Contents lists available at ScienceDirect





journal homepage: www.elsevier.com/locate/engfailanal

# Low cycle fatigue of nodular cast iron used for railway brake discs

# Blaž Šamec<sup>a,\*</sup>, Iztok Potrč<sup>a</sup>, Matjaž Šraml<sup>b</sup>

<sup>a</sup> University of Maribor, Faculty of Mechanical Engineering, Smetanova 17, 2000 Maribor, Slovenia <sup>b</sup> University of Maribor, Faculty of Civil Engineering, Smetanova 17, 2000 Maribor, Slovenia

#### ARTICLE INFO

Article history: Received 14 December 2010 Received in revised form 6 April 2011 Accepted 8 April 2011 Available online 18 April 2011

*Keywords:* Nodular cast iron LCF material parameters Railway brake disc Fatigue testing

### ABSTRACT

The objective of the present paper is to evaluate the fatigue life of nodular cast iron EN-GJS-500-7, used for railway brake discs. Tension and low-cycle fatigue properties were examined at room temperature (RT), 300 °C and 400 °C. Microstructure of the material was documented at RT and 400 °C. Tensile stress–strain curves, cyclic hardening/softening curves, cyclic stress–strain curves, stress–strain hysteresis loops and fatigue life curves were obtained for all temperatures. Young's modulus remained quite temperature stable, while proof stress and ultimate tensile strength decreased with increasing temperature. Fatigue life decreased for around 50% at 300 °C, while at 400 °C samples endured to only 10% of strain reversals of those at RT.

© 2011 Elsevier Ltd. All rights reserved.

Failure Analysis

#### 1. Introduction

Disc brakes, not only for railway applications but generally, count as safety components. Therefore, their reliability during service is essential. Disc brakes are exposed to large thermal stresses during braking. In addition to substantial mechanical forces, friction heat generation is extremely high. In heavy duty brake application, the heat flux at the interface is of the order of MW/m<sup>2</sup> [1,2]. The heat generated during braking causes temperature increase at the interface, which spreads fast through the brake components. Such severe thermal processes modify friction properties of the materials in contact, cause wear and, on a large scale, result in component deflection. All these changes inevitably affect brake performance and life.

A certain number of railway disc brakes, made of gray cast iron, shown the presence of cracks only after a few thousand kilometers. To investigate the main causes of a brake disc failure, numerical analysis [3] was done, using ABAQUS software. Numerical analysis resulted from a physical model of heat flux in dependence of braking time. Physical model was applied considering all demands and presumptions given by industry representatives. Redesign of a brake disc was suggested and a change of brake disc material to nodular cast iron has also been proposed. The selection of this material rather than other cast iron materials with lamellar or vermicular graphite, which have better thermal conductivity, is based on its superior toughness behavior, needed to endure the thermal elastic–plastic stresses around the yield strength [4].

Nodular cast iron is used for various industrial applications due to its favorable mechanical properties and low material cost. The increased use of nodular cast irons concerns many applications, especially in automotive and non-automotive transportation industries [5–7]. Because of the comprehensive application in the automotive industry, most experimental data have been limited to nodular cast iron grades with application to automotive components and in the very high cycle fatigue regime. Several other studies have been carried out with the aim to obtain properties of nodular cast iron. Kim et al. [8] investigated high temperature degradation behavior of two types of heat resistant Si–Mo ductile cast iron with particular attention paid to the mechanical properties and overall oxidation resistance. Tension and low-cycle fatigue properties

E-mail address: blaz.samec@uni-mb.si (B. Šamec).

<sup>\*</sup> Corresponding author. Tel.: +386 22207721.

<sup>1350-6307/\$ -</sup> see front matter @ 2011 Elsevier Ltd. All rights reserved. doi:10.1016/j.engfailanal.2011.04.002



Fig. 1. Schematic of the Y block used in this study (unit: mm).

 Table 1

 Chemical composition of the brake disc material (EN-GJS-500-7).

EL	С	Si	Mn	Р	S	Cr	Мо	Ni	Cu
wt.%	3.50-3.80	2.40-2.70	0.25-0.60	Max 0.050	Max 0.020	Max 0.25	Max 0.40	Max 0.15	Max 0.50



Fig. 2. Microstructure of the material at (a) RT and (b) 400 °C; left: un-etched, right: etched.

were examined at 600 °C and 800 °C. Shirani and Harkegard [9] conducted stress controlled fatigue tests at room temperature to determine fatigue properties of EN-GJS-400-18-LT ductile cast iron for wind turbine use. Fatigue tests were performed at load ratio R = 0 and R = -1. In order to evaluate the size effect, fatigue tests were carried out on two sets of specimens with different dimensions. Petrenec et al. [10] made a comparison of low cycle fatigue of ductile cast irons with

# Table 2Nodule characteristics of nodular cast iron.

Nodule count (mm <sup>-2</sup> )	Nodule area fraction (%)	Nodule diameter (µm)	Nodularity (%)
117	6.68	20.6	95



Fig. 3. Geometry of the tensile test specimen (unit: mm).



Fig. 4. Geometry of the LCF test specimen (unit: mm).



Fig. 5. Tensile stress–strain curves at RT, 300  $^\circ\text{C}$  and 400  $^\circ\text{C}.$ 

different matrix alloyed with nickel. Total strain controlled tests have been performed with the aim to compare cyclic plasticity and the fatigue life at 23 °C and -45 °C.

Table 3						
Tensile	properties	at	different	tem	peratu	ires

Sample Nr.	Temp. (°C)	Young's Modulus, E (MPa)	Proof stress, R <sub>p0.2</sub> (MPa)	UTS, <i>R</i> <sub>m</sub> (MPa)	Elongation (%)
1	RT	168,911	370	667	8.2
2	RT	171,109	369	662	7.8
3	RT	168,021	367	658	7.6
Average		169,347	368	662	7.9
60	300	167,101	318	518	4.0
61	300	153,752	299	435	2.9
62	300	161,564	323	510	4.0
Average		160,805	313	487	3.6
5	400	149,124	266	358	7.8
6	400	138,588	222	273	13.5
7	400	141,567	237	305	11.9
Average		143,093	242	312	11.1

# Table 4

Number of cycles to failure.

Strain amplitude (%)	Nr. of cycles to failure					
	RT	300 °C	400 °C			
±0.1	11,42,200	-	231,696			
±0.15	270,196	218,618	22,105			
±0.2	90,447	41,821	5011			
±0.25	47,467	10,757	1100			
±0.3	6585	4761	893			
±0.4	3087	1887	343			
±0.5	2051	867	205			
±0.8	492	66	28			



Fig. 6. Number of cycles to failure as a function of strain amplitude loading.

However, nodular cast iron is not a single material but is part of a group of materials which can be produced to have a wide range of properties through control of the microstructure. The mechanical properties of nodular cast irons are directly related to their matrix microstructure. As-cast matrix microstructure of nodular cast irons may be entirely ferritic, entirely pearlitic, or a combination of ferrite and pearlite, with spheroidal graphite distributed in the matrix. Furthermore, it is important to measure material parameters in the temperature range where they will be operating, to be able to optimize the material for its purpose. The results shown in this research are to the best of the authors' knowledge, the first published  $\varepsilon$ -N curves of EN-GJS-500-7 nodular cast iron.



Fig. 7. Cyclic stress response during strain controlled LCF tests at (a) RT, (b) 300 °C and (c) 400 °C.

The aim of present study was to investigate the tensile strength and low-cycle fatigue (LCF) behavior of nodular cast iron EN-GJS-500-7 at room and elevated temperatures. Constant amplitude axial fatigue tests provide the necessary information about the strain–life curve and cyclic stress–strain behavior of the material. As previously used in our research [11–13], a reasonable expected fatigue life (number of stress cycles  $N_f$ ), can be determined iteratively using Coffin–Manson equation:

$$\varepsilon_a = \frac{\Delta \varepsilon_e}{2} + \frac{\Delta \varepsilon_p}{2} = \frac{\sigma'_f}{E} \cdot \left(2 \cdot N_f\right)^b + \varepsilon'_f \cdot \left(2 \cdot N_f\right)^c \tag{1}$$

where  $\varepsilon_a$  is total strain amplitude,  $\Delta \varepsilon_e$  and  $\Delta \varepsilon_p$  are elastic and plastic strain range, *E* is Young's modulus,  $\sigma'_f$  the fatigue strength coefficient, *b* the fatigue strength exponent,  $\varepsilon'_f$  the fatigue ductility coefficient and *c* is the fatigue ductility exponent. The above equation, called the strain-life equation, is the foundation for the strain-based approach for fatigue.

#### 2. Experimental procedures

Customer's demand was that the brake discs can heat up to 400 °C, but the manufacturer's tests showed that the discs are usually heated up to 300 °C. This was the reason why these two temperatures and room temperature (RT) were chosen for experiments.



Fig. 7 (continued)

Nodular cast iron EN-GJS-500-7 was cast in the form of Y blocks (Fig. 1). The bottom portion of those blocks was cut into small bars in order to machine specimens for tension and fatigue tests. Those bars were used in the as-cast state. Table 1 shows the chemical composition of the material.

A metallographic analysis was carried out on two samples in order to compare the microstructures at RT and at 400 °C. Samples were metallographically prepared and observed in an optical microscope in both un-etched and etched with 3% nital condition. Fig. 2a shows the micrographs of the material at RT and Fig. 2b at 400 °C. Microstructure in both cases consisted of a ferrite–pearlite matrix with graphite nodules. The average area percent of ferrite and pearlite was 33.77 and 59.57 respectively, the rest was graphite. Some characteristics of spheroidal graphite are shown in Table 2. As seen on Fig. 2b, microstructure of the material remains stable at 400 °C.

Before fatigue tests, the monotonic tensile test has been done to evaluate the mechanical properties of the material. The tensile test was carried out at RT, 300 °C and 400 °C, where three tests were made at each temperature. Cylindrical specimens, 10 mm in diameter, with a gage length of 60 mm were prepared in accordance with the EN 1563 standard (Fig. 3). Strain was measured with an extensometer of gauge length of 50 mm until the specimen was fractured.

For determination of LCF parameters the test specimens (Fig. 4) according to ASTM E 606 standard [14] have been used. Strain controlled fatigue testing has been carried out at the same temperatures used for tensile tests, i.e., RT, 300 °C and 400 °C.

Tensile and LCF tests were conducted using a servo-hydraulic machine of 100 kN dynamic load capacity, equipped with an induction heating system. The temperature of a specimen was monitored by a thermocouple welded on the specimen surface and controlled by an induction heating system. Prior to fatigue test, temperature calibration was conducted. The temperature at the center of the specimen was controlled by a thermocouple welded in the bottom of gauge length, based on the calibration results. Considering that the brake disc undergoes repeated tension and compression when the train runs [15], applied strain was a symmetrical triangular waveform with a load ratio of R = -1. Cycling frequency was 2 Hz.

### 3. Results and discussion

The tensile stress–strain curves of EN-GJS-500-7 tested at different temperatures are shown in Fig. 5. It can be seen that the tensile tests at room temperature gave virtually identical results, while at higher temperatures there is a larger scatter of results. Table 3 summarizes their Young's modulus, proof stress, ultimate tensile strength (UTS) and elongation. Only a slight reduction in material properties occurs at 300 °C compared to RT. There is a 5% drop in average Young's modulus and 15% in average proof stress. Average UTS at 300 °C is 74% of that at RT. At 400 °C material parameters are greatly affected by the temperature. Average proof stress is 66%, while average UTS is only 47% of that at RT. Average Young's modulus is less affected and it is still at 84% compared to RT.

Table 4 shows number of cycles to failure at different strain amplitudes at RT, 300 °C and 400 °C. Results from the table are also presented in the diagram (Fig. 6). At 300 °C samples endured on average around 50% of cycles to failure at RT. Similar to other material properties, cycles to failure have dropped significantly at 400 °C. On average they account to only 10% of those at RT.



Fig. 8. Stress-strain hysteresis loops at (a) RT, (b) 300 °C and (c) 400 °C.

The cyclic stress response curves vs. number of cycles at fixed strain amplitude illustrate the path by which the materials arrive at their final stress level (Fig. 7). The character of these hardening/softening curves varies with strain amplitude and temperature. At RT straining is characterized by slight hardening towards the end of fatigue life, except at 0.8% strain amplitude, where initial hardening results in slow softening (Fig. 7a). The hardening becomes more pronounced at 300 °C (Fig. 7b), while at 400 °C initial hardening results in sustained softening up to the end of the fatigue life (Fig. 7c).

At elevated temperatures, material degradation is accelerated by fatigue and oxidation [8]. The fatigue properties are represented by the exponents in Eq. (1). During the LCF tests, cyclic stress and strain produce hysteresis curves, as shown in Fig. 8. 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. 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 total strain range ( $\Delta \varepsilon_a$ ) value. Table 5 shows the measured  $\Delta \varepsilon_p$  with various total strain amplitudes at RT, 300 °C and 400 °C.



Fig. 8 (continued)

#### **Table 5** Plastic strain ranges $(\Delta \varepsilon_p)$ at RT, 300 °C and 400 °C.

Applied strain amplitude ( $\pm \epsilon$ )	±0.2%	±0.25%	±0.3%	±0.4%	±0.5%	±0.8%
$ \begin{array}{l} \Delta \varepsilon_p \ (\text{RT}) \\ \Delta \varepsilon_p \ (300 \ ^{\circ}\text{C}) \\ \Delta \varepsilon_p \ (400 \ ^{\circ}\text{C}) \end{array} $	0.0001147	0.0002836	0.0010884	0.0026772	0.0044652	0.0115782
	0.0000768	0.0003370	0.0009371	0.0024524	0.0041977	0.0094110
	0.0002070	0.0008966	0.0015120	0.0031681	0.0048169	0.0102343



Fig. 9. Cyclic stress-strain curves for RT, 300  $^\circ C$  and 400  $^\circ C.$ 

Table 6 Low-cycle fatigue properties of EN-GJS-500-7 at RT, 300  $^\circ C$  and 400  $^\circ C.$ 

Temperature	$\sigma_{f}^{\prime}$ (MPa)	$\mathcal{E}_{f}'$	b	С	<i>K</i> ′ (MPa)	n′
RT	1355	1.4730	-0.1272	-0.8139	723	0.0801
300 ℃	949	0.4273	-0.0977	-0.7794	776	0.0901
400 ℃	756	0.2200	-0.1192	-0.8058	774	0.1131



Fig. 10. Strain-life curves at (a) RT, (b) 300  $^\circ C$ , (c) 400  $^\circ C$  and (d) all together.

The plot of stress amplitude ( $\sigma_a$ ) versus plastic strain amplitude ( $\Delta \varepsilon_p/2$ ) in log–log coordinates results in a linear curve (Fig. 9) represented by the power function:

$$\sigma_a = K' \cdot \left(\frac{\Delta \varepsilon_p}{2}\right)^{n'} \tag{2}$$



where K' is the cyclic strength coefficient and n' is the cyclic strain hardening exponent. K' and n' at different temperatures are shown in Table 6.

Fig. 10 shows the strain-life fatigue curves plotted in log-log scales, where  $2N_f$  is the number of reversals to failure for each tested specimen. When the magnitude of plastic strain amplitude is equal to the magnitude of elastic strain amplitude, transition fatigue life point occurs. The transition fatigue life is the intersection of the elastic and plastic strain lines. The region to the left of this point is considered the plastic strain dominant region, the so-called LCF region. The region to the right, where fatigue life is higher than the transition fatigue life, is the elastic strain dominant region, the so-called high-cycle fatigue (HCF) region. The transition from LCF to HCF conditions occurred at  $2N_t = 1987$ at RT,  $2N_t = 535$  at 300 °C and  $2N_t = 234$  at 400 °C. Where  $2N_t$  is transition fatigue life in reversals. At these fatigue cycles, the total strain ranges were 0.60 pct, 0.63 pct and 0.54 pct at RT, 300 °C and 400 °C respectively. Diagram in Fig. 10d shows the log ( $\varepsilon_a$ ) – log ( $2N_f$ ) for three different temperatures. The curve for each temperature is actually a graphic representation of the Eq. (1). Strain-life fatigue properties  $\sigma'_f$ , *b*,  $\varepsilon'_f$  and *c*, which are often referred to as "low-cycle fatigue properties", are shown in Table 5.

# 4. Conclusions

Tensile strength and LCF behavior of EN-GJS-500-7 nodular cast iron was evaluated under different temperatures. The LCF parameters  $\sigma'_j$ , b,  $\varepsilon'_j$  and c were determined following the standard procedure ASTM E 606. Cyclic strength coefficient K' and cyclic strain hardening exponent n' for different temperatures has also been presented. The results shown in this research are to the best of the authors' knowledge, the first published  $\varepsilon$ –N curves of EN-GJS-500-7 nodular cast iron. The following conclusions were obtained:

- 1. Matrix of the material is ferritic-pearlitic and remains stable at 400 °C.
- 2. Tensile tests at room temperature gave virtually identical results, while at higher temperatures there is a larger scatter of results. Young's modulus remained quite temperature stable, while proof stress and ultimate tensile strength decreased with increasing temperatures.
- 3. At room temperature straining is characterized by slight hardening towards the end of fatigue life. The hardening becomes more pronounced at 300 °C, while at 400 °C initial hardening results in sustained softening up to the end of the fatigue life.
- 4. At 300 °C samples endured on average around 50% of strain reversals at room temperature. Similar to other material properties, strain reversals to failure have dropped significantly at 400 °C. On average they account to only 10% of those at room temperature.

# References

- [1] Majcherczak D, Dufrenoy P, Berthier Y. Tribological thermal and mechanical coupling aspects of the dry sliding contact. Tribol. Int 2007;40:834-43.
- [2] Mackin TJ, Noe SC, Ball KJ, Bedell BC, Bim-Merle DP, Bingaman MC, et al. Thermal cracking in disc brakes. Eng Failure Anal 2002;9:63–76.
- [3] Šamec B, Oder G, Lerher T, Potrč I. Numerical analysis of a railway brake disc. In: 4th International conference on thermal process modelling and computer simulation, ICTPMCS 2010, Shanghai, China; 2010.
- [4] Sonsino CM, Hanselka H. Fatigue life assessment of cast nodular iron disc brakes for railway vehicles. Revue de Metallurgie. Cahiers D'Inf Tech 2007;104:562-8.
- [5] Nadot Y, Denier V. Fatigue failure of suspension arm: experimental analysis and multiaxial criterion. Eng Failure Anal 2004;11:485-99.
- [6] Asi O. Failure analysis of a crankshaft made from ductile cast iron. Eng Failure Anal 2006;13:1260-7.
- [7] Abebe BH. Fatigue life assessment of a diesel engine pump part subjected to constant and variable amplitude loading master thesis. Weimar: Bauhaus University; 2008.
- [8] Kim Y-J, Jang H, Oh Y-J. High-temperature low-cycle fatigue property of heat-resistant ductile-cast irons. Metall Mater Trans A 2009;40:2087-97.
- [9] Shirani M, Härkegård G. Fatigue life distribution and size effect in ductile cast iron for wind turbine components. Eng Failure Anal 2011;18:12-24.
- [10] Petrenec M, Tesarová H, Beran P, Smíd M, Roupcová P. Comparison of low cycle fatigue of ductile cast irons with different matrix alloyed with nickel. Procedia Eng 2010;2:2307–16.
- [11] Sraml M, Flasker J, Potrc I. Numerical procedure for predicting the rolling contact fatigue crack initiation. Int J Fatigue 2003;25:585–95.
- [12] Glodez S, Knez M, Jezernik N, Kramberger J. Fatigue and fracture behaviour of high strength steel S11000. Eng Failure Anal 2009;16:2348–56.
- [13] Knez M, Glodez S, Kramberger J. Fatigue assessment of piston rod threaded end. Eng Failure Anal 2009;16:1977-82.
- [14] ASTM E 606. Standard practice for strain-controlled fatigue testing. ASTM Standard; 1998.
- [15] Kim DJ, Seok CS, Koo JM, We WT, Goo BC, Won JI. Fatigue life assessment for brake disc of railway vehicle. Fatigue Fract Eng Mater Struct 2010;33:37-42.