties mentioned at the beginning of this chapter shall be determined on one specimen only,
- the runs of the straight lines in equations (2) and (3) in a double logarithmic scale are determined from the location of points with the coordinates:

[ln20,lnR_m] and [ln($2N_f$)ln(Z_{go})] in the case of equation (2) and [ln20,lnε_f] and [ln($2N_f$)lnε_Z] in the case of equation (3),

- the rotating bending fatigue strength is tested according to [15,16].

All the quantities mentioned above are obtained during testing of one specimen only, and this is the most valuable aspect of the whole method, since all the static mechanical parameters as well as those responsible for the low-cycle fatigue behaviour of the examined material enable its precise characterisation regardless of how inhomogeneous it may be.

3. Results and discussion in context of the literature data.

The results of fatigue tests carried out on ductile iron and grey cast iron are shown in Tables 1 and 2, respectively, while an example of the stress-strain relationship during specimen cycling is illustrated in Figure 2.

Table 1.
The mechanical properties of ductile iron (with spheroidal graphite) as obtained in an MLCF test

No.	R_m [MPa]	$R_{0,02}$ [MPa]	$R_{0,2}$ [MPa]	R_a [MPa]	Z_{go} [MPa]	b	c	n'	K [MPa]	$\varepsilon_{\cdot max}$
1	569,5	339,4	478,8	533,6	188,5	-0,0960	-0,4456	0,1060	933,9	**0,01069**
2	556,7	340,7	469,3	533,0	186,0	-0,0952	-0,5349	0,0907	848,9	**0,00899**
3	532,8	342,7	487,3	492,3	191,4	-0,0889	-0,3426	0,1708	1461,9	**0,01156**
4	603,8	347,9	485,9	573,1	191,8	-0,0996	-0,5249	0,1039	938,7	**0,01001**
5	492,7	308,2	483,5	491,9	182,8	-0,0861	-0,3635	0,1497	1267,2	**0,01005**
6	532,7	343,5	488,1	492,4	191,8	-0,0887	-0,3326	0,1547	1345,6	**0,01116**
7	492,0	430,9	446,4	451,8	181,8	-0,0865	-0,3603	0,1597	1318,2	**0,00977**
8	573,2	411,1	489,1	532,4	226,1	-0,0808	-0,5692	0,09174	872,9	**0,01141**

Table 2.
The mechanical properties of grey iron (with lamellar graphite) as obtained in an MLCF test

No.	R_m [MPa]	$R_{0,02}$ [MPa]	$R_{0,2}$ [MPa]	R_a [MPa]	Z_{go} [MPa]	b	c	n'	K [MPa]	$\varepsilon_{\cdot max}$
1	193,1	82,2	143.3	175,1	51,3	-0,1151	-0,4816	0,20198	599,1	**0,00432**
2	200,5	106,0	156,3	173,3	60,7	-0,1038	-0,3846	0,2035	603,8	**0,00746**
3	199,4	80,5	142,5	175,5	50,7	-0,1189	-0,6204	0,1909	550,3	**0,00372**
4	196,5	71,1	157,0	173,8	54,9	-0,1108	-0,3119	0,2103	642,3	**0,00907**
5	192,9	61,8	153,3	491,9	55,3	-0,1085	-0,3686	0,1906	535,3	**0,00786**

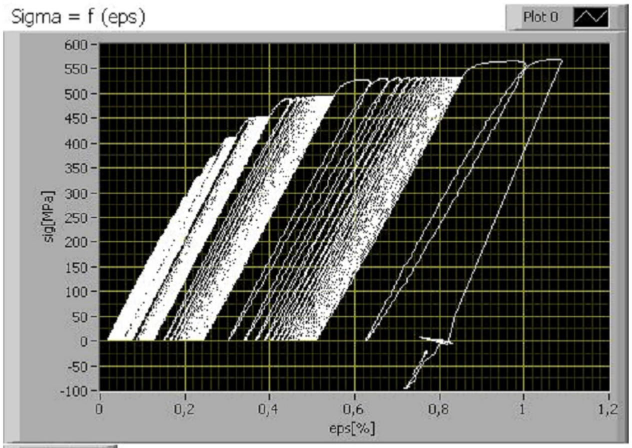


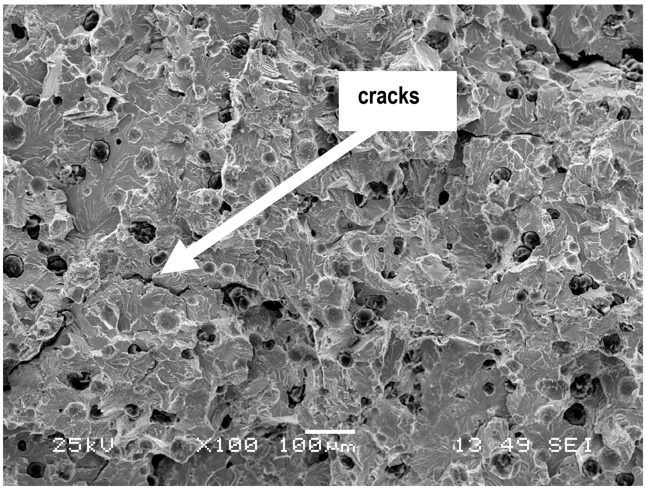
Fig. 2. The stress-strain diagram obtained during specimen cycling according to MLCF methodology. EN-GJS-600-3

Further part of the study shows fractures of selected specimens (Fig. 3). The fractures obtained in an MLCF test are of similar quality and can be classified as brittle ones.

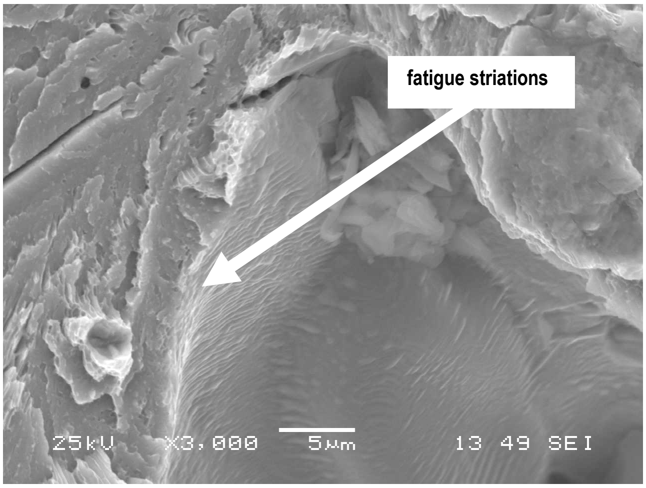
At higher magnifications, smooth fragments of the fracture forming cleavage planes are visible, as well as cracks and tears, which in ductile iron are much smaller compared with the grey cast iron, grade 250 included.

Attention draws the heterogeneity of fractures resulting from the morphologies of graphite precipitates present in the examined cast iron, the traces of which are visible on these fractures.

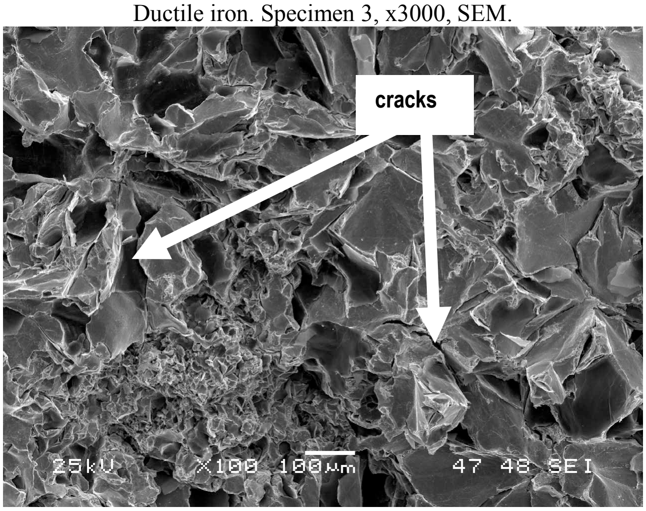
The visible cleavage planes are much larger in ductile iron, which should be associated with the distance between spheroids larger in this cast iron than the interlamellar spacing in grey cast iron, grade 250 included. At higher magnifications, fatigue striations appear as well.



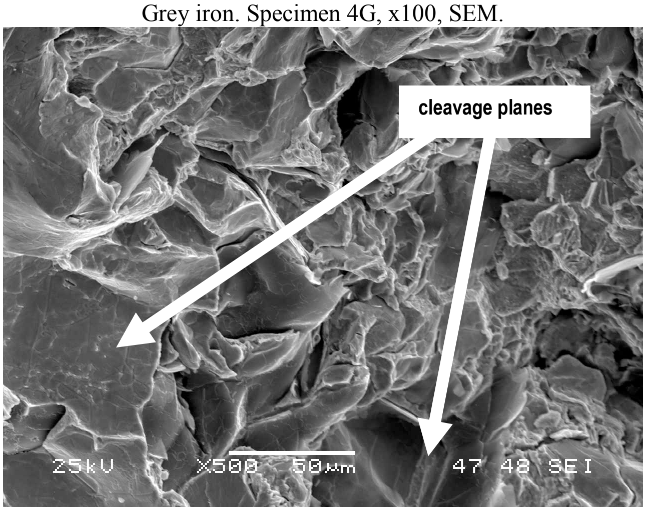
Ductile iron. Specimen 3, x100, SEM.



Ductile iron. Specimen 3, x3000, SEM.



Grey iron. Specimen 4G, x100, SEM.



Grey iron. Specimen 4G, x500, SEM.

Fig. 3. Examples of fractures obtained in ductile iron with spheroidal graphite and in grey cast iron with lamellar graphite

The qualitative and quantitative metallographic studies conducted by light microscopy on selected samples of ductile iron with spheroidal graphite and grey cast iron with lamellar graphite (showing only small variations in mechanical properties,) confirmed also small variations in the geometrical parameters of graphite related with its content and morphological features.

At the same time, previous experiences resulting from own studies also based on the proposed MLCF method have shown that to the large scatter of mechanical characteristics is corresponding a large scatter of the geometrical parameters of the individual microstructural constituents [16]. From the conducted studies [16] it follows that the undesired microstructural features are the cause of a deterioration of the mechanical properties determined by the MLCF test technique. This seemingly obvious statement would not be so interesting if not for the fact, emphasized also in [15 and 16], that the results of mechanical tests done by MLCF are collected on one specimen only, and yet they are consistent with the results of structure examinations. Hence it follows that the MLCF test proposed as a means for the fatigue life assessment is a tool much more reliable than the standard LCF test method used so far, the latter one demanding, especially in the case of materials with heterogeneous microstructure, very careful methodological approach to meet the required condition of being representative.

4. Conclusions

The conducted studies as well as the experience gained from previous research enable formulating the following conclusions:

- the fatigue life assessment based on the proposed MLCF test consumes much less time than the methods used so far,
- the proposed method is universal in nature because, without having to increase the number of specimens, reliable evaluations can be made also for structurally heterogeneous materials, and even in such cases one specimen is sufficient,
- applying the MLCF method, one specimen is sufficient to have several dozen mechanical parameters examined in one test,
- the proposed method can be considered a competitive economic alternative.

5. Summary and recommendations for the future

In view of the permanently stressed advantages of the MLCF method it seems reasonable and justified to claim the advisability of its gradual introduction to routine monitoring of the performance of materials and finished products in various areas of their application. At the same time it should be emphasized that the proposed method can be particularly useful in all those cases where considerable difficulties may arise in ensuring adequate sampling frequencies, required in the standard LCF method. Such difficulties may arise, e.g. in the case of expensive high-tech manufacturing technologies, in piece production, etc. In addition, one of the author's studies [18] has demonstrated the compliance of the results obtained by MLCF test conducted on selected materials with the corresponding characteristics obtained by the LCF test described in reference literature [18], which confirms positive verification of this method and additionally supports an argument for its introduction into wide practice.

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