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FRACTURE BEHAVIOUR OF NODULAR GRAPHITE IRON AT LOW TEMPERATURES

J. Pirs and A. H. Shabaik*

INTRODUCTION

Iron-graphite alloys are used commercially as nodular or malleable cast iron with either a ferritic or pearlitic matrix. There is evidence from the work of Pellini and coworkers [1] and Gilbert [2 - 4] that, as the number of graphite particles in ferritic nodular cast iron increases, the impact transition temperature and the energy absorbed in ductile impact fracture both decrease. Pellini has attributed the relatively low transition temperature of nodular iron to the ability of graphite particles to arrest cleavage cracks. In contrast, Moore [5, 6] reported that, in ferritic malleable cast iron, the transition temperature is unaffected by variations in the number of graphite particles. Mogford and coworkers [7] studied the influence of the dispersion of graphite on strength of the ferritic nodular cast iron and found, that the impact transition temperature decreased as the interparticle spacing between graphite nodules decreased, where the increased resistance to brittle fracture can be attributed to the arrest of microcracks by graphite nodules, which delay the attainment of general cleavage. As far as the ductile mode of fracture is concerned, Mogford and coworkers [7] found that cavities were observed at the graphite nodules after ductile fracture, which were formed by decohesion at the weak interface between primary and secondary graphite, being responsible for the low energy, required for ductile fracture of impact specimens. This is consistent with the results observed by Jolley and Gilbert [8] which have shown, that ductile fractures in ferritic nodular graphite irons tend to follow the grain boundaries and to expose the graphite nodules at the fracture face. It is known, that the grain size of the ferritic structure has an important effect on toughness, as predicted by the Petch Relation. This has been thought to be due to the resistance of grain boundary to crack propagation and to the grain size dependency of yield stress [9 - 11]. In many cases, it was observed on the cross-section of fracture surface that the crack was arrested at the ferrite grain boundary [12]. The observation of fracture surface revealed that the fracture path changed its direction at the grain boundary and steps, called river pattern [13] were formed due to the resistance to fracture. The resistance of grain boundary resulted from that the brittle fracture at low temperature is cleavage fracture on {100} plane [14] and the cleavage plane is discontinuous at the grain boundary. However, the direct correspondence of the crack propagation to the grain size has not been observed.

The objective of this study is to examine the changes from ductile to brittle behaviour and the mechanism of ductile and brittle fracture of the annealed ferritic nodular graphite cast iron at low temperatures. There have been some studies on the impact toughness of nodular-graphite cast iron in relation to the microstructures [15 - 17] but there are rel-

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*University of California, Los Angeles, U.S.A.

atively few reports in which discussions are made principally from the view point of fracture mode, based on the observation of fracture surface.

The scanning electron microscope with the advantage of continuous observation from low to high magnifications and of deep focusing depth makes it possible to observe the direct correspondence of fracture surface to microstructure. The purpose of the present study was also to clarify the problem on discontinuous mode of crack propagation experimentally using this technique.

EXPERIMENTAL PROCEDURE

The chemical composition of the investigated ferritic nodular cast irons is given in Table 1.

The as cast pearlitic structure of the nodular cast iron investigated, was completely transformed to ferritic structure, by heating cast iron bars to a temperature of 920°C and maintaining this temperature for 4 h. This was followed by furnace cool to 690°C and holding for 8 h, before finally furnace cooling. The ferrite produced by these treatments was distributed around the graphite nodules.

The brittle fracture surfaces were prepared by breaking Charpy impact specimens with 2 mm V notch at -46°C and U notch at -55°C. The ductile fracture surfaces were obtained in testing the specimens of the same nodular cast iron at room temperature, having 2 mm V notch. The results of impact testings at room temperature and sub-zero temperatures are shown in Table 2.

EXPERIMENTAL RESULTS

The secondary electron image of the crack initiation region of the impact fracture surface of the sample No. 11, is shown in Figure 1. The fracture characteristics of the sample No. 11, tested at -55°C are the following. The observation of the fracture surface, as shown in Figure 1 revealed, that the fracture propagated under the repetition of nucleation, propagation and arresting of microcracks. This microcrack propagation unit being considered as the fracture facet, each unit having one nucleus of microcrack. The unit was combined by the adjacent unit discontinuously by the nucleation of another microcrack in that unit. Grain boundaries often arrest propagating brittle microcracks, but if sufficient energy is available, the microcrack will propagate into an adjacent grain. Tipper and Hall [18, 19] have shown, that brittle cleavage fracture in ferrite occurs in a discontinuous manner resulting in the formation of steps on the fracture surface. Cleavage steps may also be formed at a microcrack/twin intersection, or when a propagating microcrack crosses a grain boundary.

The stepped nature of the brittle cleavage fracture surface, of the ferritic nodular cast iron, on the fractured surface of sample No. 11, is shown in Figure 2.

Stepped cleavage fractures may result from secondary cleavage, on planes at right angles to the primary cleavage planes, as this provides a means of connecting discontinuous cleavage microcracks. Steps formed in this way, would be expected to show relatively smooth cleavage fracture propagation of the step.

The secondary electron image of the fractured surface of specimen No. 10, tested at -45°C is shown in Figure 3.

The fracture surface as shown in Figure 3, may have some similarity with the fracture surface, which was shown in Figure 2, but still differences in the fracture mode between the two fracture surfaces exist. The microcrack propagation units are not so clearly to be distinguished in comparison with the microcrack propagation units shown in Figure 1, and it seems that the grain boundaries of ferrite may be considered as subboundaries, and cannot be regarded as an effective barrier for the crack propagation.

That grain boundaries of ferrite are sub-boundaries and do not act as an effective barrier for crack propagation can be seen from Figure 4, where two changes in cleavage fracture are visible. There are changes in cleavage fracture surface at various kinds of small angle grain boundaries, around nodular graphite. The fracture appearance depends on the kind of small angle boundaries, such as tilt boundary and twist boundary, proving that the orientation difference regarding {100} plane between adjacent grains is small and the grain boundary of ferrite may be considered as if it is a sub-boundary. The river patterns, which are clearly visible on fracture surface of {100} plane, are parallel to the direction of crack propagation. The result, shown in Figure 4, correspond to the results obtained by Turkalo [20] investigating the fracture facets of ferrite-pearlite, with the result that the fracture facet of ferrite-pearlite was pearlite colony in minimum and across a number of pearlite colonies extending to the austenite grain in maximum. Terasaki and Ohtani [21] obtained similar results to those reported by Turkalo [20] in a study on brittle fracture surfaces formed at low temperature in relation to microstructure of low carbon steels where the fracture facet of ferrite was found to be generally larger than the ferrite grain and in cases that the orientation difference regarding {100} between adjacent grains was small, the ferrite grain boundary was considered as sub-boundary.

The fracture modes and facets of the investigated nodular graphite cast iron change at testing at higher temperature. The fracture surface of sample No. 7 after impact testing at room temperature, obtained by scanning electron microscope is shown in Figure 5.

On subjecting a ductile ferritic nodular-graphite iron to impact stresses, the ferrite grain becomes distorted in direction of applied impact stresses, but the graphite nodules do not undergo the same deformations. The nodules fracture along weak interfaces between the primary graphite core and the peripheral secondary graphite which was deposited during the ferritizing heat treatment. The spaces occupied by the graphite nodules become greatly enlarged in the direction of applied stress, the core of the nodules remaining within the spaces, while the secondary graphite continues to adhere to the surrounding ferrite grains.

From the results of fractographic examination of the fractured surface of impact sample No. 7, tested at room temperature, and shown in Figure 5, can be seen, that some graphite nodules were broken out, while other nodules still remain in contact with the ferritic matrix. The ferritic matrix where the graphite nodules were broken out, can exhibit considerable plastic deformation. The plastic deformation of ferritic matrix can partly be seen in the ferritic matrix around the cavities, which were occupied by graphite nodules, before impact testing, in Figure 6. Similar results of fractographic investigations of the fractured surfaces of nodular cast irons, by means of the scanning electron microscope were obtained by Mitsche and coworkers [22], performing investigations of the fractured surfaces of nodular cast irons obtained in tensile testings and impact testings, performed at room temperature. They concluded, that plastic deformation of the ferritic matrix, can partly be due to pearlite, if the ferritizing heat treatment is incomplete, and some pearlite may be present in ferritic matrix.

SUMMARY

The fracture surfaces of ferritic cast irons with nodular graphite, were investigated in the scanning electron microscope. This technique was used to study the fracture mode of the investigated ferritic nodular irons to obtain possible connection with the microstructure. The fractured surfaces were prepared by Charpy impact tests, which were performed at room temperature and at sub-zero temperatures. The investigations of the fractured surfaces revealed two different fracture processes. The fracture process at sub-zero temperatures consisted by the repetition of nucleation, propagation and arresting of microcracks and the cleavage plane was determined as {100}. As a fracture facet was been taken the domain, having the plane nearly identical to {100} in the direction of crack propagation. The domain corresponded to the unit of nucleation and propagation of microcrack, but it should be necessary to discuss about the relation between the fracture mode and toughness: in the Petch Relation the effect of grain boundary has been discussed from the grain boundary dependency of initial microcrack for yield stress and in this aspect, the relation to the {100} plane has not been clear.

Further studies must be devoted to the question of the ability of graphite particles to arrest cleavage microcracks.

Further research will be devoted to the analysis of the distribution of graphite particles in ferritic groundmass and their influence on the distribution of stresses and possible influence on the transition temperature.

As far as the fracture mode at room temperature is concerned, the cavities observed at the graphite nodules after ductile mode of fracture, being formed by decohesion at the weak interfaces between the primary and secondary graphite, are responsible for the low energy required for ductile fracture of impact specimen.

From the results shown in Table 1 and also from the impact test details and results presented in Table 2, it can be seen that during this investigation two test series on type Meehanite SFF iron were performed. From the results of fractographic structure and fracture investigations from the impact specimens shown in this paper can also be seen, that only the results obtained on the test series C 15 are shown. The reason for such a presentation lies partly in the fact that the results of impact testings of the test series C 15 are better, as this was the case with the test series C 14, and partly in the fact, that the most characteristical results obtained during fractographic testings of the fractured surfaces are shown here. This was the case with the test series C 15.

Finally it must be stated, that the results of examinations of fractured surfaces of impact specimens of series C 14, tested at room and sub-zero temperatures, obtained with scanning electron microscope, were very similar to those reported in this paper.

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Table 1 The Chemical Composition of the Investigated Ferritic Nodular Cast Irons

Alloy Type	Test Series	T.C.%	Si%	Mn%	S%	P%
Meehanite SFF	C 14	3.41	2.32	0.26	0.004	0.031
Meehanite SFF	C 15		2.10	0.31	0.010	0.04

Table 2 The Results of Impact Testings at Room Temperature and Sub-Zero Temperatures of the Investigated Ferritic Nodular Cast Irons

Alloy Type	Test Series	Sample No.	Notch Type	Test Temperature T	Impact Value N.m
Meehanite SFF	C 14	1	V	Room	17 1/2
		2	V	Room	17 1/2
		3	V	-46°C	5
		4	V	-46°C	5 1/2
		5	U	-55°C	5
		6	U	-55°C	5
Meehanite SFF	C 15	7	V	Room	17
		8	V	Room	19
		9	V	-46°C	6 1/2
		10	V	-46°C	6
		11	U	-55°C	9
		12	U	-55°C	8 1/2

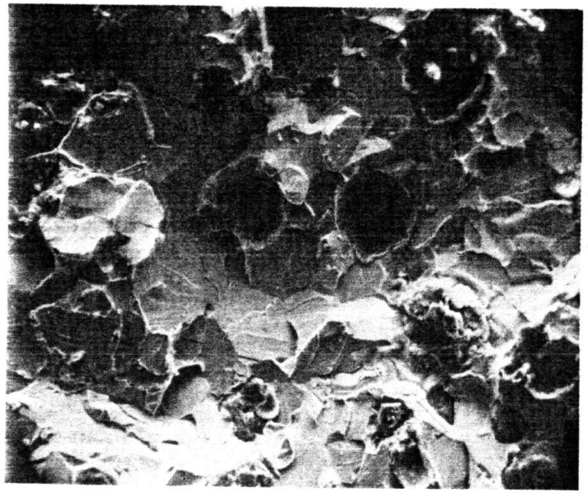

Figure 1 The Secondary Electron Image of the Crack Initiation Region on the Fracture Surface of the Sample No. 11 (X 200)

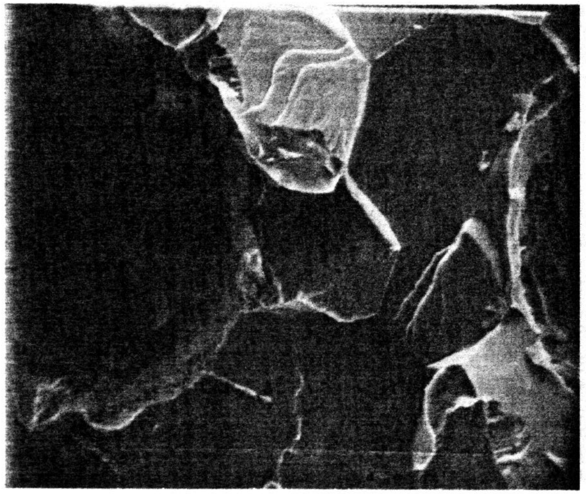

Figure 2 The Stepped Nature of Brittle Cleavage Fracture Surface of the Sample No. 11 (X 1000)

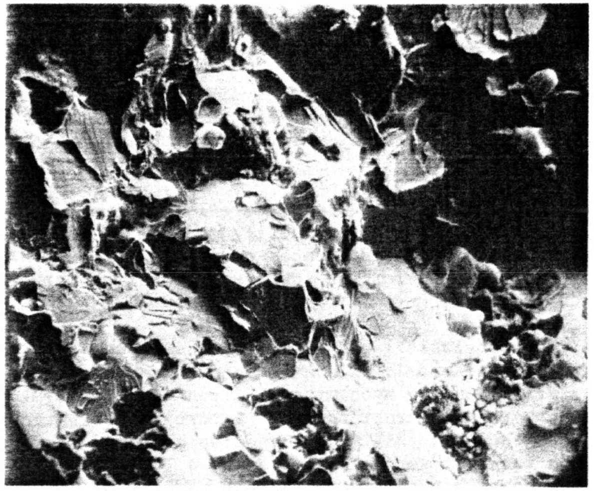

Figure 3 The Secondary Electron Image of the Fractured Surface of Specimen No. 10 (X 200)

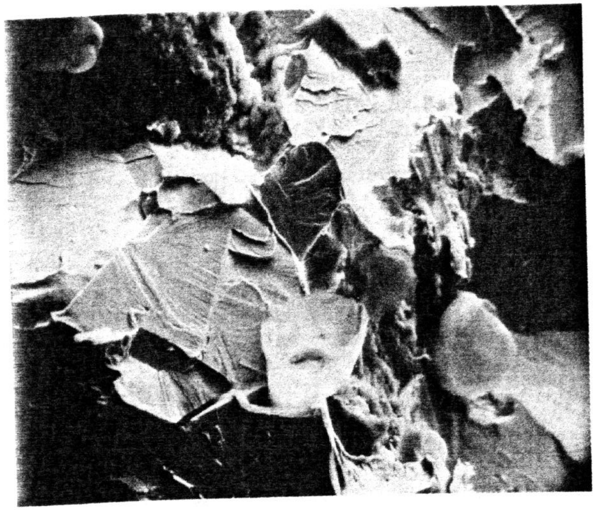

Figure 4 Change in Cleavage Fracture at the Fracture Surface of Specimen No. 10 (X 600)

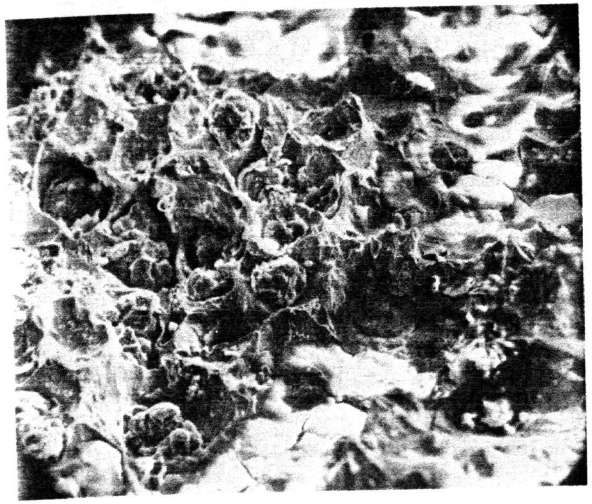

Figure 5 The Fracture Surface of Sample No. 7 After the Impact Testing at Room Temperature (X 200)

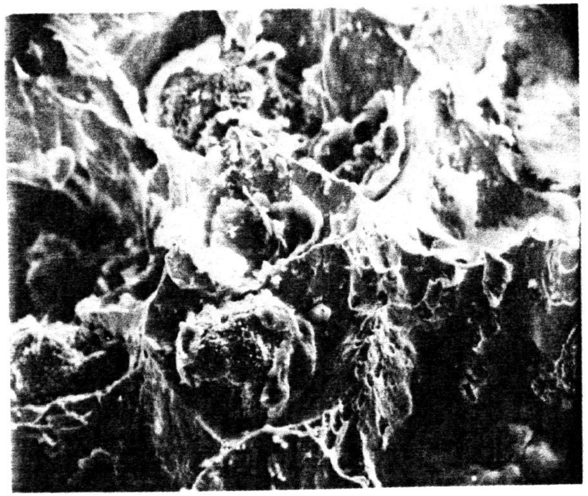

Figure 6 Plastic Deformation of Ferritic Matrix Around the Cavities Being Occupied by Graphite Nodules before Impact Testing (X 600)