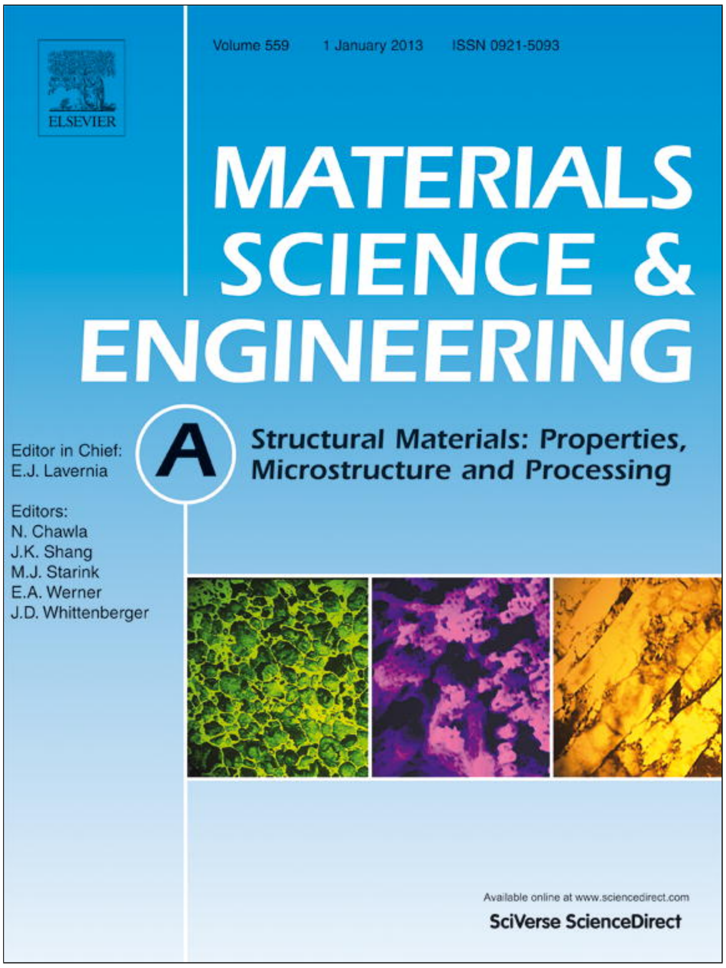
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Impact toughness and microstructure of continuous medium carbon steel bar-reinforced cast iron composite

M. Kazemi [a,*], A.R. Kiani-Rashid [a], A. Nourian [b]

[a] Department of Metallurgical and Materials Engineering, Faculty of Engineering, Ferdowsi University, P.O. Box 91775-1111, Mashhad, Iran.
[b] Khorasan Steel Complex Company, Neyshabur, Iran

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A B S T R A C T

Although nodular cast iron has popular characteristics, its toughness and tensile strength are insufficient in many applications. In the present research, an attempt was made to produce a nodular cast iron composite reinforced with medium carbon steel bar, in order to investigate its effects on improving the toughness of the material. The composite material was produced by the sand mould casting technique. Then, the samples were annealed at 900 °C for 1 h. Afterwards, the microstructures of the composite in as cast and annealed conditions were analyzed by optical and electron microscopes. Later on, the hardness and impact toughness of the cast iron composite specimens were compared with the samples without reinforcement. The results revealed a pearlitic diffusion bond between the two components of the composite, due to the diffusion of carbon from the cast iron towards the steel bar. Furthermore, the impact toughness of the composite material showed better results in comparison with that of the simple specimens.

1. Introduction

Since previous years, there has been a significant attempt to explore the potential use of ductile phase reinforcement in toughening of relatively brittle materials; however, a few investigations have been done in the case of cast iron [1–6]. Nowadays, cast iron is widely used in many engineering applications, due to good cast-ability, corrosion resistance, machine-ability, and relatively low cost; however, its mechanical properties are strongly affected by the existence of free carbon (graphite), which is formed during the solidification process [7]. There are several ways to improve the mechanical properties of cast iron, such as addition of specific alloying elements and applying different heat treatments to achieve different microstructures and various shapes of graphite [8–12].

However, it has been tried, recently, to enhance its mechanical properties by reinforcing with a higher strength material, as used in this study. Simsir [1–3] studied the microstructure and mechanical properties of gray cast iron composites reinforced with low carbon steel plates and tough steel fibers. Kurt et al. [4] worked on the influence of heat treatment on shear strength of the interface between cast iron and medium carbon steel. In addition, Akdemire et al. [5,6] investigated the effect of reinforcing of gray cast iron with steel fibers on the strength and toughness of this material.

Although, there have been a few investigations on the mechanical properties of gray cast iron composites, the influence of reinforcing ductile cast iron has not been studied; so the main objective of this study was to produce a metal matrix composite, which consists of steel bar reinforced nodular cast iron and to compare its mechanical properties with the specimens without reinforcement. Furthermore, an attempt has been made to evaluate the microstructure of the composite specimens and to study the interfacial diffusion bond between the matrix and reinforcement, producing transition region in the interface by diffusion of carbon from the cast iron to steel.

2. Experimental study

The composite specimens consist of medium carbon steel bar as the reinforcement and nodular cast iron as the matrix. The chemical compositions of these constituents are shown in Table 1. The specimens were produced using the sand mould casting technique. In order to minimize the casting defects, the samples for mechanical examinations were casted in the form of Y-blocks, as shown in Fig. 1, and the pieces of steel bar with a diameter of 4 mm were chosen as reinforcements. However, metallographic samples were casted into simple cylindrical cavities with 30 mm diameter and 100 mm length, and a steel bar with a diameter of 10 mm was chosen as the reinforcement. The size of metallographic samples was large enough to detect any microstructural variation in both components. The surface of the steel bars was ground sequentially

* Corresponding author. Tel.: +98 9151416718; fax: +98 511 8763305.
E-mail address: Kazemi.masume@stu-mail.um.ac.ir (M. Kazemi).

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Table 1
Chemical composition of the ductile cast iron and the steel bar (wt%).

Material	C	Si	Mn	P	S	Cr	Ni	Cu	Fe
Cast	3.6	2.45	0.196	0.026	0.028	0.089	0.036	0.365	Bal.
Steel	0.46	0.25	0.57	0.009	0.012	0.08	0.08	0.23	Bal.

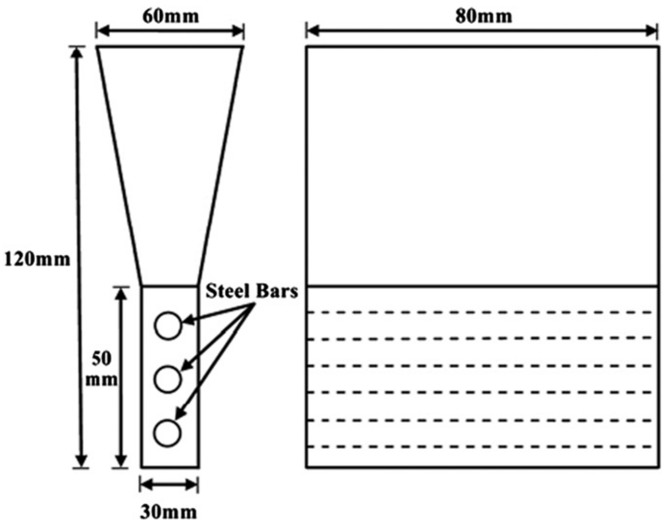

Fig. 1. Dimensions of Y-block.

using emery paper with grit size range from 320 to 1500 and washed with alcohol and dried.

The steel bars were embedded horizontally into the center of the mould and heated up to 400 °C to form good bonding and to prevent the distortion due to temperature difference, since, according to our experiment if the steel bar is not pre-heated before casting, it is not possible to obtain a complete bonding between cast iron and steel bar. The casting was done at 1350 °C and followed by cooling in the sand mould. All specimens were produced in the same casting condition and dimensions. Then, the Y-blocks were machined to produce test samples for impact and hardness tests from the center of those blocks. Afterwards, in order to study the effects of annealing heat treatment on transition region, a couple of specimens were annealed at 900 °C for 1 h. It is noticeable that special carbon stop paint was used to prevent decarburization of the samples during heat treatment.

The microstructural characteristics of the specimens were investigated by optical and electron scanning microscopes (SEM: LEO 1450VP). Also, the microstructures were evaluated by an Image Analyzer Software to determine the nodularity, size and distribution of graphite nodules, according to ASTM A247-67 standard.

In order to measure the impact toughness of the specimens, the Charpy impact test was chosen. The test was conducted at ambient temperature and was repeated three times for each condition and the average of the test results was used in evaluations. The un-notched impact toughness specimens with dimensions of $10 \times 10 \times 55$ mm^3 were ground according to ASTM A327M-91 which advised in a preferred condition for austempered cast irons. It is noticeable that the authors tried to evaluate the effect of austempering heat treatment on the fracture toughness of the composite samples, which will be reported in the following papers in comparison with the experimental specimens.

Moreover, fracture surfaces of the specimens were investigated in as cast and annealed conditions using an SEM.

3. Results and discussion

3.1. Microstructures

Regarding the micrograph of the composite specimen in unetched condition (Fig. 2), we can clearly observe that there is no crack or discontinuity between the steel bar and the cast iron. The nodularity of graphite in the cast iron region is more than 80% with an average nodule size around 20 μm; however, graphite nodules in the vicinity of the interface are much smaller in size in comparison with other parts of the cast iron.

Optical and SEM metallographic examinations of the composite specimen, etched by 2% nital, revealed three distinct regions, which consist of steel region, transition area and cast iron region (Fig. 3).

As can be seen in Fig. 3, the microstructure of the cast iron consists of graphite nodules in a ferritic–pearlitic matrix, and the steel region has a ferritic–pearlitic microstructure as the typical medium of carbon steel; however, these two areas are divided by a transition region, which consists of two segments. In the first segment, closer to the steel region, we can observe a thoroughly pearlitic microstructure. This area is the sign of diffusion of carbon from the cast iron towards the steel bar, due to the discrepancy between the chemical potential of carbon in steel and cast iron. Whereas, in the second segment of the transition region, there is a decarburized strip with ferritic structure, in which small graphite nodules are dispersed. The existence of these small graphite nodules is justifiable according to the high cooling rate of the melt in the vicinity of the steel bar at the first stage of solidification, which leads to form a large number of nuclei, so the size of the graphite nodules decreases [13–15]. In addition, diffusion of carbon from the cast iron towards the steel bar made the graphite nodules even smaller. Hence, a diffusion bond was established between the two components of the composite without any discontinuity. This phenomenon is compatible with the results of other investigations about gray cast iron composite [5,6].

Furthermore, in order to investigate the influence of annealing heat treatment on the quality of the established bond between the two components, the samples were annealed at 900 °C for an hour. The metallographic examinations revealed that the microstructure of the cast iron matrix changed into a ferritic structure and the ferritic segment of the transition region merged with the cast iron area (Fig. 4).

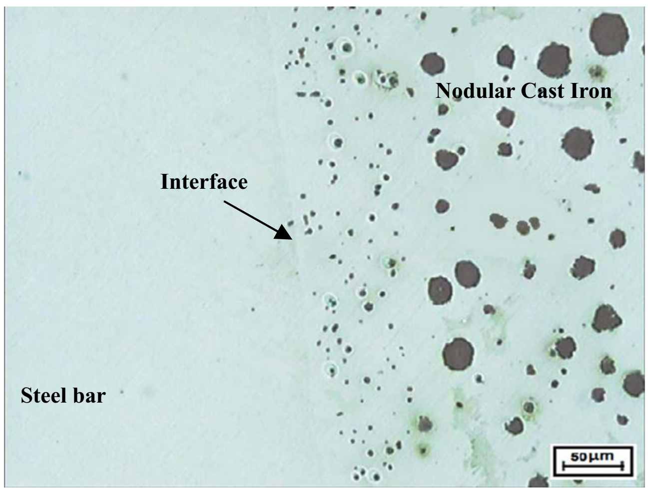

Fig. 2. Microstructure of as cast composite specimen before etching.

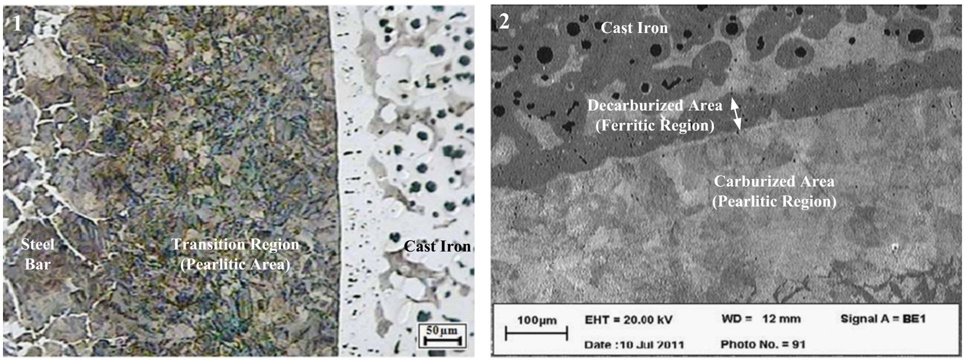

Fig. 3. Microstructures of cast iron composite in as cast condition by (1) optical microscope and (2) SEM, indicating three distict regions: cast iron region, transition area and steel region, etched by 2% nital.

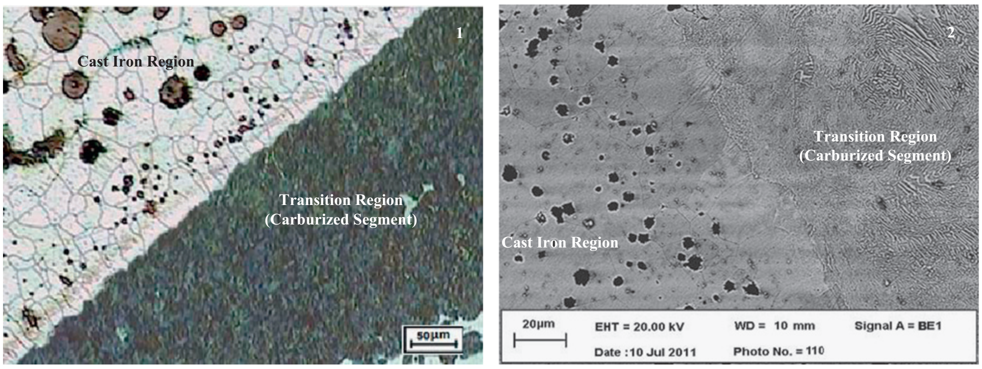

Fig. 4. Microstructures of cast iron composite in annealed condition by (1) optical microscope and (2) SEM.

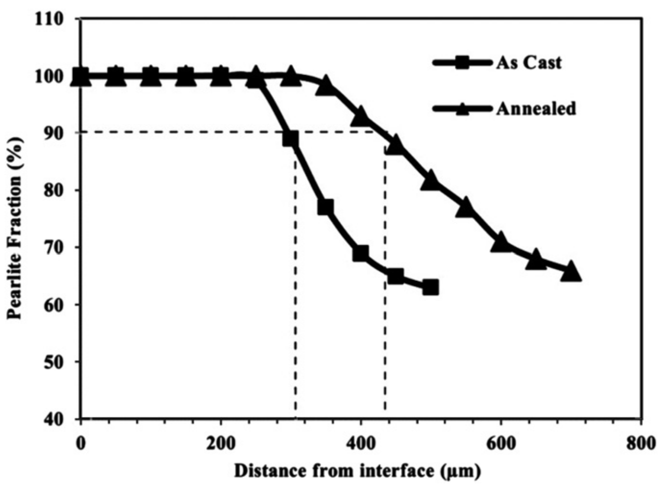

Fig. 5. Variations of volume fraction of pearlite in the transition region in as cast and annealed conditions.

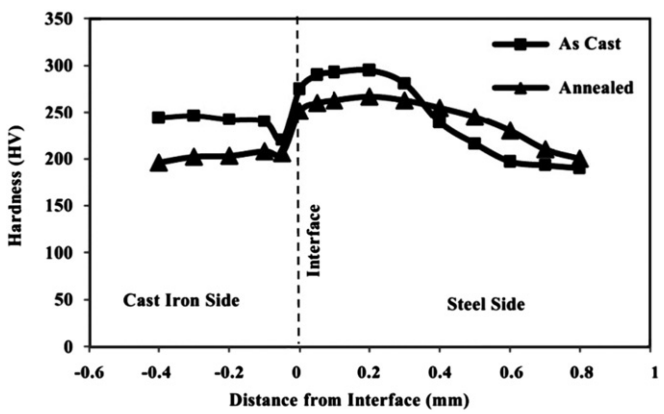

Fig.6. Variations of hardness in the vicinity of the transition region from steel to cast iron side.

The variations of volume fraction of pearlite from the interface towards the steel region in as cast and annealed conditions are compared in Fig. 5. The data, presented in this figure, was measured using an image analyzer software. In our calculations, the thickness of the transition region was considered as the area with more than 90% pearlite. As can be seen, the thickness of this region for as cast and annealed conditions was calculated to be about 310 μm and 435 μm respectively, which is justifiable according to the high diffusion rate of carbon from the cast iron towards the steel region during the annealing heat treatment.

3.2. Hardness test

Fig. 6 illustrates the variations of hardness from steel to cast iron. As can be seen, the hardness of the composite in both as cast and annealed conditions increases in the transition region, due to thoroughly pearlitic structure of this region; however, a small drop in the hardness of the cast iron side of the transition region in as cast condition is observed, which results from the ferritic structure of this area, whereas this dip cannot be seen in annealed condition because of the ferritic microstructure of cast iron region after heat treatment. In addition, the length of the transition region has been expanded after annealing heat treatment, which is compatible with the results of metallographic examinations.

Table 2
Results of the impact test on the specimens with or without reinforcement (Joules).

Specimens	As cast	Annealed
Without reinforcement	54.8	89.8
With reinforcement	63.9	104.6

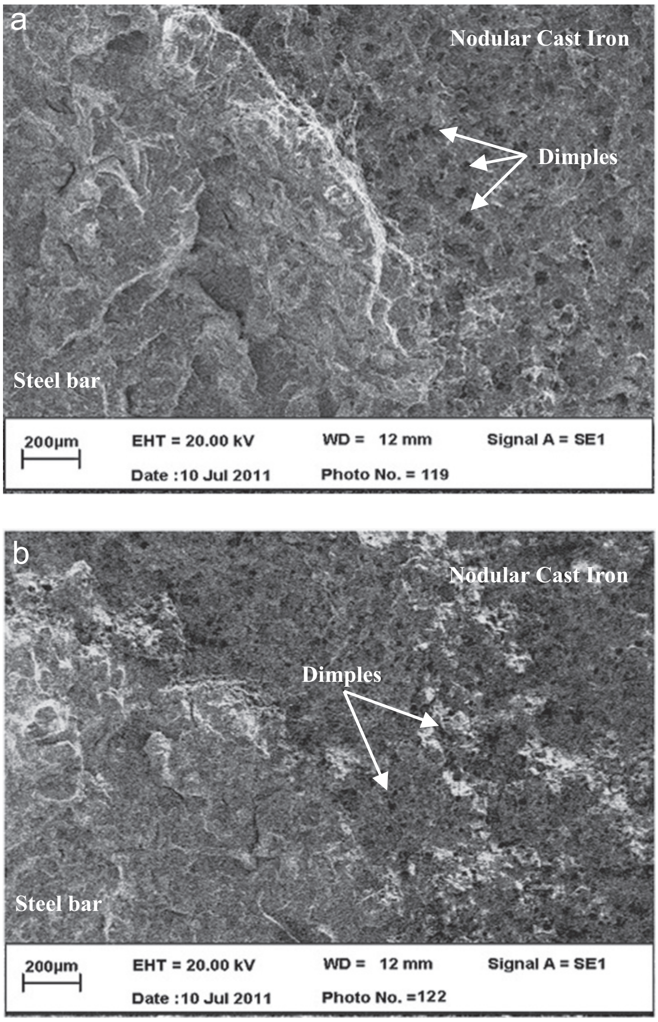

Fig. 7. SEM micrographs of fracture surface of composite specimens in (a) as cast condition and (b) annealed condition.

3.3. *Impact test*

The results of Charpy impact tests on cast iron specimens with or without reinforcement are represented in Table 2. As we can notice, reinforcing nodular cast iron by steel bar has a positive effect on its impact toughness in as cast and annealed conditions. The increase in impact toughness of the reinforced specimens is more than 16% in both conditions.

In addition, the fracture surfaces of the composite specimens, examined by SEM, are shown in Fig. 7(a) and (b). As Fig. 7(a) reveals, in the case of as cast composite specimen in the cast iron region, small dimples associated with graphite nodules are clearly visible; cavities and dimples on the fracture surface are the signs of weak interfaces between graphite nodules and the matrix. Furthermore, no localized necking can be observed and the fracture of the interface between cast iron and steel seems to be brittle. On the other hand, regarding the fracture surface of the composite specimen in annealed condition (Fig. 7(b)), we can clearly infer that there are small dimples associated with graphite nodules; moreover, localized necking can be seen especially in cast iron region which is a sign of soft fracture and there is no discontinuity between the cast iron and the steel bar.

4. Conclusions

In this study, the effect of reinforcing nodular cast iron with steel bar on impact toughness of cast iron in as cast and annealed conditions was investigated, and the following conclusions were obtained:

1. Having examined the microstructures of the composite specimen, we can observe a transition region in the interface between steel and cast iron with thoroughly pearlitic microstructure, which is the sign of appropriate diffusion bond between these two constituents.
2. The thickness of pearlitic region in annealed condition is more than that of as cast specimens, due to diffusion of more carbon from the cast iron towards the steel bar during annealing heat treatment.
3. The hardness of transition region is measured to be more than that of the other parts of the composite, due to thoroughly pearlitic structure of this area in both as cast and annealed conditions.
4. The results of impact tests demonstrate that reinforcing nodular cast iron has a positive effect on the toughness of cast iron, and the impact energy of the composite in as cast and annealed conditions increased by more than 16%.

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