



NODULAR CAST IRON FATIGUE LIFETIME IN CYCLIC PLANE BENDING

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Resume

The fatigue behavior of a component is strongly dependent also on the material and its surface condition. Therefore, the manner in which the surface is prepared during component manufacturing (surface roughness, residual stresses etc.) has a decisive role in dictating the initiation time for fatigue cracks. The fatigue behavior of the same material, a nodular cast iron, with three different surface conditions (fine ground, sand blasted and as-cast) has been investigated under cyclic plane bending. The results show differences in fatigue strength, which are associated with the surface conditions. The characteristics of the surface layers of the different test specimens were examined by metallography.

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1. Introduction

Nowadays, nodular cast irons (NCI) are rapidly finding an increasing number of engineering applications because of several manufacturing and engineering advantages such as excellent combination of high strength, ductility, toughness, fatigue strength, and wear resistance. In addition, NCI is competitive in the fabrication of machine parts of complex shape [1].

Since a cost-effective cast part is obtained by limiting machining to a minimum, the peak working stresses often develop at as-cast surfaces. Fatigue strength is a measure of the reliability of mechanical components and is sensitive to surface conditions, i.e. it increases with decreasing surface roughness and increases with increasing surface hardness following surface treatments [2]. Only few studies have been conducted on NCI in the presence of as-cast surfaces, although they are common in real applications [3, 4].

The fatigue strength of NCI with as-cast surfaces is influenced by various factors, i) surface roughness, ii) quality of surface layer

produced by casting, iii) types of defects, iii) local residual stresses after sand blasting. These factors interaction results in lower fatigue strength of NCI specimens with an as-cast surface from that observed for smooth machined specimens [2, 4, 5].

This paper presents a study of the fatigue behavior of pearlite/ferrite NCI specimens having different surface conditions, namely as-cast, sand blasted and fine ground. The dependence of the fatigue behavior on specific surface conditions is highlighted using prismatic specimens tested under cyclic plane bending ($R = 0$) with maximum stress reached at the surfaces under investigation. The structural characteristics of the different surface layers of tested specimens were examined by metallography.

2. Experimental material

The experimental material was prepared as synthetic melt from 2000 kg of pig iron, 300 kg of steel scrap, and 1500 kg of cast iron

scrap. The melting was performed using an arched alkaline furnace with basic lining and 35 kg of FeSi was added to the melted metal as an additive to increase the content of Si [6]. Chemical composition of the pearlite/ferrite NCI is given in Table 1. The cast material was supplied in the form of 140 x 100 x 20 mm plates. The fatigue specimens, Fig. 1, with as-cast surface were prepared by machining from cast plates. Sand blasting treatment was applied on cast plates, before the fatigue specimens machining. Fatigue specimens with fine ground surface were prepared from milled and fine grinded plates. No annealing treatment was performed before machining of the specimens used for tensile and fatigue testing. The tensile tests performed according to the ASTM E8 standard of the present NCI gave a tensile strength $R_m = 576$ MPa and an elongation to rupture $A = 6$ %. The structural analysis of NCI was performed on polished and etched specimens taken from cast plates. Structure details were analyzed in the light metallographic microscope according to the EN STN 42 0461 standard and by the methods of quantitative metallography [5].

Table 1
Chemical composition of pearlite/ferrite NCI (wt. %)

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

2.1. Metallographic analysis

The structure of NCI was characterized by pearlite/ferrite matrix with slightly different content of ferrite (in the range from 20 to 40 % or Fe 30 according to the standard) in different specimens. The graphite nodules were observed in fully globular shape (VI) and no perfectly globular shape (V) and they were located in ferrite, Fig. 2. Size of graphite nodules was predominately ranging from 30 to 60 μm (6 according to the standard) and with a small number of nodules ranging in the size from 15 to 30 μm (7 according to the standard). Graphite nodules count N was 260 mm^{-2} in average. Three sets of fatigue

specimens (for geometry see Fig. 1) were prepared. The first set had the evaluated surface in the as-cast condition (Fig. 3) and the opposite ones were grounded in all cases. Second set of specimens had evaluated surface after sand blasting of the as-cast surface, Fig. 3, by using compressed air pressure (i.e. 1 MPa); the erodent abrasive was of SiC sand (i.e. grain size 250-300 μm). The tested surface of the fine ground specimens, Fig. 3, had a smooth finish achieved by removing the casting surfaces by machining of plates on a vertical milling machine and finished by soft grinding on a disk sander. The soft grinding was conducted by ceramic aluminum oxide wheel under the conditions of the grinding speed of 30 m/s, down feed 0.020 mm/pass.

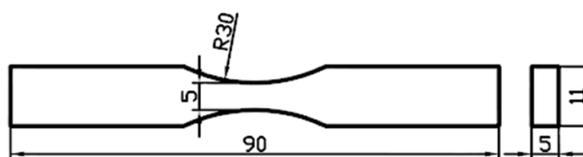


Fig. 1. Shape and dimensions of specimen



Fig. 2. Characteristic microstructure of the studied NCI, etched with 3 % Nital



Fig. 3. Surface condition of specimens (from left as-cast, sand blasted, fine ground)

2.2. Specimen surface characterization

The surface and subsurface characteristics were metallographically investigated on cross sections perpendicular to the fracture surface and are discussed with reference to Fig. 4. Typically, the as-cast surface is covered by a thin cast layer made of oxides and pores. Just below this surface layer, a pearlitic layer with variable thickness, formed due to rapid solidification and cooling was found. Below these two layers and for the rest of the cross-section, the base NCI structure was found, see Fig. 2. Thickness of these layers and the surface roughness coefficient R_v were measured and are summarized in Table 2.

The sand blasting treatment removes the thin cast layer of oxides and pores and locally deforms the metal but the vertical roughness R_v (measured on cross-sections of specimens by quantitative metallography) is still comparable to the as-cast surface, see Table 2. Only fine grinding reduced significantly the surface roughness (i.e. by one order of magnitude) by complete elimination of the surface layers (formed by thin cast layer of oxides and pores and pearlitic structure). The surface structure is shown in Fig. 2. The average surface roughness (measured by surface roughness meter) of fine ground specimens was $R_a = 2.3 \mu\text{m}$.

Table 2
Characteristics of surface layers
of the different specimens

	As-cast	Sand blasted	Fine ground
Vertical roughness coefficient R_v	0.588	0.495	0.066
Thickness of cast layer	36 μm	only locally present	removed
Thickness of pearlitic layer below cast layer	variable from 80 to 110 μm	variable from 80 to 110 μm	removed

The thin cast layer (Fig. 5) contained pores and cavities, which affect fatigue crack initiation. Fig. 6 shows that in the sand blasted specimens the pearlitic layer contains lamellar graphite, which gradually turns into vermicular

and finally nodular shape going from the surface to the core of material. The combination of lower strength of pearlite matrix with lamellar graphite is expected to negatively affect the surface layer strength in case of fatigue loading because it results in early crack initiation compared to the typical nodular cast iron structure, see Fig. 2.

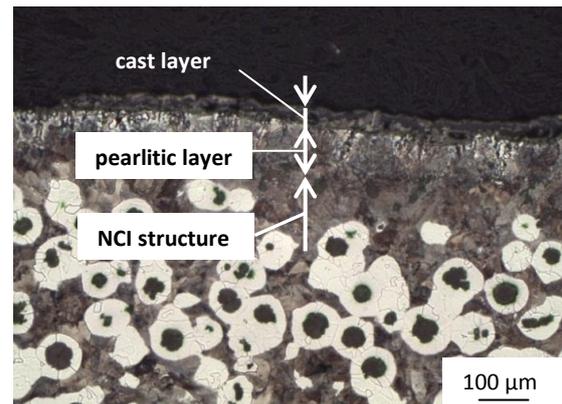


Fig. 4. Typical as-cast surface structure, etched 3 % Nital

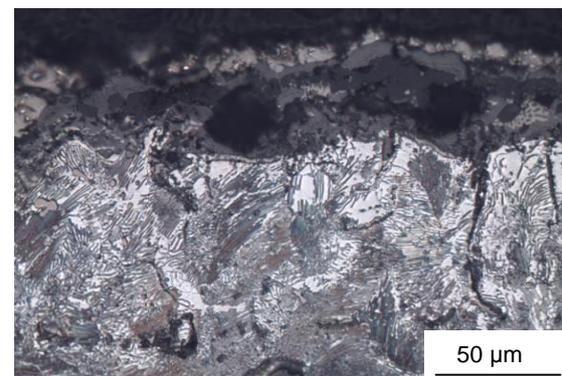


Fig. 5. Detail of surface layers of specimens with as-cast surface

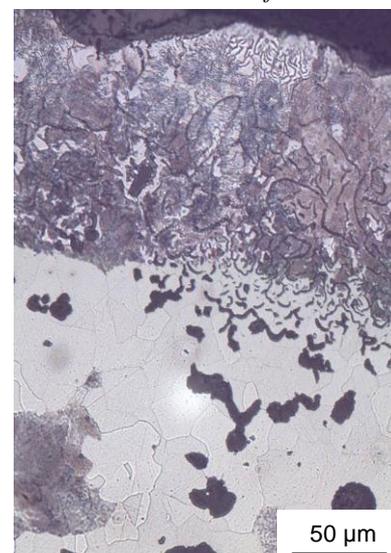


Fig. 6. Magnified view of surface layer after sand blasting

2.3. Fatigue testing

Fatigue tests were performed on specimens using a fatigue test machine for cyclic plane bending with loading ratio $R = 0$ and 25 Hz frequency. Tests were interrupted at $2 \cdot 10^6$ cycles if the specimen did not fail. The ratio $R = 0$ allowed to apply a cyclic tensile loading (the most critical in fatigue) to the surface of interest, either *as-cast*, *sand blasted* or *fine ground*. The initial stress range was associated to a fixed displacement range. A load-cell monitoring the specimen stress during the test allowed the determination of the evolution of specimen compliance. It was observed that the fixed initial stress range remained constant for a substantial part of the test followed by a continuous stress reduction in the final part because of fatigue crack initiation and propagation. A change of 5 % in peak stress was predefined as the boundary between the crack initiation and propagation phase

3. Results and discussion

Fig. 7 shows the results of fatigue tests for all specimens. Trends of the S/N dependence for different surface conditions were identified.

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 shows a decrease of approx. 20 % going from a fine ground to a sand blasted surface.

The scatter of results for specimens with as-cast surface was very large and estimation of the fatigue limit of these specimens from the S/N dependence was difficult. The large scatter of results can be explained by the presence of many defects in the cast surface layer, from which the fatigue cracks are initiated very quickly [7]. With regard to the effect of vertical roughness coefficient (Tab. 2) on fatigue strength, as expected, the fatigue strength increases as the surface becomes smoother. As-cast and sand blasted surfaces give a similar response in fatigue behavior.

Fatigue life of castings strongly depends on surface condition. Only a few studies [3, 8, 9, 10], have been conducted on NCI castings with as-cast surfaces. In the presented case fatigue fracture initiation was difficult to be observed with a scanning electron microscope (SEM).

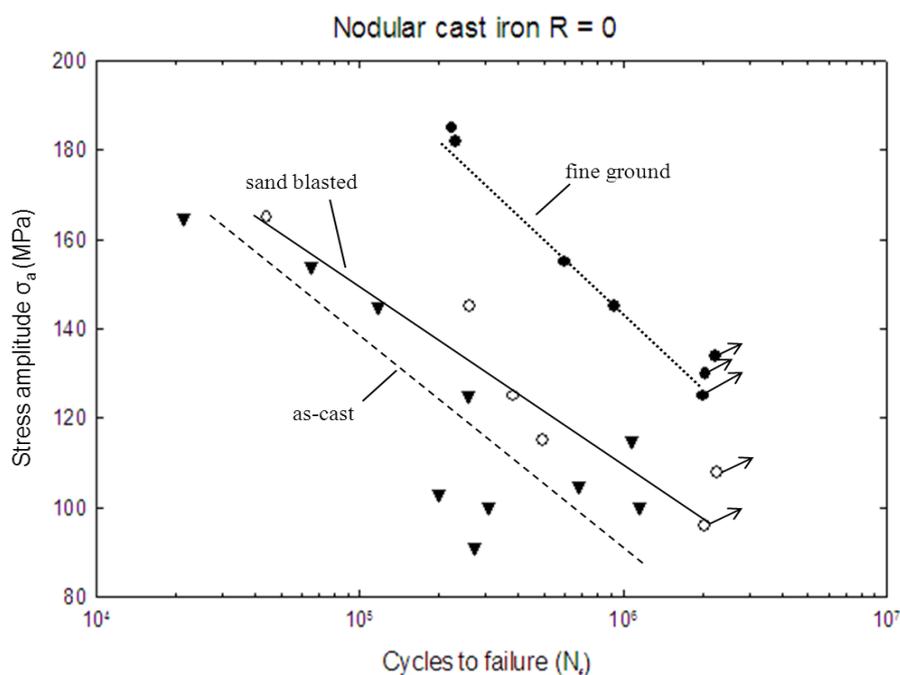


Fig. 7. S/N fatigue data after cyclic plane bending of the NCI specimens

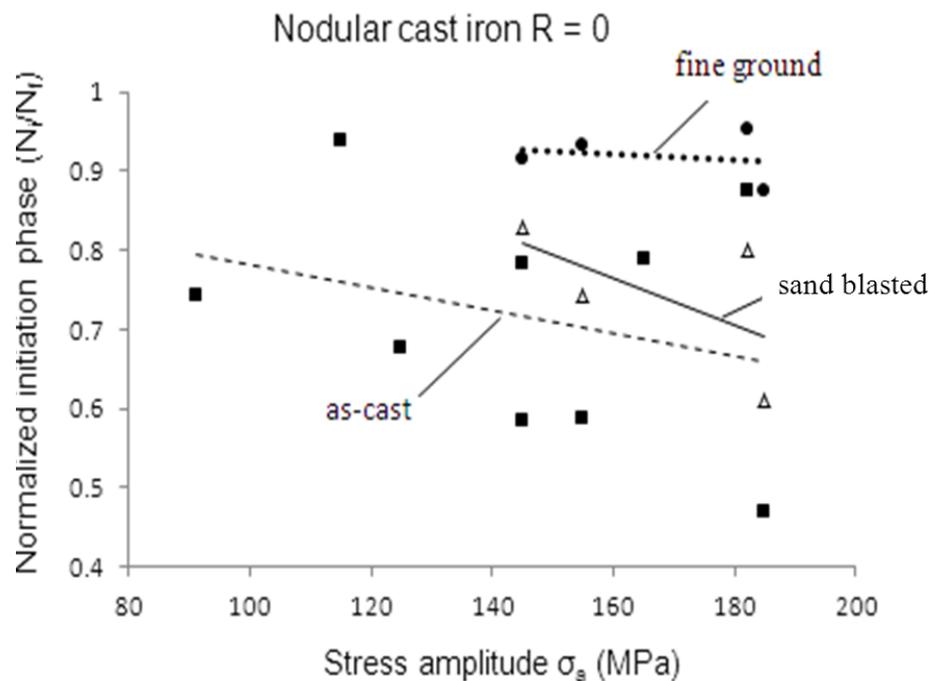


Fig. 8. Duration of initiation phase as a function of stress amplitude and surface condition

However, the surface condition is expected to influence the fatigue crack initiation considerably with a strong effect associated to high surface roughness or by surface defects. The dependence of the crack initiation phase duration on the applied stress amplitude is shown in Fig. 8, and it is defined as the number of cycles to a predefined drop in maximum stress (i.e. 5 %) normalized by the total fatigue life. 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 sand blasted 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).

4. Conclusions

A fatigue characterization of a pearlite/ferrite NCI with different surface condition has been presented. From the study, the following conclusions can be drawn:

- A fine ground surface achieves the best fatigue performance. The fatigue strength reduction of the as-cast and sand blasted surfaces with respect to the fine ground surface is significant (i.e. approx. 20 %).
- Fatigue fracture origins of nodular cast iron with as-cast surface are largely attributed to the surface roughness and defects existing in the vicinity of the as-cast surface.
- The as-cast surface layers are characterized by significantly high vertical roughness, defects and a brittle surface structure due to the presence of lamellar graphite, which is very different from the base pearlite/ferrite metal microstructure with nodular graphite.
- The fatigue crack initiation phase is predominant in the fine ground specimens, while the crack propagation phase is relevant for the other two tested surface conditions.

Acknowledgements

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