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Plain and notch fatigue strength of ductile cast iron GJS600: The role of defect sensitivity

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Abstract

The present work is aimed at exploring the applicability of the theory of critical distances (TCD) to the plain and notch fatigue prognosis of the ductile cast iron GJS600. Particular attention is paid to investigating how defectiveness influences material critical length. It was found that fatigue damage is triggered by microshrinkage porosity in plain samples and by graphite nodules in notched samples. This evidence makes cumbersome the applicability of TCD, which postulates the notch-crack equivalence. According to this postulate, the critical distance can be inferred from a plain and a notched or cracked specimen configuration. Since the plain variants examined in this paper exhibit a fatigue damage phenomenon different from the notched ones, the critical distance inferred in this way leads to inaccurate predictions of the fatigue strength of independent notched variants. To overcome this shortcoming, we explore here the possibility of inferring the critical distance from two notched variants with different notch severity.

Keywords: Notch fatigue; defects; ductile cast iron;

1. Introduction

Cast iron is an iron alloy with a high carbon content that can considerably reduce melting temperature and increase castability (Pero-Sanz Elorz et al. (2018)). To avoid the precipitation of hard and brittle cementite, Si is added to the

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chemical composition to promote the precipitation of carbon in the form of graphite. If high mechanical properties are requested, Mg and other elements are added to promote the precipitation of spheroidal nodules of graphite. This type of cast iron is denoted as spheroidal, nodular, or ductile cast iron. This is in general employed in the production of large thick-walled castings. The resulting unfavourable solidification conditions usually lead to the formation of casting defects, such as degeneration of graphite nodules and shrinkage microporosity, which impact negatively on the fatigue strength (Benedetti et al. (2019)).

Nomenclature

L_{th}	critical length estimated from plain fatigue strength and crack growth threshold
L	critical length according to LM estimated from plain and notched specimen geometries
L^*	critical length according to LM estimated from two notched specimen geometries
LM	Line Method
TCD	Theory of critical distances
ΔK_{th}	long crack growth threshold
$\Delta\sigma_{fl}$	plain fatigue strength range
$\Delta\sigma_{N,fl}$	notch fatigue strength range
$\Delta\sigma^*_{fl}$	intrinsic plain fatigue strength range

In general, machine and structural elements display geometric discontinuities, generically termed notches, that produce stress concentration and greatly affect the resulting fatigue strength. Therefore, in the fatigue design of components made of DCI, it is of paramount importance to evaluate the effect of the concomitant presence of notches and cast defectiveness. For this purpose, in this work, we will explore the fatigue strength of ductile cast iron by performing fully reversed axial fatigue tests on plain and notched specimens carrying notches of different severity, and we will try to interpret the experimental results according to a critical distance approach. The theory of critical distances (TCD) encompasses several notch fatigue calculation methods that postulate the fact that a cracked or notched member is in fatigue critical conditions when the crack or notch stress field averaged over a control volume equals the plain fatigue strength of the material (Taylor (2007)). In the classical formulation of the theory, the size of such a control volume turns out to depend on the plain fatigue strength and the long crack threshold ΔK_{th}. This paper investigates the applicability of this approach to DIC and proposes an alternative method based on the use of two notched specimen geometries to infer the material critical distance representative of the fatigue characteristics reigning in the vicinity of the notch tip.

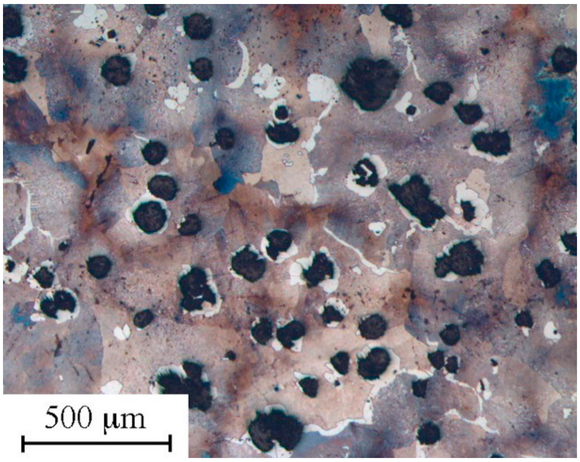

Fig. 1. Microstructure of the EN-GJS-600–3 coupons investigated in this work.

2. Material and experimental procedures

The experimentation was carried out on a GS600 pearlitic ductile cast iron, whose microstructure is shown in Fig. 1. The samples were extracted from an as-cast cylinder of high thermal modulus exposed to natural air convection, thus representative of thick-walled castings subjected to long solidification times. All the samples were taken from the bottom half of the cast cylinder to maintain a certain uniformity in microstructure and defectiveness. The fatigue characterization was conducted using the axisymmetric specimen geometries shown in Fig. 2 and tested under alternate axial loading. Specifically, the plain specimen geometry was used to determine the materials baseline fatigue S-N curve. V-notched specimen geometries are characterized by a notch depth, which was optimized to maximize the intensity of the asymptotic stress field term. Specimens (b) and (c) have a notch opening angle of 60° and differ only in the notch tip radius, whose nominal value was set to 0.2 and 1 mm, respectively. In the following, they will be denoted as sharp and blunt notches. Two additional notched geometries, denoted (d) and (e), were selected to obtain independent fatigue data to be used to validate the predictions made applying the TCD. Finally, a M(T) specimen, denoted (f) in Fig. 2, was fabricated to assess the long crack threshold ΔK_{th} under fully reversed loading. Crack extension was measured using a Fractomat® apparatus based on the indirect potential drop method. A force-shedding procedure was adopted until reaching near-threshold fatigue crack growth conditions.

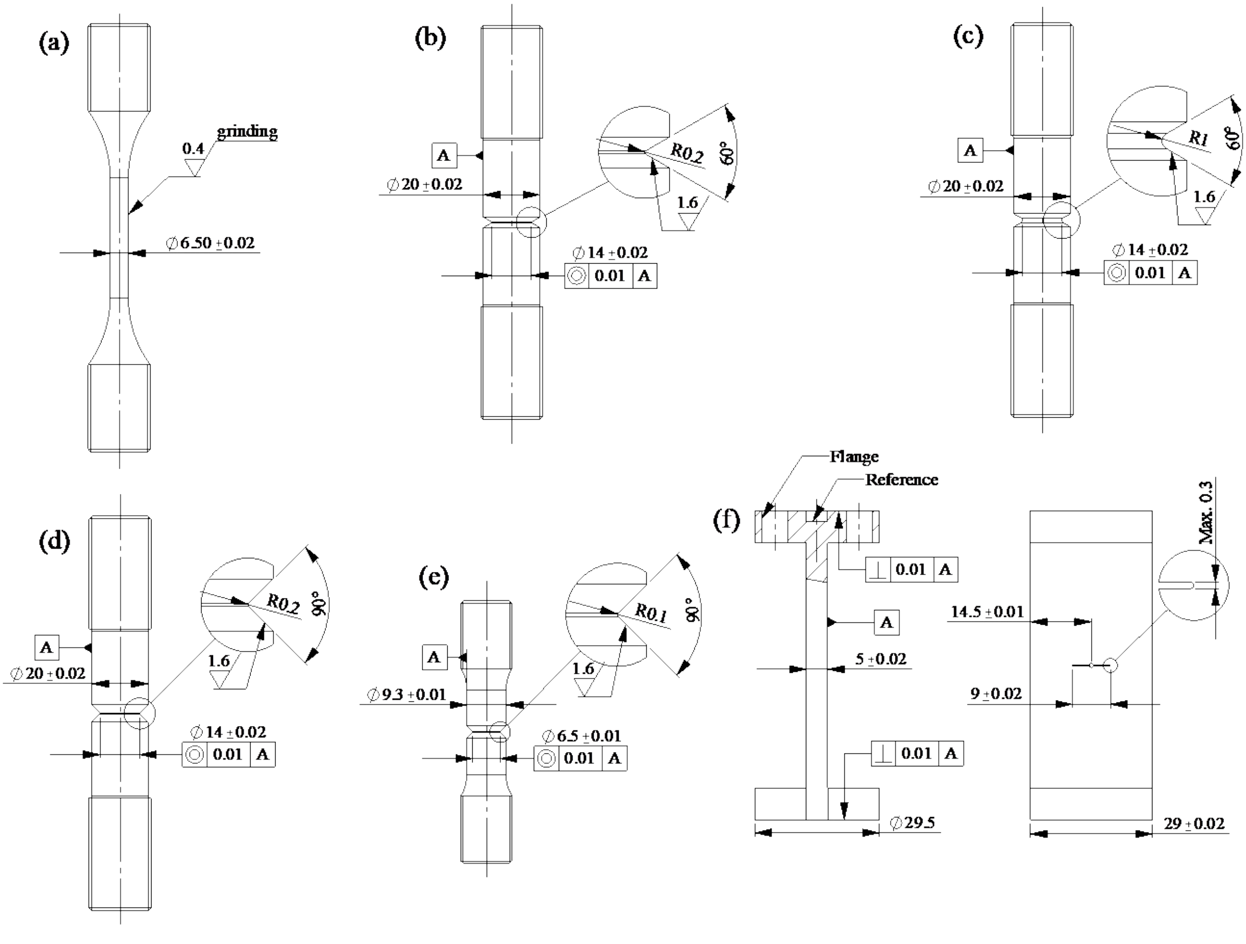

Fig. 2. Geometry of the specimens used for the fatigue characterization. (a) Plain and (b)-(e) notched specimens. (f) M(T) specimen used for the fatigue crack growth experiment. Dimension in mm. Fatigue data obtained from specimen geometries (b) and (c) were used to determine the critical distance L^* according to Blunt&Sharp approach specifically devised in the present work.

3. Experimental results and discussion

The results of the axial fatigue tests carried out on all the specimen variants are compared in Fig. 3. It can be noted that the plain fatigue data are affected by a considerable scatter, significantly larger than that of the notched counterparts. The fatigue curves of the notched variants approximately scale according to the notch stress concentration factor K_t, apart the geometry (e), which displays a superior fatigue strength with respect to that expected from K_t. Apparently, the small diameter of the specimen results in a more localized, and thus less detrimental, notch stress field.

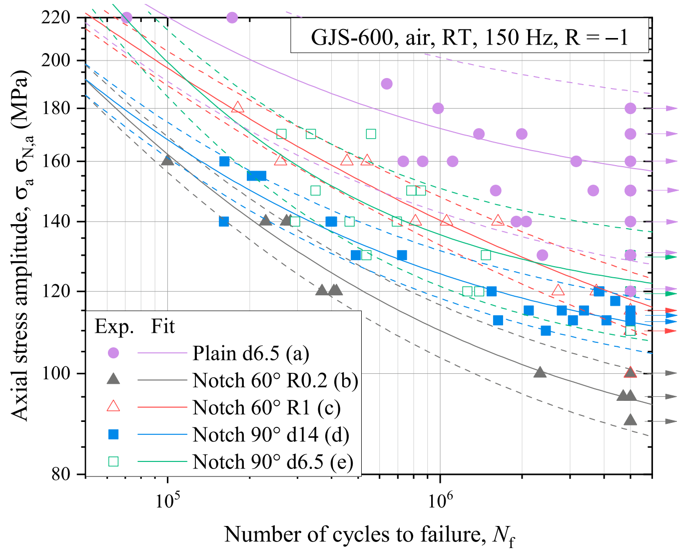

Fig. 3. Axial fatigue SN curves. Solid lines represent 50% failure probability, while dashed lines refer to 10% and 90% failure probability. Arrows indicated run-out tests.

SEM analyses were conducted to identify the dominant crack initiation mechanisms acting in the high cycle fatigue regime. In all investigated smooth samples (Fig. 4a), the crack was found to start in the vicinity of a large solidification shrinkage pore. The scenario depicted by the fracture surface of the notched variants is completely different. Despite careful search, no shrinkage microporosity was found in the neighborhood of any fatigue crack initiation site at the tip of the notched samples. The fracture surface reported in Fig. 4b indicates that the crack nucleated from a large graphite nodule located in the vicinity of the notch tip.

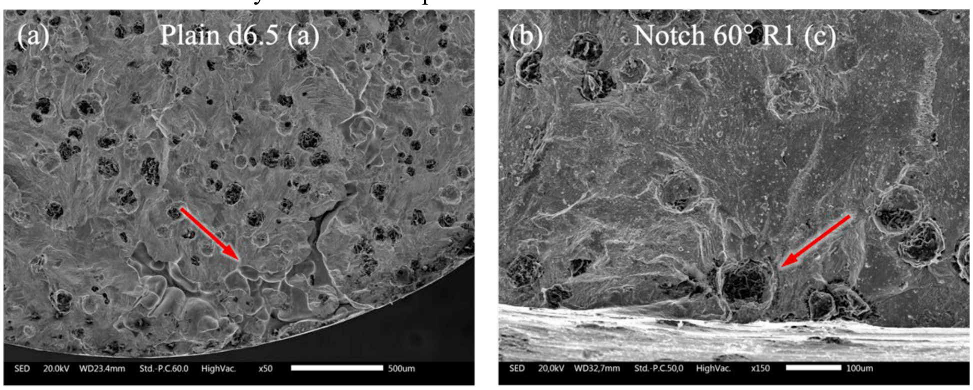

Fig. 4. SEM micrographs of the fracture surfaces around the site of initiation of the fatigue crack. (a) microshrinkage pore (red arrow) found in plain sample (a) (σ_a = 140 MPa, N_f = 1.9×10^6). (b) Graphite nodule (red arrow) that triggered the onset of fatigue cracks in the notched specimen (c) ((σ_a = 110 MPa, N_f = 5×10^6).

It is now clear that the fatigue damage mechanisms that prevail in plain and notched components are different. This could hinder the applicability of the theory of critical distances, which postulates that the critical distance L can be inferred from a plain and a notched or cracked specimen configuration. Specifically, we term "plain&threshold" the approach based on the determination of L starting from plain fatigue strength and crack threshold. With "plain&notched" we denote the inverse search method recently derived by us in this paper and based on the use of a plain sample and a notched samples with optimized shape to minimize the sensitivity to experimental uncertainty. To overcome the above discussed shortcoming, we explore in this work the possibility of inferring L from two notched geometries with different notch severity. The fatigue characteristics determined in this way are representative of the fatigue damage mechanism that rules the neighborhood of the tip of the notch. In this way, it is possible to deduce, along with the critical length L^*, an intrinsic plain fatigue strength $\Delta\sigma^*_{fl}$, which ideally represents the fatigue strength measured using miniaturized plain samples extracted from the notch tip. The mathematical formalism can be found in Benedetti et al. (2021).

Table 1. Results of the critical distance inversion methods.

Plain&treshold Specimen geometry (a)&(f)		Plain&sharp Specimen geometry (a)&(b)		Blunt&sharp Specimen geometry (c)&(b)	
$\Delta\sigma_{fl}/2\ (MPa)$	L_{th} (mm)	$\Delta\sigma_{fl}/2\ (MPa)$	L (mm)	$\Delta\sigma^*_{fl}/2\ (MPa)$	L^* (mm)
158	0.625	158	0.530	269	0.136

Table 1 lists the plain fatigue strength and the critical distance evaluated according to these three possible approaches. To apply the first approach "plain&threshold", the crack growth threshold was determined from fatigue crack growth experiments performed on a M(T) specimen. It can be noted that the two approaches based on the plain fatigue limit predict a very large value of the critical distance, above 0.5 mm, well above the values typically reported in the literature for structural metallic materials. On the contrary, the approach "Blunt&Sharp" based on two notched specimen geometries leads to an estimate of a much shorter critical distance L^*, approximately 0.14 mm, and an intrinsic plain fatigue strength $\Delta\sigma^*_{fl}/2$, (about 270 MPa) significantly higher than that displayed by the plain samples.

Table 2. Prediction of the notch fatigue strength and crack growth threshold of inde- pendent geometries not used in the calibration of the critical distance method.

Specimen geometry	Exp. (MPa/ MPam$^{0.5}$)	Plain&treshold		Plain&sharp		Blunt&sharp	
		Pred.	Err. (%)	Pred.	Err. (%)	Pred.	Err. (%)
Notch 60° R0.2 (b)	94.6	102	7.5	-	-	-	-
Notch 60° R1 (c)	118	105	-11	99.3	-16	-	-
Notch 90° d14 (d)	112	104	-7.2	97.5	-13	105	-6.4
Notch 90° d6.5 (e)	123	143	16	133	8.4	130	6.1
M(T) (f)	14.0	-	-	12.9	-7.9	11.1	-20

The predictions listed in Table 2 of the fatigue strength of independent notched variants permit assessing the suitability of these three critical distance approaches to predict the notch fatigue resistance of DCI. A systematic comparison is possible only for variants (d) and (e), which are used in neither of these approaches. Interestingly, the "Blunt&Sharp" approach is the only one able to keep the absolute relative error well below 10%. Conversely, the "Plain&Threshold" and "Plain&Sharp" predictions are affected by larger errors, since these latter two approaches are influenced by fatigue damage mechanisms occurring in plain and M(T) specimens that are scarcely representative of those taking place in notched coupons.

4. Conclusions

A significant difference was found in the defectiveness triggering the fatigue damage. In plain samples, a few shrinkage pores were found on the fracture surface. The largest pore is responsible for the initiation of fatigue crack. In notched samples, the likelihood that such critical pore is located in the process zone ahead of the notch tip is very low; therefore, the fatigue damage is promoted by the largest graphite nodule therein located. This evidence must be taken into account when applying a critical distance approach to predict the fatigue strength of DCI. A novel inverse search based on the use of two optimized notched geometries differing in the notch root radius and hence in the resulting stress concentration factor is better suited to TCD fatigue calculation of intrinsically flawed materials, such as additively manufactured materials, which will be a matter of future investigations.

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