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Effect of in-mould inoculant composition on microstructure and fatigue behaviour of heavy section ductile iron castings

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Abstract

In this paper, the influence of the in-mould inoculant composition on microstructure and fatigue behaviour of heavy section ductile iron (EN GJS 700-2) castings has been investigated.
Axial fatigue tests under nominal load ratio R=0 have been performed on specimens taken from the core of large casting components. Metallographic analyses have been carried out by means of optical microscopy and important microstructural parameters that affect the mechanical properties of the alloy, such as nodule count, nodularity and graphite shape, were measured. Furthermore, Scanning Electron Microscopy was used to investigate the fracture surfaces of the samples in order to identify crack initiation and propagation zones.
Cracks initiation sites have been found to be microshrinkages close to specimens' surface in most cases. It was found that in-mould inoculant composition strongly influences the alloy microstructure, such as nodule count and shrinkage porosities size, as well as the fatigue resistance of heavy section ductile iron castings.

Keywords: cast iron, fatigue, heavy section casting, inoculation, microstructure, electron microscopy.

1.Introduction

In the last few years, an increased production of heavy section ductile iron castings has been noted. Examples of this trend are the increased productions of wind turbine parts, engine blocks or hydraulic presses components. The use

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of this type of material is justified by its excellent mechanical properties (tensile strength, ductility, wear resistance) and castability properties. In heavy section castings, the control of the microstructure during the solidification and cooling is very difficult. As a matter of fact, the microstructure depends on cooling rate, alloying elements, casting temperature, spheroidizing and inoculation treatments. Mechanical properties are influenced by microstructure and solidification defects of the alloy. In ductile iron castings, major defects that negatively influence the material properties are correlated to graphite particles shape and dimensions in the thermal centre of castings (for example low nodule count or chunky graphite (CHG)). Shrinkage cavities or inclusions are other detrimental defects that reduce mechanical resistance (T.M. Rowley, (1993); Zhang et al., (1989)). Microstructure and defects may be conveniently controlled by specific inoculants and inoculation practice. For example, in Ferro et al., (2013), authors have shown how inoculant containing rare earth metals and bismuth drastically reduce the formation of chunky graphite in heavy section ductile iron castings. In Skaland, (2003) it was found that the control of chemical composition and process parameters is fundamental to obtain sound castings. In particular, high nodule counts that prevents the formation of shrinkage cavities are obtained above all by optimizing the inoculation process.
It is well known that fatigue resistance of mechanical components depends mainly on the microstructure, notch factors and surface conditions (Atzori et al., (2011); Ferro et al., (2012); Mourujärvi et al., (2009)). Graphite nodules and defects work like shrinkage cavities and act as crack initiation points. The greater the casting dimensions, the greater the solidification times and the lower the nodularity and nodule count. In such conditions, the fatigue resistance decrease. Ferro et al., (2012) demonstrated that even if chunky graphite significantly reduces tensile strength and elongation at failure of samples, it did not affect the yield strength and fatigue limit of the castings. Scanning emission microscopy analyses have shown that microshrinkages near the specimens surface act as crack initiation points and probably hide the influence of CHG on fatigue strength.
Nadot et al., (1999) observed that crack initiation point is a unique microporosity in proximity of the specimen surface. They also found that in uniaxial fatigue tests the fatigue limit is much more sensitive to surface defects than internal defects. These results are confirmed by other works (Collini and Pirondi, (2014); Collini et al., (2011)) where it is observed that microshrinkage cavities strongly influence the fatigue behaviour of ductile iron castings. In Kainzinger et al., (2013) several fatigue tests have been performed on specimens taken from different points within a wind turbine hub. It has been found that the crack propagation is influenced by the microstructure while crack initiation is influence above all by microshrinkage porosities. In other works (Berto et al., (2013); Tovo et al., (2014)) smooth and notched specimens, taken from thick-wall ductile iron castings, have been tested under multiaxial loading conditions. About the fatigue strength of notched specimens, it was shown that by using the strain energy density (SED) approach, a quite narrow SED-based scatter band (scatter index equal to 1.90) is obtained. Furthermore, cast iron was observed to be characterized by an unusual sensibility to the out-phase loading in multiaxial fatigue tests. While a comprehensive study of fatigue behaviour of EN-GJS-400-18-LT has been performed with the evaluation of both geometrical and technological size effect on fatigue behaviour of this material (Shirani and Harkegard, (2011);Shirani and Harkegard, (2011); Shirani and Harkegard, (2014); Shirani et al., (2010); Zambrano and Harkegard, (2010); Zambrano et al., (2012)), fatigue behaviour of EN-GJS 700-2 heavy section ductile iron castings was studied only in few recent works (Christoph Bleicher et al., (2015)) and needs more investigations. Compared to previous works, in this paper the influence of inoculant chemical composition on microstructure and fatigue resistance of heavy section pearlitic ductile iron castings have been investigated. By an optimization of the inoculation process, it is possible to increase the nodule count and reduce the microshrinkage cavities with a significant reduction of the scatter band in the fatigue tests results.

2.Experimental Procedures

The castings used in this work were blocks 300x250x300 mm^3 with feeders on top surfaces; such dimensions were chosen with the aim to enhance the solidification time. The mould, produced with furan sand, contained 4 samples. The material under investigation was nominally an EN-GJS 700-2 ductile cast iron. Two different castings, named A and B, were produced by varying the in-mould inoculation treatment. In particular, a type of inoculant containing only Si, Al and Ca was used for casting A, while a combination of two different types of inoculants containing RE and Bi were used for casting B. The final chemical compositions of the melts and the in-mould inoculants chemical compositions are summarized in Table 1 and Table 2 respectively.

Table 1 - final chemical composition (wt%)

Cast	C	Si	S	P	Mn	Ni	Cr	Mo	V	Cu	Ti	Al	Sb	Mg
A	3,65	1,95	0,009	0,018	0,30	0,016	0,030	0,002	0,02	1,25	0,015	0,01	0,002	0,059
B	3,75	2,25	0,009	0,017	0,30	0,016	0,025	0,001	0,02	1,20	0,014	0,01	0,003	0,063

Table 2 - chemical composition (wt%) of the in-mould inoculants

In-mould inoculants					
Casting	Si	Al	Ca	RE	Bi
A	70 - 78	3.2 - 4.5	0.3 - 1.5		
B	70 - 75	0.8 - 1.2	0.8 - 1.2	0.8 - 1.2	0.8 - 1.2
B	70 - 75	3.5 - 4.5	<1.5	0.5 - 0.8	0.5 - 0.8

Each block was sectioned in order to obtain specimens (Figure 1) from the areas of most interest to this work which are those characterized by the longest solidification time (about 3 hours). Tensile and fatigue tests were carried out at room temperature by using a universal MTS machine (250 kN). Fatigue life tests were conducted by using a sinusoidal signal in uniaxial tension with a frequency of 15 Hz and a load ratio R=0. The fracture surfaces of some samples were investigated by means of FEG-ESEM (Field Emission Gun – Environmental Scanning Electron Microscope) (FEI, Quanta 250 FEG) in order to identify crack initiation and propagation zones. With the aim to evaluate the influence of microstructure on fatigue strength, metallographic analyses were carried out in a section near the fracture surface of fatigue specimens. In particular, following the ASTM E2567 standard, nodule count, nodularity and nodule size were evaluated. For each specimen, ten acquisitions (100x magnification) were used.

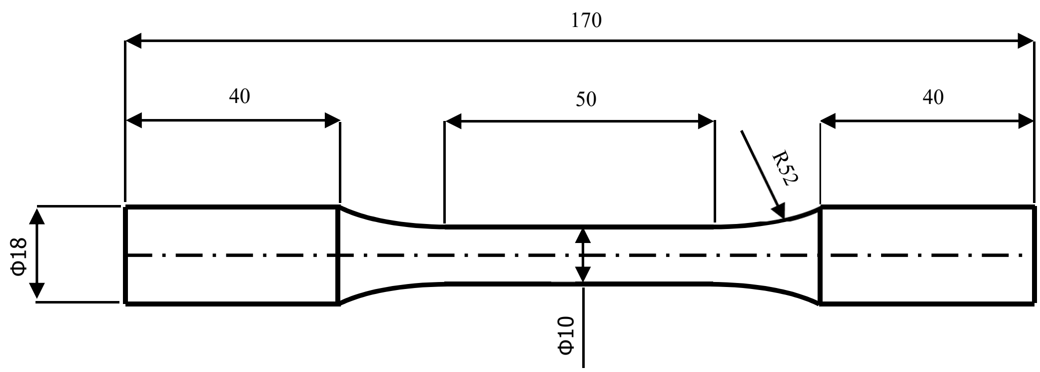

Figure 1 Geometry of the specimens for mechanical tests

3.Results and Discussion

3.1 Tensile Tests Results

In order to evaluate the mechanical properties of the alloy, tensile tests were carried out at room temperature. The obtained mean values of five tests are reported with their standard deviations in Table 3. It can be noted that the mean value of tensile strength is much lower than the nominal value of 700 MPa (the alloy was classified as EN-GJS 700-2 ductile iron). This is not surprising because the specimens were taken from the core of the casting where the microstructure of the material is difficult to control.

Table 3 - Mechanical properties of specimens taken from the castings

Casting	σ_R [MPa]	σ_y [MPa]	ε_R %
A	579 ± 5.1	364 ± 3.4	2.6 ± 0.3
B	513 ± 10.3	368 ± 4	1.9 ± 0.2

3.2 Fatigue Tests Results

Fatigue tests results were statistically elaborated by using a log-normal distribution. The mean curve related to a survival probability of 50% and Haibach's scatter band defined by lines characterized by a survival probability of 10% and 90% were calculated. Results obtained with samples coming from castings A and B are reported in Figure 2 and Figure 3, respectively. It can be noted that the difference between the two fatigue curves are related both to the mean value of the stress amplitude at $2 \cdot 10^6$ cycles, and to the scatter index T_σ. In particular, the value of $\sigma_{a,\, Ps\, 50\%}$ at $2 \cdot 10^6$ cycles related to casting B is about 12% higher than the value of $\sigma_{a,\, Ps\, 50\%}$ at $2 \cdot 10^6$ cycles obtained for casting A and the scatter index T_σ for casting B is 28% lower than that for casting A.

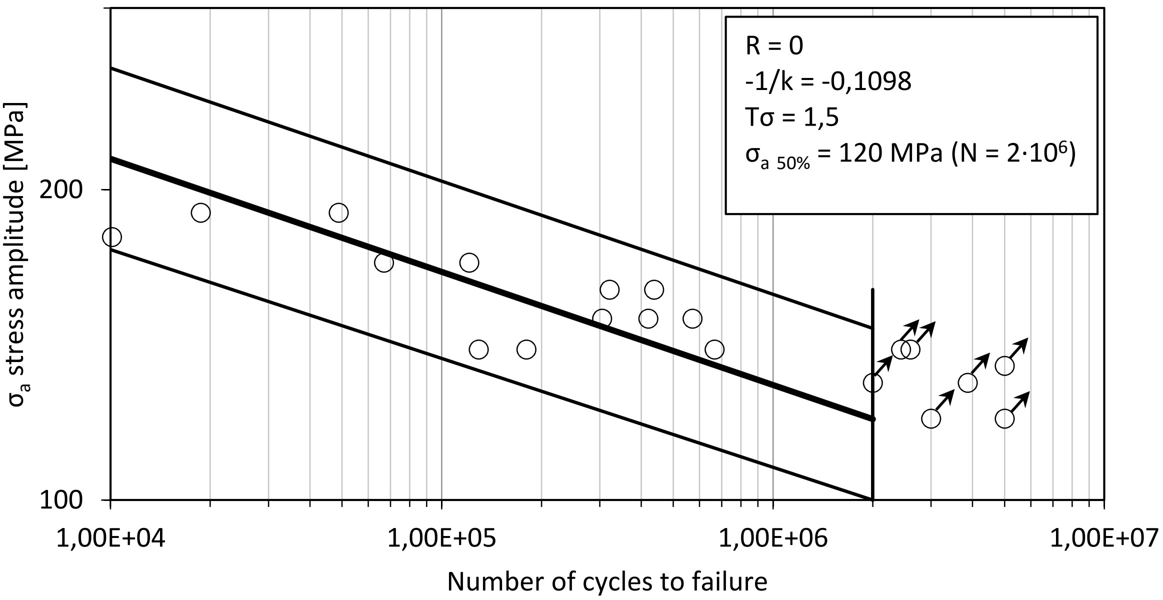

Figure 2 Fatigue life of specimens taken from casting A

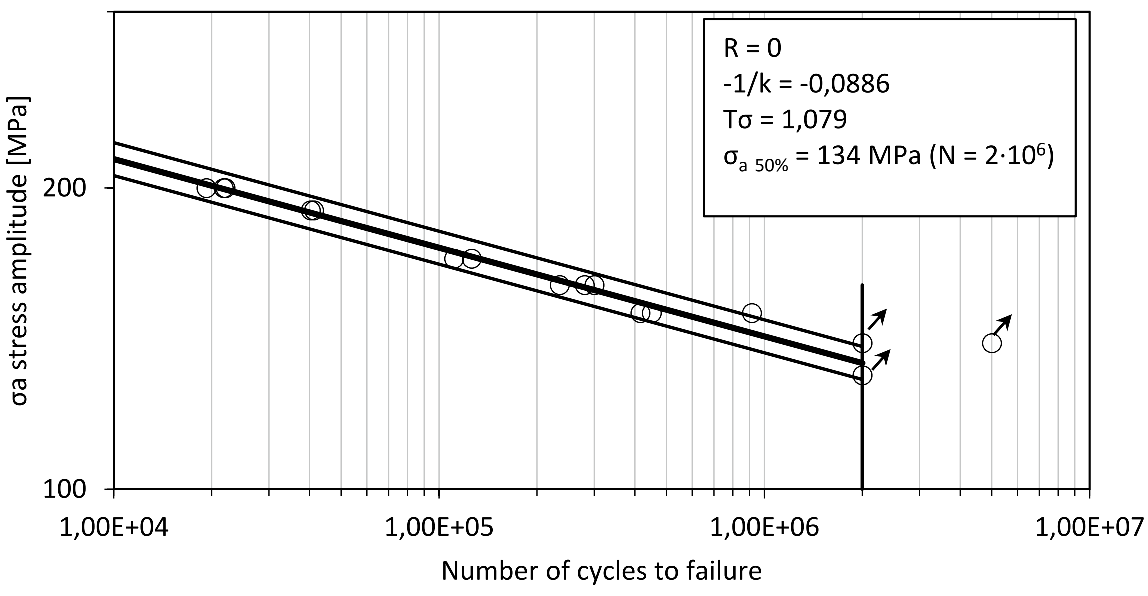

Figure 3 Fatigue life of specimens taken from casting B

3.4 Microstructure and fractography

The results of image analysis are summarized in Table 4. It is noted that the nodularity and nodule count were found to be higher for casting B compared to casting A, while the mean nodule diameter of casting B was lower than that observed in casting A. This result shows a better effect of inoculants on the final microstructure of casting B with respect to A. After etching with Nital 5, the micrographs of both A and B samples show a pearlitic matrix with some percentage of ferrite at the grain boundaries and surrounding the graphite nodules. However, ferrite percentage was observed slightly higher in casting B than casting A. It is worth noticing that in some specimens taken from casting B, small amount of degenerated spiky graphite has been found. A micrograph of such defect is shown in Figure 5. The formation of such degenerated graphite shape is attributed in literature to the presence in the melt of detrimental elements such as lead, antimony, bismuth. This last is present in inoculants used for casting B (**Errore. L'origine riferimento non è stata trovata.**). The use of nodulariser containing rare earths may prevent this type of defect (Ecob, (2005)).

Table 4 microstructural properties of samples

Casting	Nodularity (%)	Nodule Count (mm^{-2})	Mean Nodule Diameter (μm)	Graphite fraction %
A	74 ± 17	26 ± 15	66 ± 15	9.8 ± 1.5
B	81 ± 9	52 ± 17	45 ± 6	10.9 ± 1.2

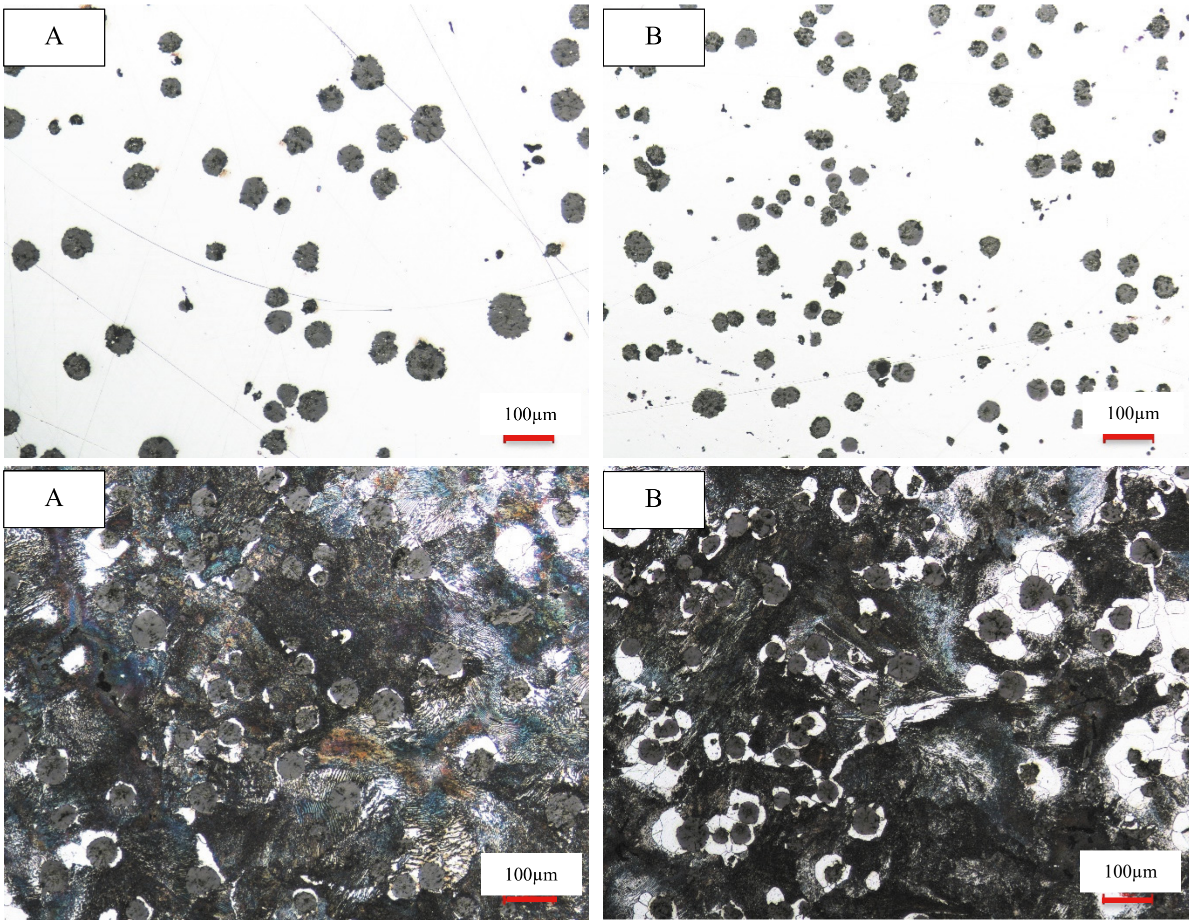

Figure 4 Micrographs of specimens taken from casting A and B

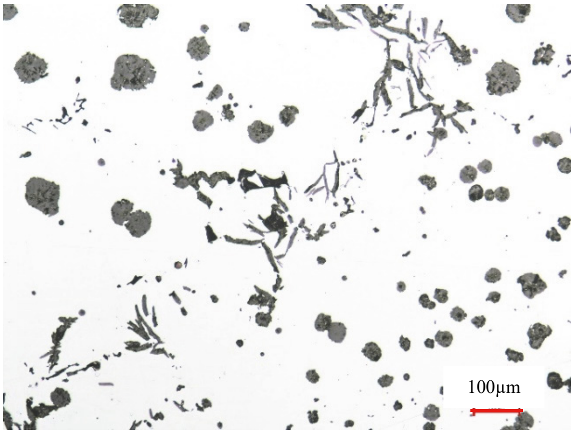

Figure 5 Micrograph of degenerated graphite from casting B

Fracture surfaces of broken specimens under fatigue loading have been investigated. Figure 6 shows shrinkage porosities near the sample surface which have been identified as cracks initiation sites, as reported in literature (Christoph Bleicher et al., (2015); Ferro et al., (2012); Kainzinger et al., (2013); Nadot et al., (1999); Shirani and Harkegard, (2014)). It can be observed that such cavities are on average greater in casting A than in casting B. This is because a better inoculation treatment induces higher nodule count and graphite expansion effect that reduces shrinkage porosities dimensions. It is suggested that post-inoculation of casting B focused its effect to the end of solidification where graphite expansion is more effective in countering the shrinkage. On the other hand, post inoculation of casting A affected above all the early stage of solidification and gave very little contribution to expansion in the last part of solidification when most needed. This confirms the higher mean value of the stress amplitude $\sigma_{a,\ Ps\ 50\%}$ at $2{\cdot}10^6$ cycles and the narrower scatter band observed in the fatigue life diagram of cast iron B compared to that of cast iron A. It has been also observed that the fatigue cracks pass around the graphite nodules, which slow the propagation while final failure happens in a brittle manner by cleavage that occurs along crystallographic planes in each grain fractured (Figure 7). The presence of degenerated graphite in casting B is suggested to have detrimental effects on the ultimate tensile stress and elongation at failure, without decreasing the yield stress and the fatigue resistance.

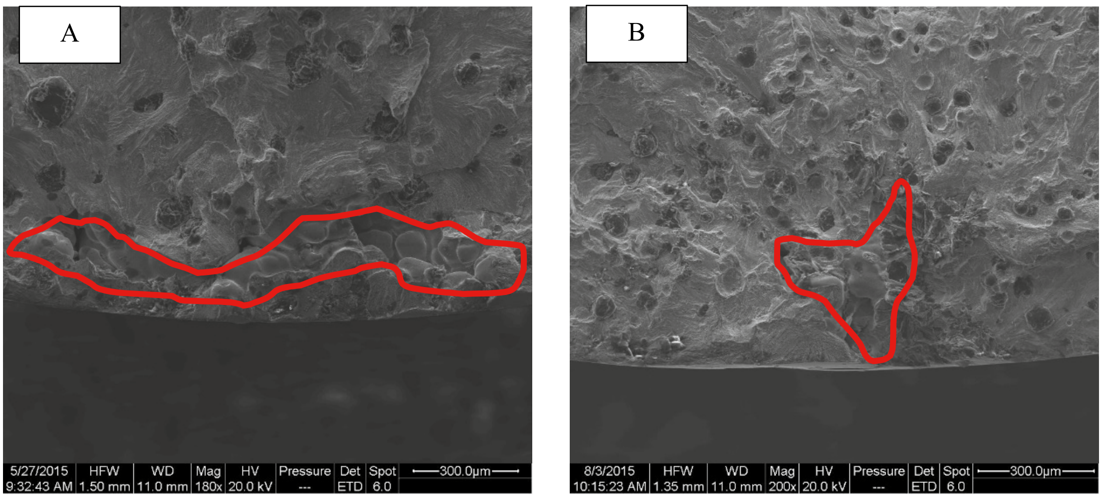

Figure 6 SEM micrographs of crack initiation zones of specimens taken from castings A and B

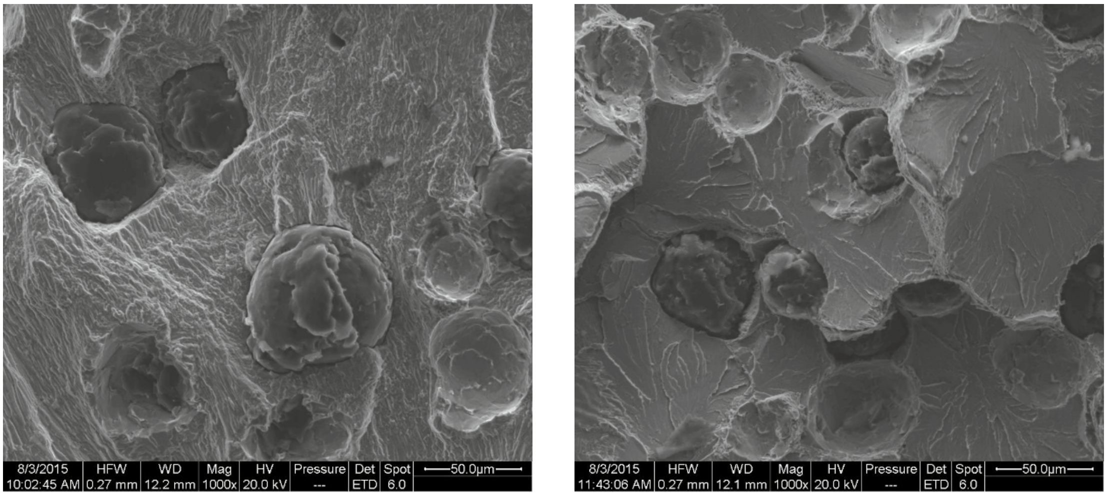

Figure 7 SEM micrographs of propagation zone (left) and static failure zone (right)

4.Conclusions

The influence of in-mould inoculants chemical composition on microstructure, mechanical properties and fatigue behaviour of ductile cast iron characterized by long solidification time has been investigated.
The inoculation treatment affects the metallurgical parameters of the casting with nodularity and mean nodule count of casting B higher than values measured on casting A. However, in casting B, small amount of degenerated graphite, classified as spiky graphite, has been found in the longest solidification zones. This was attributed to the presence of Bismuth in the chemical composition of inoculants used for the in-mould treatment of casting B.
Fatigue limit $\sigma_{a,\,Ps\,50\%}$ at $2\cdot10^6$ cycles of casting B was found 15 MPa higher than the $\sigma_{a,\,Ps\,50\%}$ at $2\cdot10^6$ cycles for casting A, while the scatter index $T\sigma$ in the case B is 28% lower than A. Fractography of specimens A and B showed that microshrinkages close to specimens surface act as crack initiation points from which the fatigue fracture propagate around the graphite nodules. Degenerated graphite did not affect the fatigue resistance in the presence of microshrinkage porosities.

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