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Surface conditions and the fatigue behavior of nodular cast iron

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Abstract

Since fatigue is largely a surface-controlled phenomenon, the use of as-cast specimen surfaces is expected to give different fatigue strength from that observed for smooth specimens. In the present work the fatigue behavior of pearlite/ferrite NCI specimens having different surface conditions, namely i) as-cast, ii) shot-blast and iii) fine-ground is discussed. The dependence of the fatigue behavior on specific surface condition is highlighted using prismatic specimens tested under cyclic plane bending with maximum stress reached at the surface of interest. The results show a scatter in fatigue life for all the investigated stress amplitudes, which can be associated with the surface conditions.

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1. Introduction

Nodular cast iron (NCI) is a construction material with a wide range of applications in engineering practice [1]. For optimal application of NCI it is important to know its basic mechanical properties including the fatigue strength. The fatigue strength of NCI is influenced by the matrix structure, the percentage of nodular graphite, and the presence of casting defects and geometrical notches. Experimentally, it has been shown that fatigue strength increase with increasing content of pearlite in the matrix, [2]. Fatigue strength is also sensitive to surface conditions. Namely, fatigue strength increases with decreasing surface roughness and increasing surface hardness as for surface treatments [3]. The effect of matrix structure on the fatigue strength is less pronounced in the presence of notches [4]. Since a cost-effective cast part is obtained by reducing machining to a minimum, the highest working stresses often develop at as-cast surfaces. Only few studies have been conducted on NCI with casting surfaces, although they are common in real applications, [5]. Specimens with as-cast surfaces are

expected to show a reduced fatigue strength compared to machined and fine-ground specimens. In addition to surface roughness, fatigue strength of NCI with as-cast surfaces is influenced by i) mechanical properties of the surface layers, and iii) local residual stresses.

This paper presents a study of the fatigue behavior of pearlite/ferrite NCI specimens having different surface conditions, namely as-cast, shot-blast and fine-ground. The dependence of the fatigue behavior on specific surface condition is highlighted using prismatic specimens tested under cyclic plane bending with maximum stress reached at the surface of interest. The characteristics of the surface layers in the different test specimens are examined by metallography. The role of the surface conditions on fatigue initiation is discussed on the base of a SEM investigation of selected fatigue fracture surfaces. The implications for fatigue model development are finally discussed.

2. Experimental details

2.1. Material and specimen preparation

The nodular cast iron for this study was prepared by melting 2000 kg of pig iron, 300 kg of steel scrap, and 1500 kg of cast iron scrap in an arched alkaline furnace. The bath was added 35 kg of FeSi alloy [6]. The resulting chemical composition of the pearlite-ferrite NCI is given in Table 1. The cast material was supplied in the form of 140x100x20 mm plates. No annealing treatment was performed before machining the specimens used for tensile and fatigue testing.

Table 1 Chemical composition of pearlite-ferrite NCI [%]

C	Si	Mn	S	P	Mg	Cr	Cu	Ni
3.68	2.62	0.51	0.005	0.05	0.034	0.2	0.02	0.01

A preliminary microstructural analysis was performed on polished and etched specimens taken from casting plates. Structural details were analyzed in the light metallographic microscope according to the norm EN STN 42 0461 and by the methods of quantitative metallography. The graphite nodules were observed in fully and partly not fully globular shape, see Fig. 1a.

Size of graphite nodules was predominately ranging from 30 to 60 μm (VI 6) and with a small number of nodules ranging in the size from 15 to 30 μm (VI 7). Graphite nodule count N was in average 260 mm^{-2} . The structure of NCI was characterized by a pearlite-ferrite matrix, Fig. 1b, with graphite nodules typically located in ferrite.

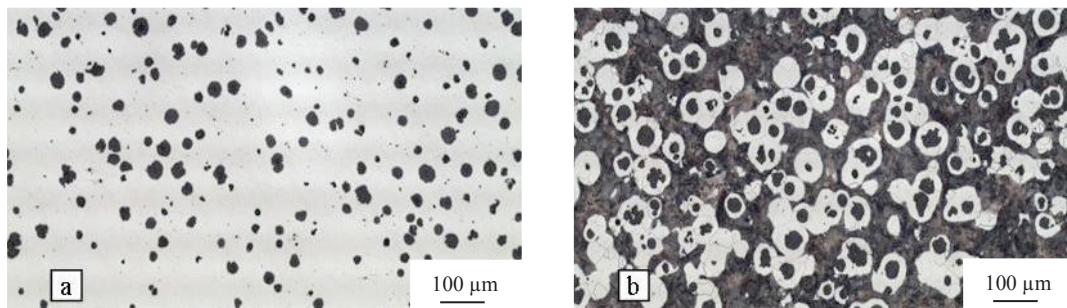


Fig.1 Microstructure of nodular cast iron, a) non etched, b) etched with 3% Nital

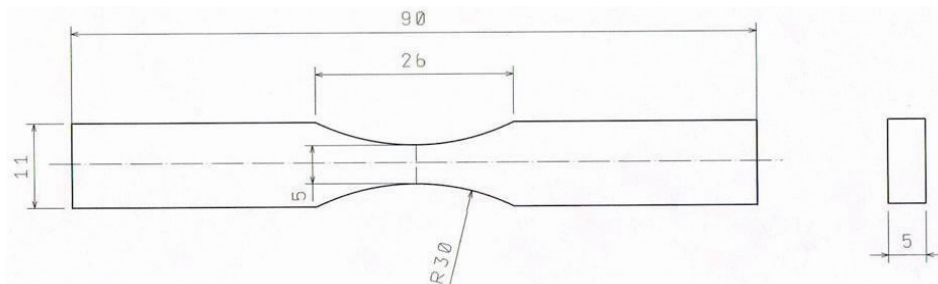


Fig. 2 Shape and dimensions of specimen

Standard dog-bone specimens with fine ground surfaces were extracted for tensile testing. The average mechanical properties of the present NCI were tensile strength $R_m = 576$ MPa and elongation to rupture $A = 6$ %. The bending loading configuration was adopted for fatigue tests to enhance the role of the surface state. The fatigue specimens were machined according to shape and dimensions shown in Fig. 2.

Three sets of fatigue specimens were prepared. One set (Fig. 3a) had one test surface in the as-cast condition and the other fine ground. Specimens indicated as shot blast (Fig. 3a) had the as-cast test surface shot blast after machining. The test surface of the fine ground specimens (Fig. 3a) had a smooth finish achieved by removing the casting surfaces by soft grinding.

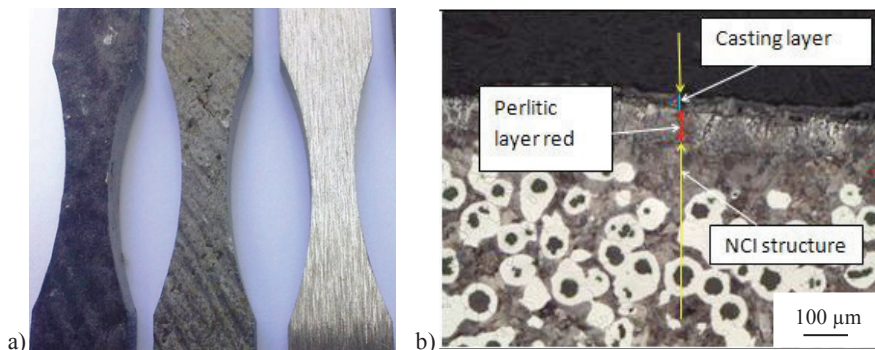


Fig. 3a) Specimen surface condition (from left) as-cast, shot-blast and fine ground; b) typical as-cast surface structure

2.2. Specimen surface characterization

The surface and subsurface characteristics were investigated and are discussed with reference to Fig. 3b. Typically, the free surface is covered by a thin cast layer made of oxides. Immediately below, a pearlitic layer formed by rapid solidification and cooling is found. Below these two layers and for the rest of the cross-section, the base NCI structure is found. Thickness of these layers and the surface roughness coefficient R_v were measured and are summarized in Tab. 2.

The shot blasting treatment removes the surface scale and locally deforms the metal but the vertical roughness is still comparable to the as-cast surface, see Tab. 2. Only fine grinding reduces significantly the surface roughness (i.e. by one order of magnitude) by elimination of the cast surface layers entirely.

The fully pearlitic layer removed by machining is approx. 100- μm -thick. Additional evidence is provided by the magnified view of the surface layers presented in Fig. 4a.

Table. 2 Characteristics of surface layers of the different specimens

	As – cast	Shot blast	Fine ground
Vertical roughness coefficient R_v	0.588	0.495	0.066
Thickness of casting layer	36 μm	Only locally present	Removed
Thickness of pearlitic layer	80 μm	110 μm	Removed

The casting layer contained many pores and cavities, which may affect fatigue crack initiation. Fig. 4b shows that in the shot blast specimens the pearlite layer contains lamellar graphite, which gradually turns into vermicular and finally spherical shape with depth. This combination of high strength pearlite and elongated graphite is expected to negatively affect the surface layer strength in fatigue favoring early crack initiation compared to the typical nodular cast iron structure, see Fig. 1b.

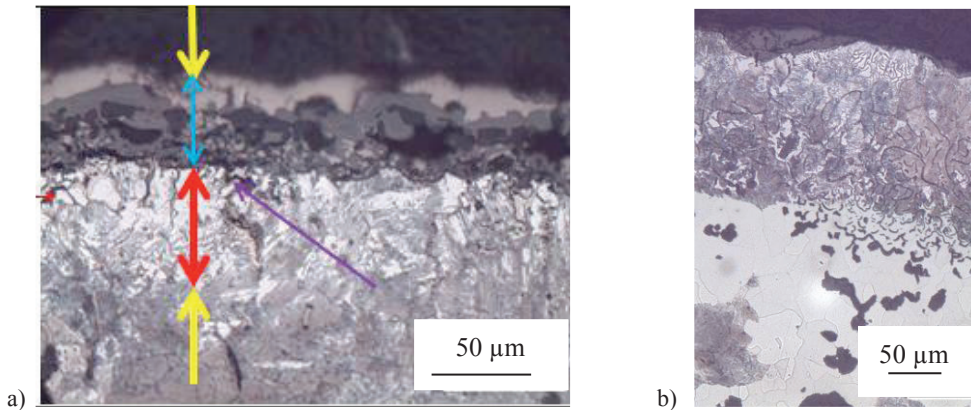


Fig. 4 Magnified view of surface layers of a) as-cast material; b) material after shot blasting

2.3. Fatigue testing

A plane cyclic bending loading condition was applied to the specimens using an Amsler-type testing machine operated at 25 Hz. Tests were interrupted at $2 \cdot 10^6$ cycles if the specimen did not fail. The load ratio $R = 0$ was defined for all fatigue tests, so that the specific surface of interest is subjected to the maximum tensile stress (the most critical in fatigue) and the opposite surface to a compressive stress range. A constant cyclic displacement condition was applied and the maximum and minimum stresses of the load cycle monitored continuously with a load-cell in series with the specimen. The stress amplitude is observed to remain substantially constant for the first part of the test followed by a continuous stress reduction in the final part because the specimen compliance changes due to fatigue crack initiation and evolution. A change of 5 % in peak stress was predefined as the boundary between the crack initiation and propagation phases.

3. Results and discussion

3.1. S/N data

Figure 5 shows the results of fatigue tests for all the specimens in terms of the cyclic stress amplitude σ_a vs. number of cycles to rupture N_f . One run-out was obtained for a fine ground specimen test at $\sigma_a = 125$ MPa. A ranking of the three surface conditions in fatigue is experimentally obtained with the best performance associated to the fine ground surface. At 10^6 cycles, the fatigue strength show a decrease of approx. 20% going from a fine ground to an as-cast surface. The surface roughness coefficient of the three surfaces, see Tab. 2, is coherent with the fatigue ranking of Fig. 5. The apparent scatter for the fine ground specimens is limited and increases with the other two surface conditions. As-cast and shot blast surfaces give a similar response in fatigue. However, the S/N trend of shot blast specimens appears to increase the fatigue life with respect to the as-cast surface at high stresses, but the treatment may reduce the life at low stresses.

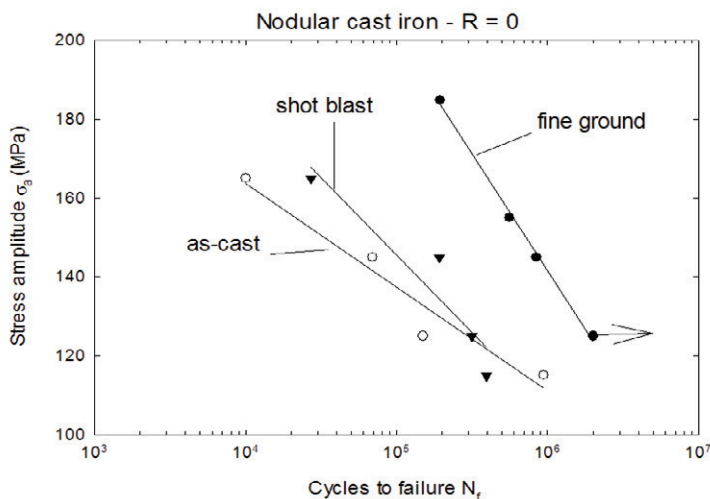


Fig. 5 S/N fatigue data for cyclic bending the NCI

3.2. Fatigue initiation

In previous studies, [5], fatigue fracture origins were traced to slag, pinholes, casting sand or the surface. In this case fatigue fracture initiation was difficult to be observed with a scanning electron microscope (SEM). However, the surface condition is expected to influence the fatigue crack initiation phase considerably with a strong effect associated to high surface roughness or by surface defects. From inspection of Fig. 4, both are observed in the surface layers of an as-cast surface. Fig. 6 shows the dependence of the initiation phase, defined as the number of cycles to a predefined drop in maximum stress (i.e. 5%) and normalized by the total fatigue life, as a function of applied stress and surface condition. Most of the fatigue life (i.e. > 0.9) of the fine ground specimens is spent for crack initiation. On the other hand, as-cast and shot blast surfaces favor early fatigue crack initiation and a considerable fraction of the fatigue life is spent for crack propagation to failure (i.e. < 0.6).

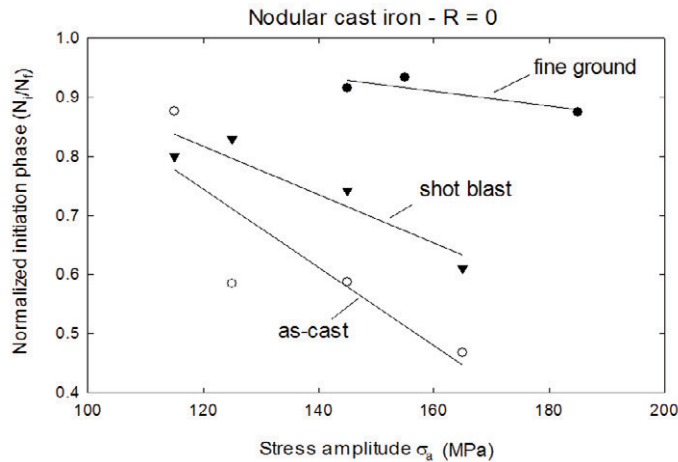


Fig. 6 Duration of initiation phase as a function for stress amplitude and surface condition

This phenomenon amplifies with applied stress and suggests the adoption of a fracture mechanics based approach to fatigue strength estimate.

4. Conclusions

The role of surface condition on fatigue strength of nodular cast iron was investigated. Specimens with as-cast, shot blast and fine ground surfaces were tested. The following conclusions are reached:

- Fine-ground surface achieve the best fatigue performance, with as-cast and shot blast surfaces associated to reduced strength (i.e. approx. 20 % less);
- The as-cast surface layers are characterized by significant roughness, defects and a brittle surface microstructure, which is quite different from the base pearlitic/ferritic base metal;
- The fatigue crack initiation phase is predominant in the fine ground specimens, while the crack propagation phase is relevant for the other surface conditions.

Acknowledgements

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