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Elevated temperature low cycle fatigue of grey cast iron used for automotive brake discs

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ABSTRACT

This paper evaluates the fatigue life properties of low carbon grey cast iron (EN-GJL-250), which is widely used for automotive brake discs. Although several authors have examined mechanical and fatigue properties at room temperatures, there has been a lack of such data regarding brake discs operating temperatures. The tension, compression and low cycle fatigue properties were examined at room temperature (RT) and at brake discs' working temperatures: 500 °C, 600 °C and 700 °C. The microstructure of the material was documented and analysed. Tensile stress–strain curves, cyclic hardening/softening curves, stress–strain hysteresis loops, and fatigue life curves were obtained for all the above-mentioned temperatures. It was concluded, that Young's modulus is comparable with both tension and compression, but yield its strength and ultimate strength are approximately twice as great in compression than in tension. All the mechanical properties remained quite stable until 500 °C, where at 700 °C all deteriorated drastically. During fatigue testing, the samples endured at 500 °C on average at around 50% of cycles at room temperature. Similar to other materials' properties, the cycles to failure have dropped significantly at 700 °C.

1. Introduction

Along with the improved power performances and higher speeds achieved by vehicles over recent years, brake systems have been required to meet conflicting requirements for stable braking performance and quality. Brake discs, in general, count as in-constructed safety components. Therefore, their reliability during service is essential. Disc brakes are exposed to large thermal stresses during routine braking and extreme thermal stresses during hard braking. It is not unusual for the temperatures at the brake disc surface to reach 700 °C and even more [1]. Such severe thermal processes modify the friction properties of the materials during contact, cause wear, and on a larger scale, result in brake disc deflection and cracking. All these changes inevitably affect brake performance and life. Analyses have shown that the thermal cracking of automotive disc brakes is a low cycle thermo-mechanical fatigue and occurs on the brake disc's friction surface [2].

In order to ensure safe operations of brake discs during their entire fatigue lives, all of them must pass severe homologation fatigue testing. The problem is that such validation is very time-consuming and expensive. In addition, the tests cannot be performed during the early pre-development phases. Therefore, over recent times, numerical prediction of fatigue life has become available due to the cost reductions and speed increases of the computational systems [3–6]. Such methodology of validating the brake disc is very practical but detailed mechanical and fatigue material properties are needed.

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Although over recent years new advanced materials have been developed, such as MMC (metal matrix composite), carbon-ceramic, carbon–carbon, and others, graphite flake cast iron has long been used as the material for brake discs because of its overall excellence regarding thermal fatigue strength, anti-squeal and anti-vibration characteristics, low cost, and wear resistance [4]. In the case of small and medium-sized vehicles, low carbon graphite flake grey cast iron (EN-GJL-250) is widely used as it provides optimal mechanical and thermal properties [7]. The same grade of grey cast iron is also used for other automotive parts such as cylinder blocks, pump housing, and valve bodies, where tensile strength is non-critical. Several studies have been carried out with the aim of obtaining properties of EN-GJL-250 grey cast iron. Yamabe et al. [7] investigated the thermal fatigue strength of grey cast iron by simulating high-speed braking tests using an actual brake disc. Based on this study, they developed a new, low cost material for brake discs using some additives.

Kim et al. [3] conducted high cycle fatigue tests of the EN-GJL-250 material at room temperature (RT) and at 300 °C. The tests were performed at a constant amplitude loading at a frequency of 10 Hz. They found that the difference at that temperature hardly affected the fatigue strength. The *S–N* (stress amplitude vs. cycles to failure) data they obtained can serve for the high cycle fatigue prediction, but are inappropriate for the low cycle fatigue prediction, which is the case in the presented analysis. The authors also concluded, that the yield strength and the ultimate tensile strength of the cast iron for the brake disc was hardly changed up to 300 °C. The work also lacks material properties during compression.

Maluf et al. [4] conducted low cycle isothermal and thermo mechanical fatigue tests performed on four grey cast iron alloys with different chemical compositions that are used in the production of automotive brake discs. The samples were taken from casted Y-shaped blocks. The tests were conducted only at a deformation amplitude of 0.3% and at temperatures RT, 300 °C and 600 °C and were therefore incomplete for usage in numerical predictions of fatigue life. The results showed the alloys under study did not show a significant difference at RT, 300 °C, and 600 °C, as indicated by the ε–*N* (strain amplitude vs. cycles to failure) curves. The carbon equivalent (CE) was apparently uncorrelated with the fatigue life.

Šamec et al. [8] published a study of the low cycle fatigue material properties of EN-GJS-500-7 nodular cast iron used for the production of railway brake discs. The temperature and strain ranges were chosen to enable universal usage of the materials' properties during brake disc fatigue estimation in most braking procedures. Nevertheless nodular cast iron is, due to its cost and low damping properties, rarely used within the automotive brake industry and therefore the results cannot be used for estimating an automotive brake disc's fatigue life.

Grey cast iron is part of a group of materials that can be produced for having a wide-range of properties through controlling the microstructure. The mechanical properties of grey cast irons are directly related to their matrix microstructure. The as-cast matrix microstructures of grey cast irons is often entirely pearlitic, with graphite lamellas finely distributed in the matrix.

When analysing the materials' properties, it is important to measure the materials' parameters within a the temperature range where the material will be operating or will be tested, in order to be able to optimise the construction made from that material – in our case, the brake disc. The results shown from this research are to the best of the authors' knowledge, the first published detailed low cycle fatigue material properties of EN-GJL-250 grey cast iron at brake disc operating temperatures. The presented data is therefore essential when predicting the low-carbon grey cast brake disc low cycle fatigue life, particularly during the standard brake disc fatigue homologation tests. The reason for a lack of such data is that the low cycle fatigue tests at elevated temperatures are very time consuming and very costly due to the need for a special-purpose testing machine.

The main aim of the presented study was to investigate the mechanical properties and low cycle fatigue (LCF) behaviour of grey cast iron EN-GJL-250 at room and elevated temperatures. Constant amplitude axial fatigue tests provided the necessary information about the strain–life curve and cyclic stress–strain behaviour of the material. As previously used in our research [9,10], a reasonably expected fatigue life (number of cycles to crack initiation N_i), could be determined iteratively using the Coffin–Manson equation [11]:

$$\varepsilon_a = \frac{\Delta\varepsilon_e}{2} + \frac{\Delta\varepsilon_p}{2} = \frac{\sigma_f'}{E} \cdot (2 \cdot N_i)^b + \varepsilon_f' \cdot (2 \cdot N_i)^c, \qquad (1)$$

where ε_a is total strain amplitude, $\Delta\varepsilon_e$ and $\Delta\varepsilon_p$ are the elastic and plastic strain ranges, *E* is Young's modulus, σ_f' the fatigue strength coefficient, *b* the fatigue strength exponent, ε_f' the fatigue ductility coefficient, and *c* the fatigue ductility exponent. Eq. (1), called the "Coffin – Manson equation", is the foundation for the strain-based approach for fatigue life prediction.

2. Experiment

Using brake dynamometer testing and finite element method (FEM) analyses, it was discovered that during the standard brake disc fatigue homologation test, also known as the "crack test" [12], the maximum temperatures reached were between 500 °C and 700 °C. The results of this study will be published subsequently. The maximal temperature was reached at the brake disc rubbing surface and depended on the brake disc geometry, vehicle inertia, effective diameter, etc. Room temperature (RT) and temperatures 500 °C, 600 °C and 700 °C were chosen for the experiments in order to ensure that the presented material properties could be universally employed when predicting the brake disc fatigue lives of most automotive brake discs.

Table 1
Chemical composition of the brake disc material (EN-GJL-250).

Element	CE	C	Si	Mn	P	S	Cr
weight%	4.02	3.32	2.11	0.56	0.055	0.09	0.098

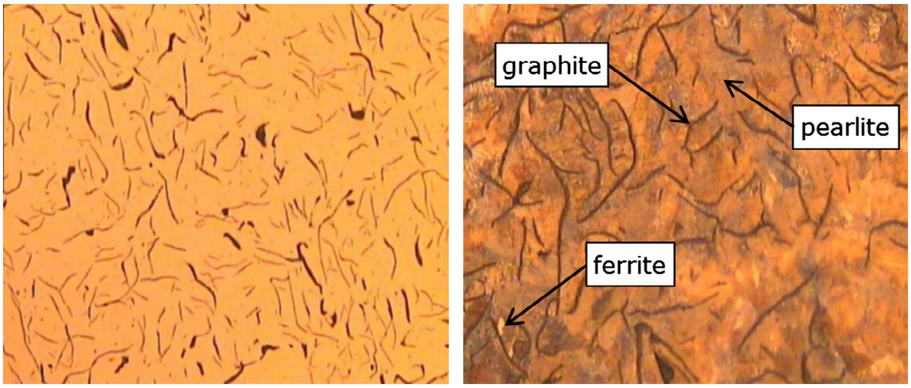

Fig. 1. Microstructure of the material at RT; left: un-etched, 100×; right: etched, 200×.

The specimens for metallographic examinations, static and fatigue tests were taken from the actual brake discs. On each brake disc, three specimens were taken from the outer friction plate (orientation as in the location in the vehicle) and three from the inner friction plate. All the brake discs used in this research were cast in the same batch. Table 1 shows the actual chemical composition of the discussed material.

A metallographic analysis was carried out in order to investigate the material's microstructure. Samples were metallographically prepared and observed using an optical microscope in both non-etched and etched with 2% nital solution. Fig. 1 shows the micrographs of the material at the inner friction plate. The microstructure consisted of a pearlite matrix with graphite flakes (dark areas). Some traces of ferrite were also visible (white areas located next to the graphite flakes). Some characteristics of the microstructure are shown in Table 2. For the desired heat transfer properties the flakes should be as large in as non-oriented ("A" type – eutectic graphite) as possible. In addition, for the desired fatigue properties, the flakes should be as non-oriented but as small as possible, as graphite flakes represent micro cracks, which results in low tensile ultimate strength and in undesired fatigue properties. Therefore, the microstructure of a grey cast iron is always a compromise between thermal and fatigue properties.

The monotonic tensile and compression tests were done for evaluating the mechanical properties of the material. The tensile and compressive tests were carried out at RT, 500 °C, 600 °C, and 700 °C, where four specimens were tested at each temperature. The results were then analysed using the Weibull probability theory, but only those with 50% probability are presented in this paper. Cylindrical specimens, 7 mm in diameter, with gauge lengths of 50 mm were prepared in accordance with the EN 1563 standard (Fig. 2b). Strain was measured using an extensometer of gauge length 40 mm (Fig. 2c), until the specimen was fractured.

The same specimen geometry in accordance with the ASTM E 606 [13] standard was used for determining the LCF parameters. Strain-controlled fatigue testing was carried out at the same temperatures used for the tensile tests. Tensile and LCF tests were conducted using a servo-hydraulic MTS 810 material testing system of 100 kN dynamic load capacity (Fig. 2a), equipped with an induction heating system within the CIMOS d. d. company. The temperatures of each specimen were monitored by thermocouple welded onto the specimens' surfaces and controlled by an induction heating system. Temperature calibration was conducted prior to the fatigue test. The temperature at the centres of the specimens were controlled by thermocouples welded at the bottoms of the gauge lengths, based on the calibration results. Considering that the brake discs underwent repeated tension and compression during their braking cycles [1], the applied strains were symmetrical triangular waveforms with load ratios of $R = -1$. Cyclical frequencies were set at 2 Hz. At each strain level and each temperature, two specimens were tested.

Table 2
Metallographic characteristics of grey cast iron.

A – graphite	Flake size	Perlite/ferrite	Fe_3C	R_m	HB
85%	4–5	99/1	In trace	292–293 MPa	215–217

3. Results and discussion

The monotonic stress–strain curves of EN-GJL-250 tested at different temperatures are shown in Figs. 3 and 4. It was established that the tested grey cast iron was a very brittle material, with low plastic deformation and that its behaviour was different during tension than compression. Its compressive strength was even comparable to low and medium carbon

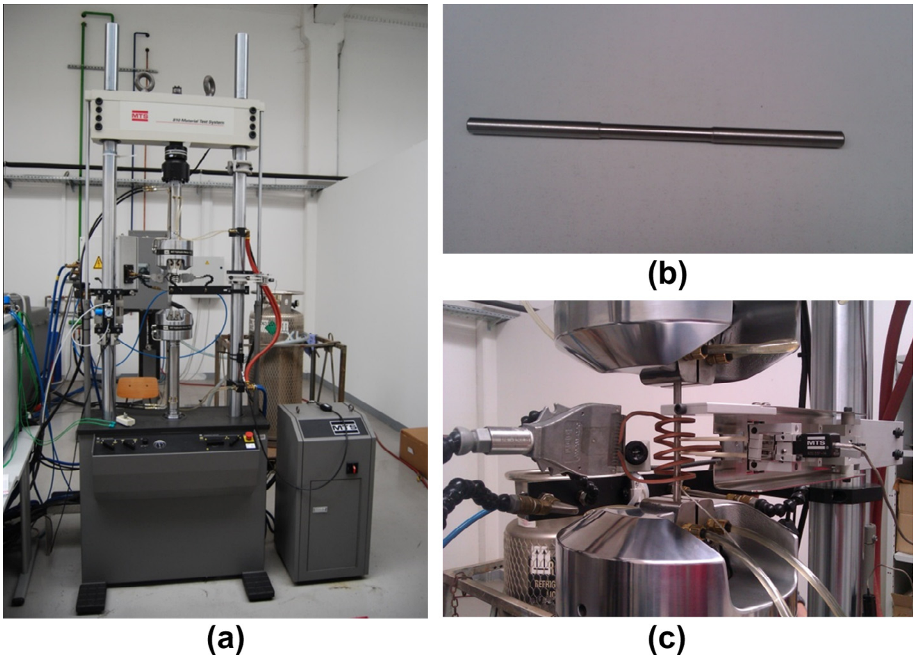

Fig. 2. Material testing machine MTS 810 (a), test specimen (b), induction heater and MTS ceramic extensometer (c).

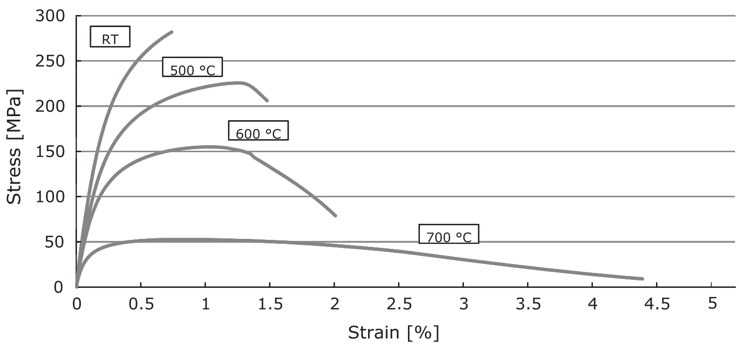

Fig. 3. Tensile stress–strain curves at RT, 500 °C, 600 °C and 700 °C.

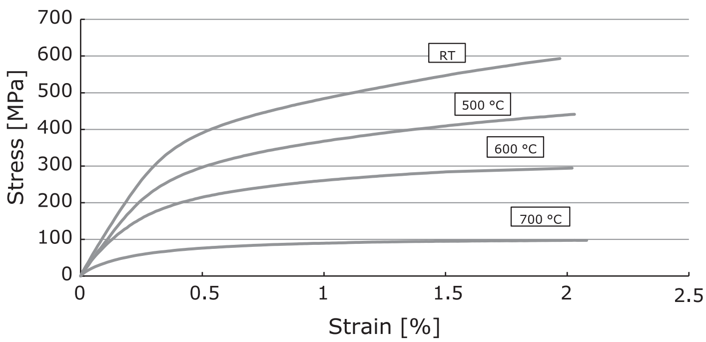

Fig. 4. Compression stress–strain curves at RT, 500 °C, 600 °C and 700 °C.

Table 3
Tensile properties at different temperatures (50% Weibull).

Temp. (°C)	Young's modulus, E (GPa)	Yield strength, $R_{p0.2}$ (MPa)	UTS, R_m (MPa)	Elongation A_{10mm} (%)
RT	104	244	284	0.75
500	84	182	228	1.488
600	77	133	158	2.020
700	48	48	53	4.439

Table 4
Compressive properties at different temperatures (50% Weibull).

Temp. (°C)	Young's modulus, E (GPa)	Yield strength, $R_{p0,2}$ (MPa)	UCS, R_m (MPa)	Deformation A_{10mm} (%)
RT	109	411	>578	N/A (>2)
500	88	305	>441	N/A (>2)
600	86	206	>287	N/A (>2)
700	43	68	>98	N/A (>2)

Table 5
Number of cycles to failure.

Strain amplitude (%)	No. of cycles to failure (mathematical average)			
	RT	500 °C	600 °C	700 °C
±0.07	1.079.248	707.627	338.409	25.543
±0.10	119.119	174.527	103.180	6.998
±0.15	14.297	4.076	2.753	2.340
±0.20	1.838	1.449	714	722
±0.25	435	337	228	559
±0.30	229			

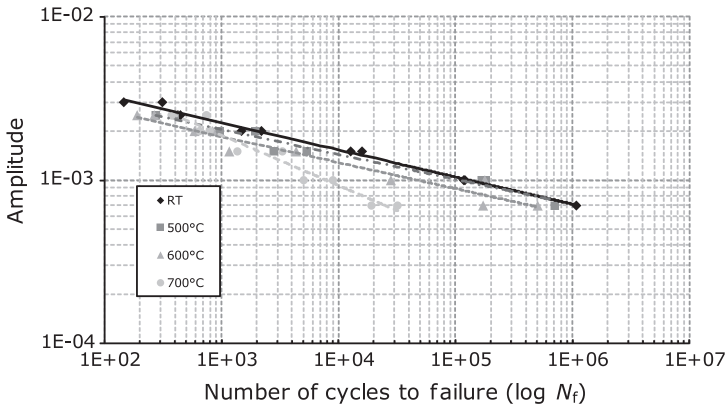

Fig. 5. Number of cycles to failure as a function of amplitude loading.

steel. Tables 3 and 4 summarised the Young's modulus, yield strength, ultimate tensile/compressive strength (UTS/UCS) and elongation/deformation. Young's modulus was obtained by fitting curves using the least square method, to the average curve of the tensile/compression tests. It must be clearly noted, that the Young's modulus of the grey cast iron was not constant as it is in the case of steel, but decreases with strain. Therefore, when analysing the loadings with small deformations, such as vibrations that produce noise, the incremental value of Young's modulus must be considered [14]. Young's modulus was comparable in both tension and compression, but the yield strengths and ultimate strengths were approximately twice as great during compression than in tension. The deformations during the compression tests were limited to max. 2% due to the limitation of the testing machine. Only a small reduction in tensile material properties occurred at 500 °C compared to RT. There was a 20% drop in the average Young's modulus and 24% in the average yield strength. Average UTS at 500 °C was 80% of that at RT. At 700 °C the materials' parameters were greatly affected by the temperature. Average yield strength was 20%, whilst average UTS was only 18% of that at RT. The average Young's modulus was less affected and was still at 46% compared to RT. The reason was the eutectoid transformation of grey cast iron that took place at around 738 °C [15]. A conclusion

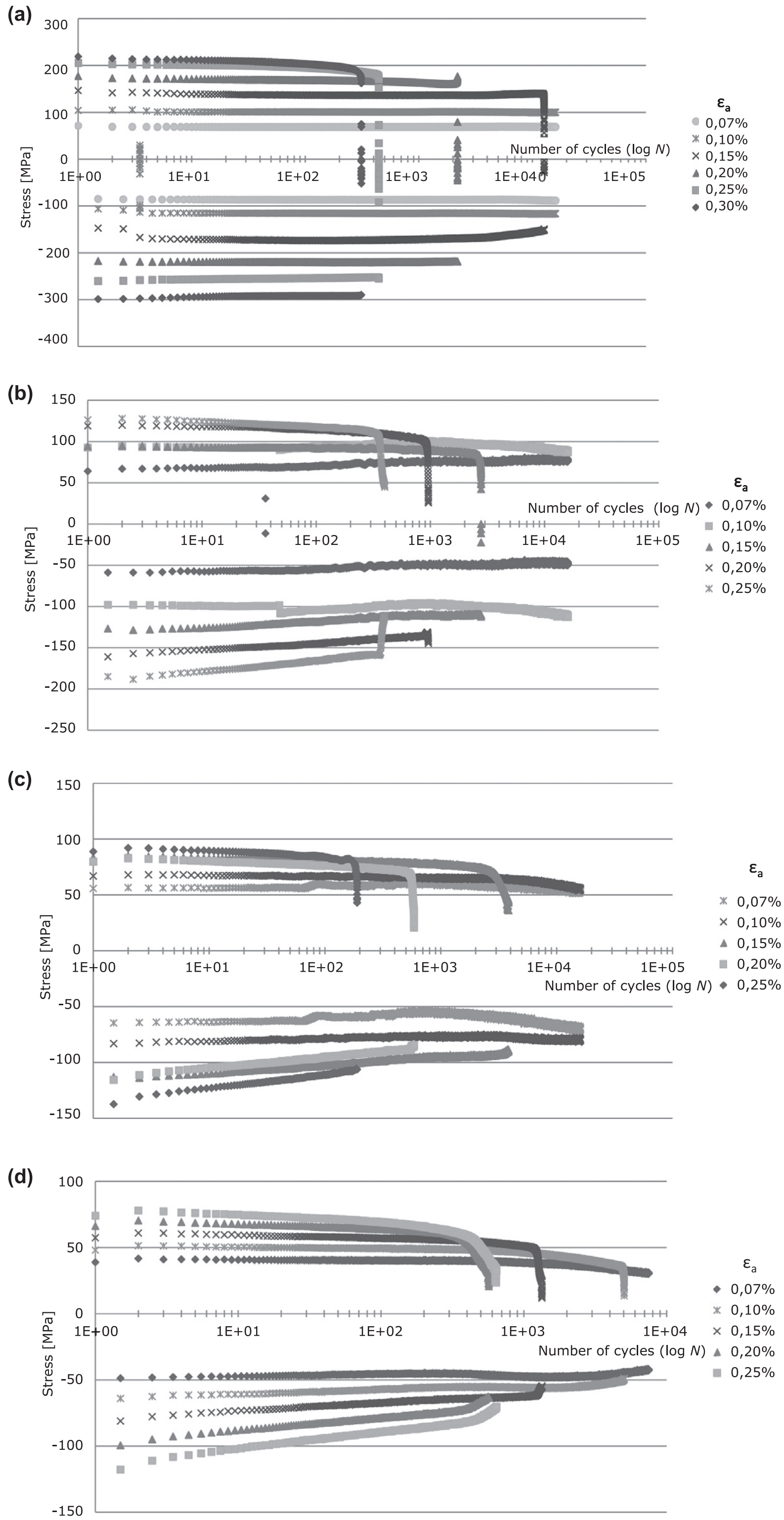

Fig. 6. Cyclic stress response during strain controlled LCF tests at (a) RT, (b) 500 °C, (c) 600 °C and (d) 700 °C.

can be made that because of significant drop in material properties, 700 °C should be the maximal allowed operational temperature of a grey cast brake disc. Table 5 shows the number of cycles to failure at different strain amplitudes at RT, 500 °C,

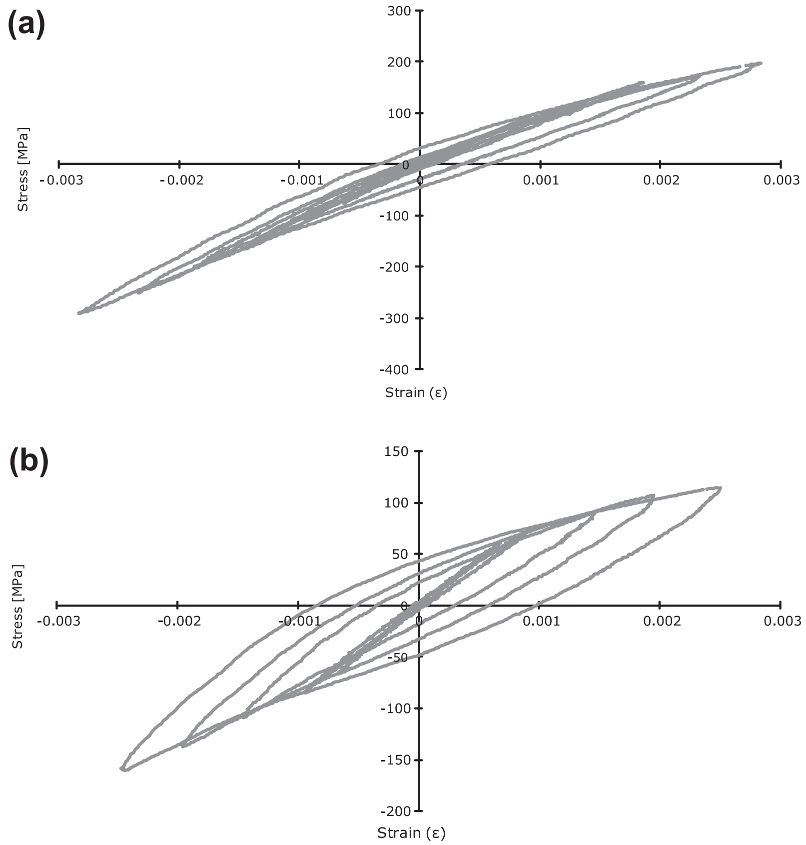

Fig. 7. Stress–strain hysteresis loops at (a) RT, (b) 500 °C, (c) 600 °C and (d) 700 °C.

600 °C, and 700 °C. Strain–amplitude curves are presented in the diagram (Fig. 5). At 500 °C the samples endured, on average, around 50% of the cycles to failure at RT. Similarly to other material properties, the cycles to failure dropped significantly at 700 °C.

The cyclic stress response curves vs. number of cycles at fixed strain amplitudes illustrate the paths by which the materials reach their final stress levels (Fig. 6). The characters of these hardening/softening curves varied with strain amplitudes and temperatures. At RT, the straining was characterised by slight softening towards the end of fatigue life (Fig. 6a). The softening became more pronounced at 500 °C (Fig. 6b), whilst at 700 °C the softening was more evidently (Fig. 6d). No hardening was detected. Some parallel deviations of the softening curves at the end of fatigue life can be attributed to the undesired slip of the extensometer due to high temperatures.

At elevated temperatures, the materials' degradations accelerated by creeping and oxidation [4]. The fatigue properties are represented by the exponents in Eq. (1). During the LCF tests, cyclic stresses and strains produce hysteresis curves, as shown in Fig. 7. The hysteresis loop defined by the total strain range ($\Delta\varepsilon_a$) and the total stress range ($\Delta\sigma_a$) represents the elastic plus plastic work on a material undergoing loading and unloading [8]. The plastic strain range ($\Delta\varepsilon_p$) was measured from the width of the hysteresis curve at half-life and elastic strain range ($\Delta\varepsilon_e$) was simply calculated from the total strain range ($\Delta\varepsilon_a$) value.

The diagrams in Fig. 8 show the log (ε_a) – log ($2N_f$) for all the obtained temperatures, where $2N_f$ was the number of reversals to failure for each tested specimen. When the magnitude of the plastic strain amplitude was equal to the magnitude of the elastic strain amplitude, transition fatigue life point occurred ($2N_t$). The transition fatigue lives were at the intersections of the elastic and plastic strain lines. The region to the left of this point was considered the plastic strain dominant region, the so-called LCF region. The region to the right, where the fatigue life was higher than the transition fatigue life, was the elastic strain dominant region, the so-called high cycle fatigue (HCF) region. The transitions from LCF to HCF conditions occurred at $2N_t = 76$ at RT, $2N_t = 225$ at 500 °C, $2N_t = 542$ at 600 °C and $2N_t = 1332$ at 700 °C, where $2N_t$ was transition fatigue life. At these fatigue cycles, the total strain ranges were 0.65%, 0.37%, 0.24% and 0.22% at RT, 500 °C, 600 °C and 700 °C, respectively. The curves for each temperature were actually graphic representation of Eq. (1). The strain–life fatigue properties σ_f', b, ε_f' and c, are shown in Table 6.

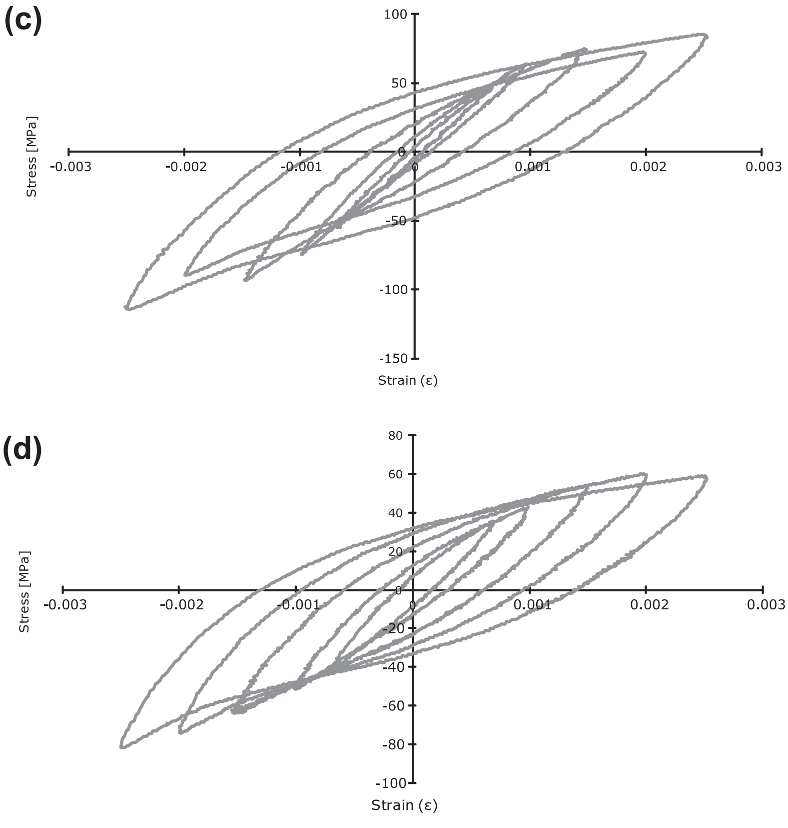

Fig. 7 (*continued*)

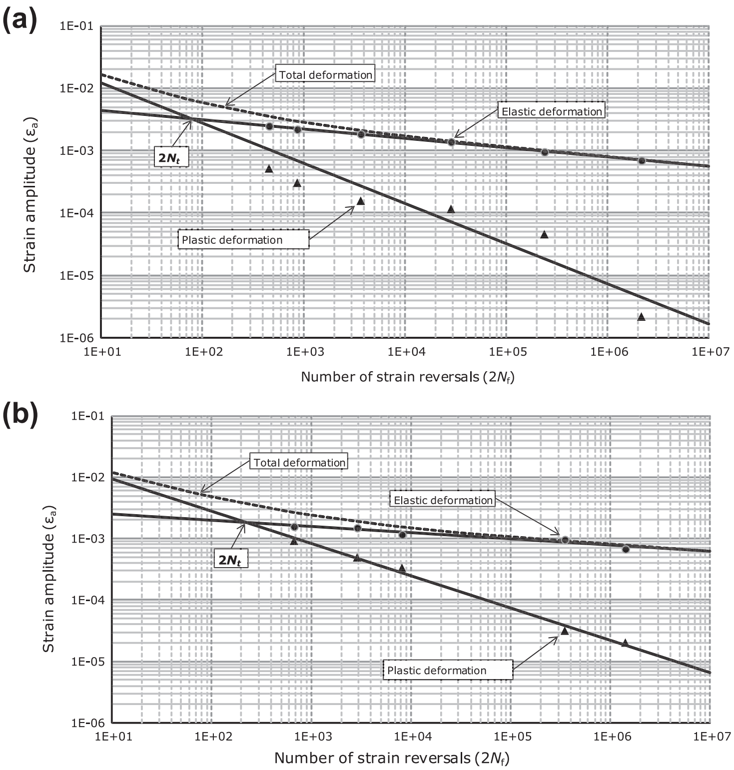

Fig. 8. Strain–life curves at (a) RT, (b) 500 °C, (c) 600 °C and (d) 700 °C.

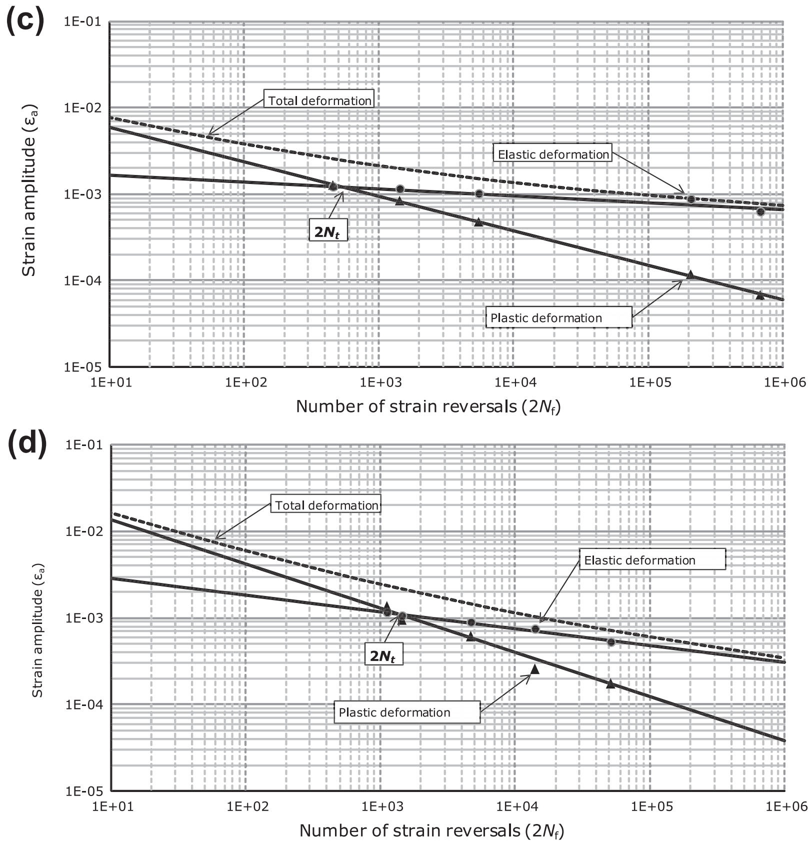

Fig. 8 (*continued*)

Table 6
Low cycle fatigue properties of EN-GJL-250 at RT, 500 °C, 600 °C and 700 °C.

Temperature	σ_f' (MPa)	ε_f'	b	c
RT	659.2	0.0533	−0.1495	−0.6428
500 °C	274.7	0.0318	−0.1022	−0.5258
600 °C	163.2	0.0149	−0.0793	−0.3983
700 °C	205.3	0.0434	−0.1939	−0.5087

4. Conclusions

The mechanical properties during tension and compression, and the LCF behaviour of EN-GJL-250 grey cast iron were evaluated under different temperatures. The LCF parameters σ_f', b, ε_f' and c were determined by following the standard procedure ASTM E 606 [13]. The results shown in this research are to the best of the authors' knowledge, the first published detailed low-cycle fatigue material properties of EN-GJL-250 grey cast iron at brake disc operating temperatures. The following conclusions could be obtained:

– It was discovered that during the standard brake disc fatigue homologation test also known as the "crack test" [12], the maximum temperatures reached were between 500 °C and 700 °C. Therefore the material and fatigue properties of the low carbon brake disc grey cast iron (EN-GJL-250) were analysed at room temperature (RT), 500 °C, 600 °C, and 700 °C.
– The microstructure of the analysed material was pearlitic with graphite flakes finely distributed in its matrix.
– The tested grey cast iron was a very brittle material, with low plastic deformation and behaves differently during tension compared to compression. Young's modulus was comparable between both tension and compression, but the yield strength and ultimate strength were approximately twice as large during compression than in tension. Young's modulus, yield strength and ultimate tensile strength remained quite stable until 500 °C, where at 700 °C all the mechanical properties deteriorated drastically.

– At room temperature straining was characterised by slight softening towards the end of fatigue life. The softening became more pronounced at 500 °C, whilst at 700 °C the softening was more evident. No hardening occurred.
– At 500 °C samples endured, on average, at around 50% of cycles at room temperature. Similar to other material properties, the cycles to failure dropped significantly at 700 °C.
– A total of 74 specimens were tested at brake disc operating temperatures and strain amplitudes to ensure the universal usage of the results in a brake disc fatigue life prediction.

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