Materials and Design 111 (2016) 353–361

Contents lists available at ScienceDirect

Materials and Design

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

Fatigue design of heavy section ductile irons: Influence of chunky graphite

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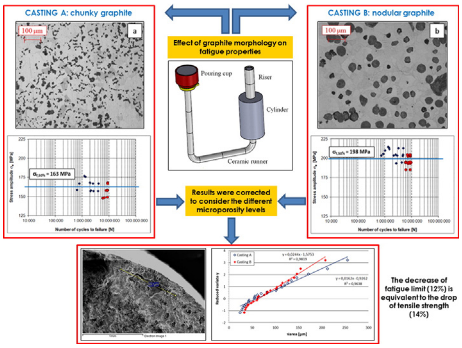
HIGHLIGHTS

- An average content of 33% of chunky graphite reduced the fatigue limit of ductile iron of about 12%.
- The reduction of fatigue strength was calculated considering the different level of microporosities in the two sets.
- No relationship was found between chunky graphite and the fatigue fracture initiation.
- Chunky graphite was a preferential path for the propagation of the fatigue crack.
- The decrease of fatigue limit due to chunky graphite is equivalent to the reduction in tensile strength.

GRAPHICAL ABSTRACT



ARTICLE INFO

Article history:
Received 1 May 2016
Received in revised form 31 August 2016
Accepted 1 September 2016
Available online 02 September 2016

Keywords:
Ductile cast iron
Chunky graphite
Fatigue limit
Microporosity
Analysis of statistics of extremes
Fracture analysis

ABSTRACT

The influence of chunky graphite on mechanical properties, especially on fatigue resistance, of an EN-GJS-400 ferritic ductile iron, was investigated by tensile and rotating-bending tests. The samples for the experiments were machined from two heavy section castings. The first one was cast with the addition of a Ce-containing inoculant to promote chunky formation and the second one by using a standard Ce-free inoculant. The presence of chunky graphite in the samples decreased tensile strength and elongation at break, while no significant effect on the hardness and yield strength was measured. Also fatigue strength was negatively affected, with a decrease of fatigue limit of about 12%. This value was calculated also taking into account the different amount of microporosity in the two sets of samples and its effect on the fatigue strength by using the Murakami approach.
Fracture analysis showed that chunky graphite has a limited influence on fatigue crack nucleation if compared to micro-shrinkages, while it behaves as a preferential path for crack propagation. A simple way to consider the presence of chunky graphite in the fatigue design of heavy section ductile irons is proposed on the basis of the present results and taking into consideration the published data too.

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1. Introduction

The effect that micro-scale defects have on the mechanical performance of metallic materials is one of the main topics in the field of engineering design [1–5]. In the same way, the mechanical properties of iron castings are largely influenced by microstructural defects, such as

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http://dx.doi.org/10.1016/j.matdes.2016.09.002
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Nomenclature

$\sqrt{\text{area}}$	equivalent length of the surface of the defect perpendicular to the direction of the maximum principal stress in Murakami's equation
YS	Yield Stress
UTS	Ultimate Tensile Strength
HB	Brinell Hardness
HV	Vickers Hardness
$\sigma_{f,50\%}$	fatigue limit with a survival probability of 50%
T_σ	stress-based scatter index (ratio between fatigue limit values calculated with 10% and 90% probabilities of survival respectively)

porosities, anomalous graphite morphologies and non-metallic inclusions [6–8]. This class of materials includes the ductile cast iron (DCI), which is commonly chosen to realize mechanical components and machine parts with structural functions [9]. Heavy section wind turbine elements, railway brake discs, crankshaft, wheels, gears, pumps, valves, pipes are only a few examples of industrial applications [7]. This is mainly due to the interesting combination of mechanical and technological properties of this material. The low cost with the greatest fluidity and the least shrinkage of any ferrous alloys justify the increasing use of ductile cast iron for the production of heavy section structural castings, which in some case undergo cycling loads and therefore have to fulfill fatigue strength requirements [10].

Despite its hardness is almost equal to that of a large number of low alloyed steels, the fatigue strength of ductile cast iron is lower because the structure contains graphite and casting defects [11]. The fatigue damaging micromechanisms of a ductile cast iron are strongly affected by their microstructure, in terms of graphite characteristics (shape, distribution, and size) and metal matrix features (phases distribution and volume fraction) [12–14]. Specific heat treatments have been developed to modify the structure of different grades of ductile cast iron and improve their fatigue properties [15].

Defects or matrix discontinuities, such as non-metallic inclusions or micro-shrinkages, have also a strong effect on the fatigue strength [16]. Results from recent papers show that the localization of such inhomogeneities on the surface is particularly deleterious for the fatigue behavior of cast iron components, much more than internally located ones [17].

Regarding the effect of graphite, the nodules shape and size affect the fatigue strength of the material because in the initial stage of the failure process the microcracks nucleate around them and join, bringing the sample quickly to final rupture [18]. For a constant chemical composition, the nodule characteristics are mainly affected by casting dimensions. The larger the casting wall, the lower the cooling rate becomes and consequently nodularity and nodules number decrease [10]. In heavy section castings, several different graphite morphologies such as vermicular, spiky, coral, exploded and chunky graphite are formed during solidification step [19].

Chunky graphite consists of large blocks of branched and interconnected network within eutectic cells. It is usually found at the thermal centers of heavy sections at the end of slow cooling rate solidification [19]. Macroscopically, it appears as black spots on the fracture surface or cutting surface. Spheroidization treatments using cerium and rare earths in excessive amounts or high carbon equivalents contribute to the formation of chunky graphite [20]. Many studies tried to assess the causes and the mechanism of growth of chunky graphite, but a generally accepted theory for its formation has not yet been found [21–22].

Common accepted solutions to prevent chunky formation are the addition of elements such as Sb and Bi, low carbon equivalent compositions and the use of chills to induce a uniform and rapid cooling of the part [20].

Some works have shown that the presence of chunky graphite reduces mechanical properties in terms of tensile strength and elongation, while hardness and yield strength are not affected [16,23]. Few studies have instead investigated the influence of chunky on the fatigue behavior of heavy section components. Mourujärvi et al. carried out rotating-bending fatigue tests on a normalized ductile cast iron EN-GJS-800 containing different amounts of chunky [24]. In this work, it was shown that the increase of chunky content up to 20% and more involves a significant decrease of fatigue life of castings, with a drop of fatigue limit in the order of 30–40%. More recently, Ferro et al. performed uniaxial fatigue tests ($R = 0$) on ferritic ductile irons matrix containing 40% of chunky on average [10]. In this case, the decrease of fatigue resistance was quite limited, with a reduction of fatigue limit of only 14%. The authors tried to justify the unexpected result considering that microporosities can hide the negative effect of chunky graphite, but this explanation is not completely clear, as the size of microporosities shown in the paper is equal or smaller than that reported by Mourujärvi [24].

The uncertainty about the quantitative effect of chunky on fatigue resistance of ductile irons brings the designer to approach the problem of chunky graphite in a not unanimous way. Nowadays, for example, some designers neglect the effect of chunky on fatigue resistance of cast irons, while some others put strong limitations on the presence of chunky, discarding the part if it exceeds a certain amount.

The aim of this study is to give a more comprehensive interpretation about the influence of chunky graphite on fatigue resistance of ductile cast irons, which could help the designer to face this problem.

One possible reason of the controversial literature is the difficult to study the effect of the chunky and the micro-shrinkages on fatigue properties separately. Considering that the specimen for fatigue testing are cut from heavy section castings, with a random distribution of micro-shrinkages changing from one casting to another one, the risk to compare sets of samples with a different level of microporosity is rather high.

In this work, the study on chunky graphite was performed by rotating-bending fatigue tests carried out on samples collected from two different EN-GJS-400 cast irons, one of which was cast with the addition of a Ce-containing inoculant to promote the chunky formation.

The novelty of the approach was to evaluate the effect of chunky graphite on fatigue strength excluding the contribution due to differences in microporosity in the two sets of samples used for rotating-bending tests. For this purpose, the analysis of statistics of extremes was performed and the maximum size of micro-shrinkage cavities was predicted for both sets. The corresponding lower fatigue bounds were calculated by the Murakami equation [16,25] and this difference was used to determine the net effect of chunky on fatigue strength. The results showed that the decrease of fatigue limit due to chunky graphite is equivalent to the tensile strength reduction. This result has to be considered a general conclusion, as it fits with other published data referring to different fatigue loading conditions or considering ductile irons with a different matrix microstructure. The conclusion is also supported by the fractographic analysis, which proved that chunky graphite has no synergic effect with microporosity for the initiation of fatigue cracks.

2. Experimental procedure

2.1. Materials

A specific casting geometry was designed to investigate the effect of the chunky graphite on fatigue resistance. It consists of a simple cylinder with a diameter of 300 mm and 520 mm in height. The mold was made by silica sand and resin. An exothermic feeder was used at the pouring cup, while the runner was built up with ceramic tubes. To reduce defects, like gas porosities, the bottom casting was chosen, placing the ingate at the base of the cylinder. Finally, a ceramic tube was also used to create the riser (Fig. 1).

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