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Technical Report

Investigation of microstructural and mechanical properties of austempered steel bar-reinforced ductile cast iron composite

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A B S T R A C T

In this study, the effect of reinforcing nodular cast iron with steel bar on impact toughness was investigated. The composite material was produced by the sand mould casting technique. Afterwards, austempering heat treatment was applied to the specimens at two different temperatures of 350 °C and 400 °C. The samples were evaluated by optical and scanning electron microscopies; then, hardness and Charpy impact toughness tests were conducted at ambient temperature on the cast iron specimens with or without reinforcement. The results revealed that impact toughness of the nodular cast iron increased by reinforcing with the steel bar. Furthermore, austempering heat treatment greatly influenced the impact toughness of reinforced specimens; however, the impact toughness of the austempered composite at 350 °C was more than that of the austempered specimens at 400 °C.

1. Introduction

Cast iron is considered to be an important metallic material, which is extensively used in many applications, due to good cast-ability, machine-ability, wear resistance and relatively low cost. However, the application of this material is restricted by its low toughness and strength because of the existence of free graphite in the microstructure, which can play the role of internal cracks or holes [1–3].

Since previous years, several attempts [4–7] have been done to improve the mechanical properties of cast iron, including addition of specific alloying elements and different heat treatments to achieve various microstructures and different shapes of graphite and they have been influential to some extent. Zandira and Boutorabi [4] studied the influence of addition of Al on fracture characteristics of nodular cast iron. Furthermore, Kayali et al. [5] investigated the effect of boro-tempering heat treatment on mechanical properties of ductile iron. Moreover, Balachandran et al. [6] studied the mechanical properties of gray cast iron alloyed with Cu, Ni and micro-alloyed with Ti and Nb in the quenched and tempered and austempered conditions. Monchoux et al. [7] also studied the influence of a ferritization heat treatment on the fracture toughness of ferritic spheroidal graphite cast iron.

In the case of nodular cast iron, it has been shown that mechanical properties can be greatly enhanced by austempering heat treatment [8–11], which generally involves austenitizing, rapidly cooling to an intermediate temperature and holding at that temperature for enough time. Finally it is air or water cooled to room temperature. The microstructure of austempered cast iron consists of ferrite and high carbon austenite, so the product of austempering reaction in ductile iron is called "ausferrite" [12–15]. A lot of studies [8,10,14–18] have been done to determine the effects of austempering heat treatment on the mechanical properties of ADIs. Refaey and Fatahalla [14] investigated the relationship between microstructure, fracture toughness and wear behavior of ADI. Moreover, Putatunda et al. [15–17] studied the influence of different austempering parameters on microstructural characteristics and fracture toughness of ductile cast iron. Furthermore, Kim et al. [8] examined the dependence of mechanical properties of austempered ductile iron with austempering temperature. In addition, Eric et al. and Lin et al. [10,18] separately investigated the effect of alloying elements on microstructure and properties of ADI specimens.

On the other hand, one of the newest ways to improve the mechanical properties of cast iron is to produce a composite material reinforced with a stronger and tougher material. Simsir et al. [19–22] investigated the influence of low carbon steel plates and tough steel fibers as reinforcement on microstructure and mechanical properties of gray cast iron composites. Kurt et al. [23] studied the effect of heat treatment on the shear strength of the interface between cast iron and medium carbon steel. Furthermore, in our previous paper [24], the microstructural characteristics of steel bar-reinforced nodular cast iron and its effect on toughness of as cast and annealed specimens were studied; however the objective of the present investigation is to evaluate the influence of supplementary austempering heat treatment on the impact properties of

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the mentioned composite and to compare its properties with nodular cast iron without reinforcement.

2. Experimental study

In current investigation, the sand mould technique was used to produce the composite samples, in which a medium carbon steel bar was used as the reinforcement within nodular cast iron as the matrix. The chemical analysis of the steel bar and the cast iron are shown in Table 1. The samples for mechanical examinations were cast in the form of Y-blocks of approximate size of $60 \times 80 \times 120$ mm, which is described in the previous paper [24] and the steel bars with 4 mm diameter were chosen as the reinforcement.

However, metallographic samples were cast into cylindrical cavities with 30 mm diameter and 100 mm length reinforced with steel bars of 10 mm diameter. The size of metallographic samples was large enough to detect any microstructural variation in both constituents.

The surfaces of the steel bars were ground using emery paper with grit size range from 320 to 1500. Having cleaned of all dirt, the steel bars were embedded within the moulds, and heated up to 400 °C to decrease the amount of distortion caused by the temperature difference and also to form good bonding between the two components. The melt was cast at 1350 °C and then the castings were cooled in the mould. Afterwards, the Y-blocks were machined to produce test samples for the Charpy impact test. In addition, the specimens of nodular cast iron without reinforcement were produced with the same conditions and dimensions.

Furthermore, in order to enhance the impact properties of the samples, a supplementary austempering heat treatment was applied. It has been mentioned that ductile iron is usually austempered in the temperature range between 260 and 400 °C [10,15]. A lower transformation temperature produces a fine, high strength, wear-resistant structure, while a higher transformation temperature results in a coarser structure that exhibits high fatigue strength and good ductility [25]. Therefore, as the scope of the present paper is to investigate the improvement of impact properties of the composite specimens, a higher temperature range was chosen. So, after austenitizing at 900 °C for 1 h, the specimens were austempered at two different temperatures of 350 °C and 400 °C for 30, 60 and 90 min. Finally, the samples were quenched in water. However, since the bainitic transformation was not completed in the specimens austempered below 90 min, we focused mostly on austempering for 90 min.

For metallography examination, the samples were prepared and etched with 2% nital and the microstructural evaluation was performed using optical (OM) and scanning electron microscopies (SEM: Oxford S360). In addition, the impact energies of simple and composite specimens were compared using the Chapy impact test at ambient temperature. The test was conducted according to ASTM: A327M-11 using un-notched specimens with dimensions of $10 \times 10 \times 55$ mm^3. It is noticeable that the test was repeated three times for each condition and the average values were used in evaluations. Furthermore, the hardness values of specimens in as cast and austempered conditions were measured in Vickers scale and the hardness profiles of the composite specimens in different conditions were compared.

3. Results and discussion

3.1. Metallographic evaluation

Metallographic examinations of composite specimens in as cast condition revealed three different regions: the cast iron region, which consists of nodular graphite in a ferritic–pearlitic matrix (Fig. 1(a)), the steel region with ferritic–pearlitic microstructure as the typical medium of carbon steel (Fig. 1(c)) and the transition region, which can be observed between these two regions and consists of two areas (Fig. 1(b)). The first area, closer to the cast iron, is a decarburized ferritic region with small nodules of graphite and the steel side of transition region, as the second area, has a thoroughly pearlitic microstructure, due to diffusion of carbon from the cast iron to the steel region. So, a diffusion bond was established between two constituents of the composite.

In addition, the microstructures of composite specimens, austempered at two different temperatures of 350 °C and 400 °C were shown in Figs. 2 and 3. As can be seen, the microstructures of the composite in the cast iron region comprise platelets of ausferrite. Although the platelets of ausferrite in the specimen austempered at 350 °C have an acicular appearance, this phase in the specimen austempered at 400 °C is completely feather-shaped or plate-like, which is the characteristic of upper ausferrite [10,15,25].

On the other hand, austempering heat treatment at both temperatures did not result in thoroughly bainitic microstructures in the transition and the steel regions. As Figs. 2 and 3 reveal, the microstructures of the transition region consist of bainite and pearlite; however, in the steel region, in addition to the aforementioned phases, some ferrite can be detected in the grain boundaries, which is justifiable according to TTT diagram [25–27]. On the other hand, in both specimens, the amount of bainite in the transition region is more than that in the steel region. Since the transition region contains more carbon in comparison with the steel region due to diffusion of carbon from the cast iron towards the steel bar, which causes the TTT diagram to shift to the right [25–27]. Comparing the microstructures of the steel region in two austempering conditions, we could clearly notice that the amount of bainite in the specimen austempered at 350 °C is more than that in the specimen austempered at 400 °C, which can be attributed to the cooling rate from the austenitizing to austempering temperatures.

3.2. Hardness test

Fig. 4 shows the variation of hardness of the specimens in as cast and austempered conditions. As it was mentioned in our previous paper [24], the hardness of the transition region in as cast condition is higher than that of the steel region due to diffusion of carbon from the cast iron to the steel region and establishing a fully pearlitic region according to Fig. 1(b).

Furthermore, it can be perceived that, increasing the austempering temperature from 350 °C to 400 °C causes the hardness of the specimens to decrease. In the case of cast iron region, higher values of hardness at lower austempering temperature can be attributed to finer structure of ausferrite (Figs. 2 and 3). Moreover, it has been reported that increasing the austempering temperature

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 iron	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.

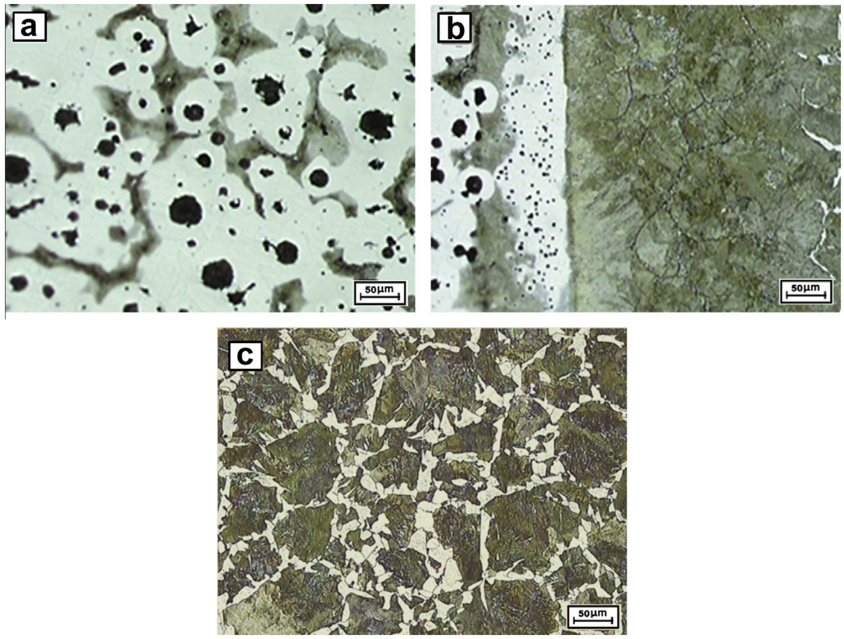

Fig. 1. Optical microstructures of cast iron composite in as cast condition: (a) cast iron region, (b) transition area and (c) steel region.

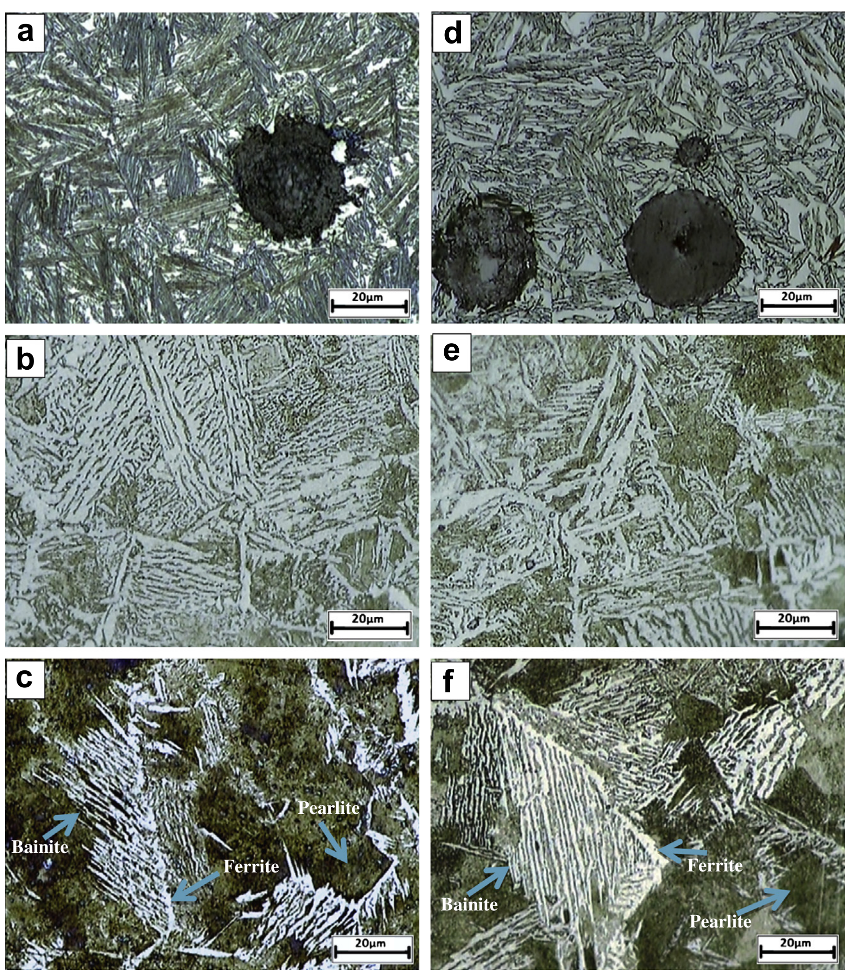

Fig. 2. Optical microstructures of composite specimens austempered at: (a) 350 °C in cast iron region, (b) 350 °C in transition region, (c) 350 °C in steel region, (d) 400 °C in cast iron region, (e) 400 °C in transition region and (f) 400 °C in steel region.

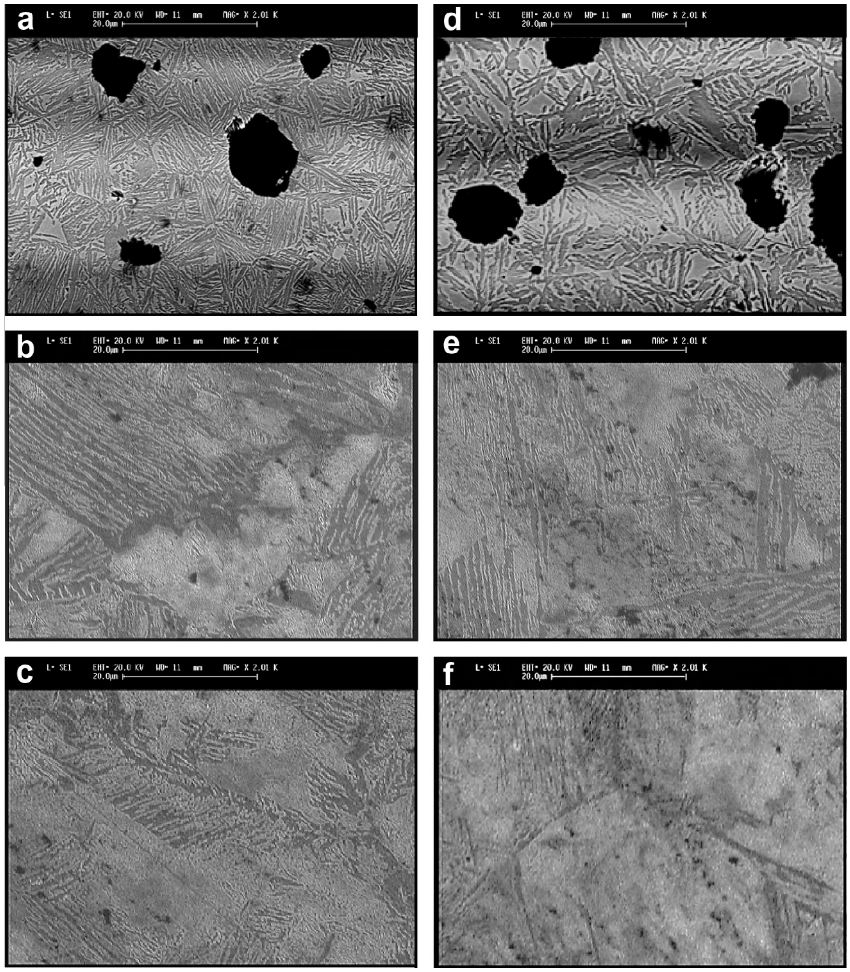

Fig. 3. SEM microstructures of composite specimens austempered at: (a) 350 °C in cast iron region, (b) 350 °C in transition region, (c) 350 °C in steel region, (d) 400 °C in cast iron region, (e) 400 °C in transition region and (f) 400 °C in steel region.

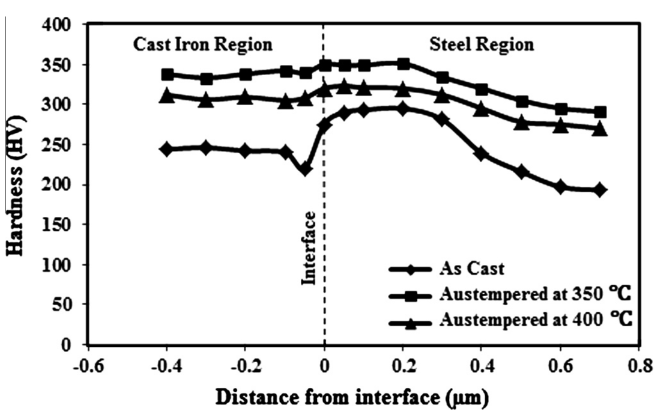

Fig. 4. The variations of hardness in the vicinity of transition region from steel to cast iron side.

leads to increasing the amount of retained austenite, which can affect the strength and hardness of ADIs [10,15,16].

In addition, increasing the austempering temperature also results in decreasing the hardness of the transition and the steel regions. As it is clear in Fig. 2, the amount of bainite, in the microstructures of these regions, decreases at higher austempering temperature, which results in decreasing the hardness of these regions.

Table 2
Impact fracture energies of the cast iron with or without reinforcement (Joules).

Specimens	As cast	Austempered at 350 °C	Austempered at 400 °C
Reinforced cast iron	63.9	99	95
Simple cast iron	54.8	85	79

3.3. Impact toughness

Table 2 represents the impact energies of the simple and composite specimens in as cast and austempered conditions. As can be seen, the fracture toughness of the reinforced specimens were improved either in as cast or austempered conditions due to the influence of reinforcing of cast iron. On the other hand, the fracture toughness of the austempered specimens were well enhanced in comparison with as cast condition, which shows the positive effect of austempering heat treatment on the fracture toughness. However, the impact energies of the austempered specimens at 350 °C showed higher values in comparison with the austempered specimens at 400 °C. In the case of ductile iron, it has been proved that the fracture toughness of ADI depends on retained austenite content and the morphology of the ausferrite. Although, increasing the austempering temperature brings about increasing the austenite phase within the ausferrite, the morphology of ausferrite is coarsened at higher austempering temperature [10,15,16], which results in decreasing the toughness of the specimens at higher austempering temperature.

4. Conclusions

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

(1) Metallographic analysis revealed a transition region in the interface between the cast iron and the steel wire, due to diffusion of C from the cast iron to the steel, and a diffusion bond was established between the constituents of the composite.
(2) The microstructure of the cast iron region was completely ausferritic after austempering heat treatment; however, the transition and the steel regions consist of bainitic–pearlitic and bainitic–pearlitic–ferritic microstructures after austempering heat treatment respectively.
(3) The hardness values of austempered composite specimens were higher than those of the as cast specimen. In addition, increasing austempering temperature from 350 °C to 400 °C resulted in decreasing the hardness of all three regions.
(4) The impact toughness of the reinforced nodular cast iron with steel bar was well enhanced in comparison with simple cast iron specimens, especially in austempered condition; however, increasing austempering temperature from 350 °C to 400 °C caused the impact fracture toughness to decrease.

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