Chapter 4
Rotating Bending Fatigue of Spheroidal Cast Irons

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Abstract Cast iron probably represents one of the most widely utilized constructive materials in our modern industrial world. This is due not only to the excellent mechanical and tribological properties, but also to a certain flexibility of the same. In fact, it can be produced in various types of metal alloy, which differ significantly in properties: from the poorly performing, but economical white cast iron, to the excellent resistant nodular cast iron. In this study, several preliminary results on the experimental measurement of fatigue resistance are proposed for two distinct families of cast iron, the ductile and the vermicular. While the former is well known, with a great variety of applications, vermicular cast iron is almost unfamiliar at the moment in terms of utilization, despite different potentials. This experiment compares the results of the Rotating Bending Fatigue test for cast iron specimens made under foundry process conditions as identical as possible in the way to reduce bias.

Keywords Metal alloys · Foundry · Spheroidal cast iron · Mechanical properties · Fatigue behavior · Fatigue limit

4.1 Introduction

4.1.1 Spheroidal Cast Iron

The spheroidal cast iron (SGI), also known as ductile cast iron, is a cast alloy in which graphite, instead of in the form of lamellae, occurs in nodules in the shape of spheroids. The nodules are located in a metal matrix whose structure is a function of

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the chemical composition of the specific type of cast iron, of the cooling rate at the time of solidification and of any subsequent heat treatments [1, 2].

The spheroidal form of graphite produces a lower concentration of tension than the lamellar one; moreover, the spherical shape is the one that, with the same volume, has the smallest surface and the matrix is therefore less damaged, thus being able to better exploit its characteristics [3, 4].

Furthermore, in spheroidal cast iron, graphite nodules exert a stopping action for cracks, unlike lamellar graphite which offers a preferential way for their propagation. Spheroidal cast iron shows a notable improvement of all mechanical characteristics including the fatigue behavior [5–7].

4.1.2 Spheroidal Cast Production

Spheroidal cast iron is produced starting from a base cast iron and adding appropriate magnesium alloys that can favor the spheroidization of the cast iron (Fig. 4.1). Concentrations of chemical elements in molten alloys and process temperatures must be kept under strict control to ensure the correct formation of the microstructure [1, 3].

This accuracy in process and products is important in general for every cast iron, but even more relevant in the case of SGI. For example, a variation of only 2% of Si leads to an increase in the temperature of the stable eutectic and the lowering of the metastable one from the initial 6 to 40 °C with effects on spheroidization. Each modification in the structure affects the main characteristics of the alloy, but even

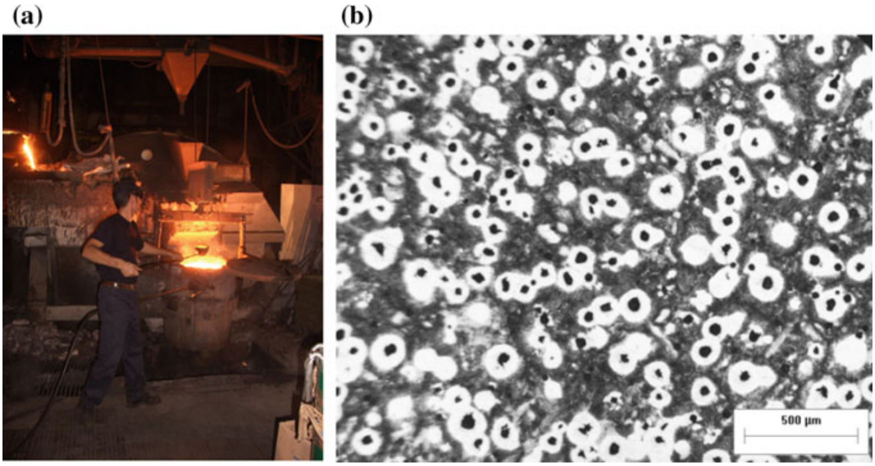

Fig. 4.1 Production of spheroidal cast iron: **a** sampling for process control; **b** microstructure with evidence of the spheroids

more so for those properties that are intrinsically linked to the benefits offered by the spheroids, such as fatigue strength [2–4, 6, 8].

Thus, the study of those properties such as fatigue strength, linked to the propagation of cracks across the microstructures, deformed by nodules, becomes even more fundamental in terms of appearance such as, for example, tensile strength.

4.1.3 Aim and Scope

In line with what just said, this article describes an experimental study aimed at measuring the fatigue strength of a ductile iron produced in a cupola furnace at the SCM Foundry, Italy. This work is part of a broader investigation that led the research team to study some of the main mechanical [9, 10] and tribological properties [11] of nodular cast iron under carefully controlled process conditions, including the development of advanced techniques for data interpretation based on machine learning [12–14]. In particular, regarding the fatigue resistance, a characterization study of SGI is already available, but based on a push–pull load configuration [15]. The present work complements these results by adopting a rotating load configuration.

4.2 Materials and Methods

4.2.1 Samples Production

The fatigue behavior of SGI was investigated by a four-point rotating bending test in accordance with ISO 1143 [16] and ISO 12107 [17]. Standardized specimens were extracted from a metallic block and shaped by tool machining (Fig. 4.2).

Table 4.1 reported the chemical composition (in % of weight) of ductile (SGI) and vermicular (CGI) irons.

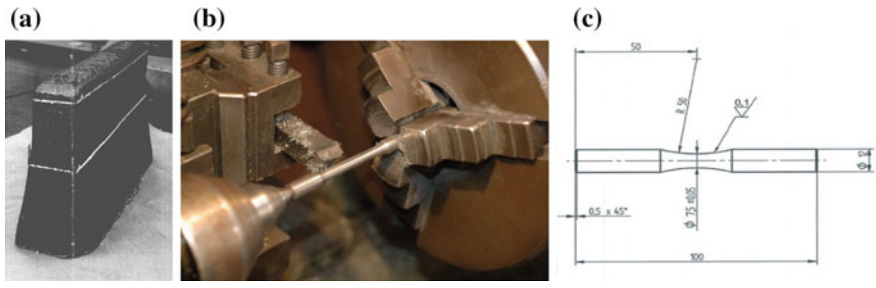

Fig. 4.2 Production of standardized specimens for rotating bending fatigue tests (ISO 1143): **a** metallic block from sand casting; **b** tool machining; **c** ‘dog-bone’ shape

Table 4.1 Chemical composition (in % of weight) of ductile cast iron (SGI)

Fe	C	Si	Mn	P	S	Ni	Cr
93.1	3.66	2.65	0.218	0.032	0.004	0.069	0.062
Cu	Mo	Mg	Sn	Ti	Pb	Al	Zn
0.062	0.002	0.055	0.013	0.034	0.007	0.011	0

4.2.2 Fatigue Life

ASTM considers the 'fatigue life' as the number of stress cycles applied before a failure in the specimen occurs. For some materials, such as cast iron, there is a stress value below which the material will not fail regardless of the number of cycles.

The standards also define, as known, different methods for determining the fatigue behavior of a material, including the identification of the fatigue strength.

In this investigation, fatigue tests were carried out by applying a sinusoidal stress. The tests were performed at different stress levels (S) by recording at how many cycles the failure occurs (N). Each completed test leads to a known failure time (F). In the absence of failure, the test can be terminated without this information. Anyway, for these samples that have finished early (*run-out*), the data (R) can be also considered for evaluation and analyzed using typical statistical techniques.

However, the results may depend on the number of specimens used and on the sequel of loads applied to these specimens.

For this reason, special attention was paid to applying the regulations in the present study. Specifically, the fatigue tests were implemented with a sequence of loads defined using the *modified staircase method* in accordance with the ISO 12107 standard. This method aims to reduce the number of tests and samples.

In brief, it is based on the procedure to decrease the test stress (σ_0) when a previous test has led to failure and increase it if not. The step of change of load (d) is the same, both in the case of increase or decrease, possibly equal to the uncertainty of this kind of measure. The procedure is repeated until all samples are tested.

In the present case, from the knowledge of the general properties of SGI and assumptions of similar investigation, it was decided to use an initial test stress of $\sigma_0 = 215$ MPa, equivalent to 1/3 (33%) of a characteristic value of the Ultimate Tensile Stress (UTS) of SGI. As modification value, $d = 10$ MPa was chosen. Test limit was set to 10^7 cycles (*run-out*). These parameters are also summarized in Table 4.2.

Table 4.2 Parameters definition for modified staircase method

Parameter	SGI
UTS	650 MPa
Fraction	33%
σ_0	215 MPa
D	10 MPa
Test time	10^7 cycles

Table 4.3 Results from rotating bending fatigue tests

Sample	Stress	Cycle		Sample	Stress	Cycle	
1	215	3,000,000	F	9	235	10,000,000	R
2	205	10,000,000	R	10	245	434,000	F
3	215	10,000,000	R	11	235	239,000	F
4	225	10,000,000	R	12	225	1,175,000	F
5	235	574,000	F	13	215	10,000,000	R
6	225	10,000,000	R	14	225	945,800	F
7	235	10,000,000	R	15	215	10,000,000	R
8	245	495,000	F				

F–failure; ***R***–run-out

4.3 Results and Discussion

4.3.1 Experimental Data

N. 15 samples were tested by rotating bending fatigue tests considering a stress level between 205 and 245 MPa. *N*, 7 of them failed (‘*F*’) while *N*. 8 samples run out to 10^7 cycles (‘*R*’). Table 4.3 reports the experimental data.

The same table also exhibits details regarding the test progression. For instance, the first test took place at 215 MPa of load (σ_0) leading to a fail after $3.0 \cdot 10^6$ cycles. Then a 10 MPa reduction in the stress level was implemented and new test showed no fail up to $10 \cdot 10^6$. Thus, the stress level was increased again for additional 10 MPa, but, also in this case, no failure occurred. Then, stress level was increased once again, for additional 10 MPa. And so on.

Figure 4.3 graphically shows the same experimental values. In this case, samples are not reported in the testing order but respect to the level of stress. The filled circles, as symbols, indicate failures while other symbols indicate run-outs. Data show, for instance, that the run-outs are mainly concentrated at lower load values.

4.3.2 Fatigue Limit

Fatigue properties were estimated considering the probabilities of failure of 10% and confidence levels of 90% in accordance with ISO 12107, as shown in Table 4.4. With the scope it was necessary to evaluate the following parameters:

$$A = \sum_{i=1}^{l} i f_i \tag{4.1}$$

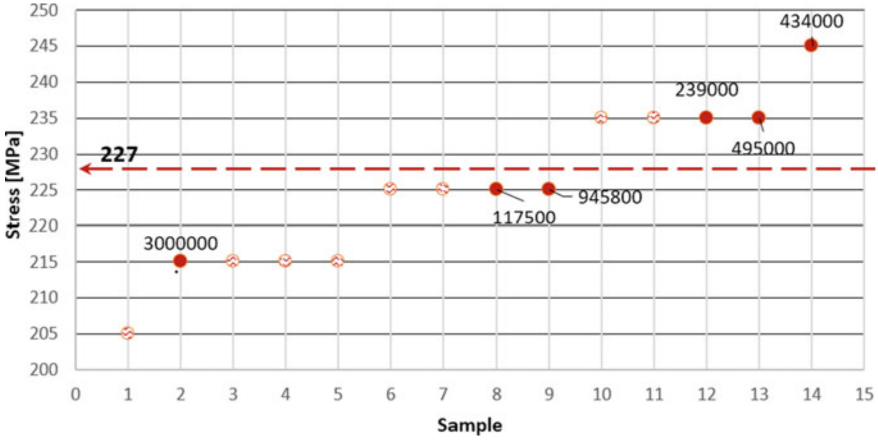

Fig. 4.3 Graphical representation of results from rotating bending fatigue tests

Table 4.4 Scheme for fatigue limit determination at 50% probability of failure

Stress (Mpa)	Sample															Event	
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	F	R
245								F		F						2	0
235					F		R		R		F					2	2
225				R		R						F		F		2	2
215	F		R										R		R	1	3
205		R														0	1
																7	8
d =	10 Mpa															SUM	
σ_0	205 Mpa																

i	ni	i*ni	i^2*ni
1	0	1	0
4	2	8	16
3	2	6	12
2	2	4	8
1	1	1	1
0	0	0	0
	7	19	37
	N	A	B

F–failure; ***R***–run-out

$$B = \sum_{i=1}^{l} i^2 f_i \tag{4.2}$$

$$C = \sum_{i=1}^{l} f_i \tag{4.3}$$

$$D = \frac{BC - A^2}{C^2} \tag{4.4}$$

As a consequence, the fatigue limit at 50% probability of failure can be determined as:

$$\sigma_{D(50\%)} = \sigma_o + d\left(\frac{A}{N} \pm 0.5\right) = 227\,\text{MPa} \tag{4.5}$$

4.4 Conclusions

This experimental study provides results regarding the measure of fatigue resistance for ductile cast iron (SGI). Several standards were followed as a reference in the testing and data analysis. Specifically, using 4-points rotating bending fatigue test, up to 10^7 cycles, and 15 specimens, it detects 227 MPa as fatigue limit. This value, much lower than other material resistances (e.g., ultimate tensile stress) makes evident the attention of designers in using cast iron in the presence of high number of load cycles.

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