Research Article

The Effect of Cooling Rate on Bainite Phase Formation in Austempered Nickel-Molybdenum Gray Cast Iron

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Received 24 August 2011; Accepted 26 September 2011

Academic Editor: E. J. Nassar

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Taking into account the importance of the amount of bainite phase on the microstructure of cast irons and its influence on the improvement of mechanical properties, this research selected an alloy of gray cast iron containing Nickel-Molybdenum and conducted the austenitising and austempering processes at 900°C and 400°C for 60 minutes, respectively. The way of bainite phase formation and the effect of sample thickness, that is, cooling rate, were examined by selecting a standard staircase sample. The results indicated that, by increasing the cross sections of samples, the martensite percentage decreases and the phase proportion of bainitic ferrite increases.

1. Introduction

Gray cast irons which are annually produced more than other cast alloys in the world are one of the most usable Fe-C-Si alloys. These cast irons had limited application for many years because of low tensile strength, specially low ductility which is due to the presence of thick flake graphite with random distribution. Nowadays different methods are used to control morphology, size, and distribution of graphite shape and matrix structure to improve the mechanical properties of gray cast irons. These methods include modifying the structure through the heat treatment process, alloy making, and controlling cooling rate [1–4].

Austempering heat treatment process is one of the processes which improve mechanical properties through creating bainitic structure [5].

The thickness of austempered grey cast iron samples also affects their mechanical properties. By increasing the thickness, the hardness decrease and the formation of upper feathery bainite becomes more likely. Moreover, at thin sections, because of high cooling rate, upper bainite turns into lower acicular bainite. In some cases the low thickness leads to formation of acicular martensite which causes increase in hardness. On the other hand, by increasing the

thickness in grey cast iron samples, the amount of alloy elements segregation increases which can affect the mechanical properties of samples [6].

Dorazil and his colleagues believe that carbiding elements of Mn and Mo do segregation during solidification. They reported that Mn and Mo can have more concentration on eutectic cell boundaries and so decrease the elongation and toughness in casting samples [7]. Moreover, another investigation done on the ductile cast irons has indicated that Cu, Ni, and Si have higher concentration next to graphite compared with intergranular areas. Also Mn is an element which is segregated in intergranular areas and acts reversely [8].

The present study attempts to find out the effect of thickness in bainite phase formation in gray cast irons by investigating the microscopic structure of staircase-casted samples of grey cast irons.

2. Materials and Methods

In this investigation, first a staircase model was provided from Al. The thickness of five stairs of this model was 3, 5, 10, 25, and 40 mm, respectively, the length was 90 mm, and the width was 30 mm. Because of low-heat transformation in the

TABLE 1: The dimensions of stairs after cutting.

Stair number	Length (mm)	Width (mm)	Thickness (mm)
1st stair	10	15	3
2nd stair	10	15	5
3rd stair	10	15	10
4th stair	10	15	25
5th stair	10	15	40

CO₂ sand mould compared with the green dune sand mould, moulding was done by using CO₂ method and sodium silicate glue. A molten with chemical composition of Fe-3.2C-1.5Ni-1Mo-0.37Mn-2.4S-0.04Si-0.04P was provided in underground furnace. To provide the sample, the following steps were done: (1) pouring the 1450°C molten into the mould, (2) Ejecting the sample which was cooled down to the surrounding temperature from the mould, (3) separating the stairs from gates.

Then the casted sample went through the following heat treatment cycle. (1) Austenitising in resistance furnace at 900°C for 60 minutes, (2) keeping the sample in molten salt bath in resistance furnace at 400°C for 60 minutes, (3) ejecting the sample from the salt bath and cooling it in the air.

After finishing austempering heat treatment cycle, the stairs were separated from the casted staircase model and 5 samples were obtained with dimensions as shown Table 1.

Then, the separated stairs mounted to examine the microstructure and hardness. The examination of microscopic structure of each sample was done using optical microscope and scanning tunneling microscopy (STM). Also microstructure image processing software (MIP) was used to calculate the percentage of each available phase in order to examine the effect of thickness on the cooling rate of samples.

3. Results and Discussion

3.1. Microstructure

3.1.1. Before Etching. Figure 1(a) shows the microscopic structure of first stair from the austempered staircase sample before etching. In this figure, based on the ASTM-A247, the observed graphites are types B and D. Type B has been distributed randomly in different directions and it is seen in cast irons with less thickness. Type D has very fine layers which have been formed in this stair because of less thickness and high cooling rate. The graphite particles with random directions are usually found in ferrite matrix.

Figure 1(b) shows the microscopic structure of second stair from the austempered staircase sample before etching. In this figure also, the observed graphites are types B and D. The difference is in the amount of type B which is more than type D because of more thickness of second stair compared with the first one. The speed of cooling is still high.

Figure 1(c) shows the microscopic structure of third stair from the austempered staircase sample before etching. In this

figure, the distribution of graphite is of types D and E. Type E is much more than Type D and is formed in low cooling rate.

Figure 1(d) shows the microscopic structure of forth stair from the austempered staircase sample before etching. The observed graphite in this stair is mainly type A. This type of graphite is consistently distributed in the matrix and it is formed here because of low cooling rate of this stair which is due to its more thickness compared with previous stairs.

Figure 1(e) shows the microscopic structure of fifth stair from the austempered staircase sample before etching. The observed graphite in this stair is type of A for different stairs.

Figure 2(a) shows the microstructure of first stair after etching. In this structure, the martensite, bainite and graphite phases are observed in a matrix of retained austenite. The amount of these phases has been shown in Table 2.

The produced martensite microstructure is coarse and large which is the result of high cooling rate of this stair. The produced bainite microstructure is upper feathery bainite which is the result of high austempering temperature.

Figure 2(b) shows the microstructure of second stair after etching. The amount of martensite in this stair decreases because of lower cooling rate which is the result of more thickness of the stair. The shape of martensite is smaller compared with the first stair while the bainite is coarser and larger.

Figure 2(c) shows the microstructure of third stair after etching. Compared with the first stair, in this stair, the martensite structure is much smaller and thinner and its amount decreases. However a considerable increase is observed in the amount and shape of bainite. At high cooling rate, because of little distance of rose shape graphites from each other, the diffusion distance between particles decreases and so the low segregation occurs.

Figure 2(d) shows the microstructure of forth stair after etching. Compared with the third stair, in this figure the amount of martensite has decreased and it has become coarser. The amount of bainite has decreased but it has become larger. On the other hand, the amount of retained austenite has increased. The reasons for these changes in the stair are the created segregations while solidification and the increase of alloy elements such as Ni and Mo in the stair. The Ni element is solved in the retained austenite and makes it stable. This stability decreases the speed of carbon diffusion in the network and consequently decreases the speed of bainite formation. Moreover, because of the effect of Ni on CCT diagram which moves it downward, an upper bainite structure with feather-shaped and coarser structure is formed.

Figure 2(e) shows the microstructure of fifth stair after etching. In this figure, the amount of bainite has decreased but its feather-shaped structure has become greater. The amount of martensite has also decreased and it has become coarser compared with the previous stair. On the other hand, the amount of retained austenite has increased.

Also the upper bainite phase is observed next to flake graphite because of decreasing the amount of carbon in areas in which the graphite is formed and consequently the

FIGURE 1: Light microscopy images; (a) first stair, (b) second stair, (c) third stair, (d) fourth stair, (e) fifth stair.

amount of carbon in the matrix decreases and the condition for bainite transformation is provided (Figure 3).

3.2. Result of Hardness Test. Table 3 shows the results of hardness test. The results show that by increasing the stair thickness from stairs 1 to 3 the Brinell hardness (BH) of samples decreases. This is due to decrease in cooling rate of stairs which is the result of increase in thickness which leads

to decrease in the amount of martensite and increase in the amount of bainite. From stairs 4 to 5, the hardness increases because of the segregation of alloy elements specially Ni, Mn, and Mo. This segregation has a greater effect than thickness factor and leads to coarsening the martensite and increasing its hardness and decreasing the amount of bainite.

The microhardness results of bainite and martensite phases are shown in Table 3. The results indicate that from

FIGURE 2: (a) first stair, (b) second stair, (c) third stair, (d) fourth stair, (e) fifth stair.

TABLE 2: The percent of available phases in microstructure after etching.

Stair number	Retained austenite	Martensite	Bainite
1st stair	26.22%	22.35%	36.45%
2nd stair	19.99%	19.10%	45.63%
3rd stair	16.98%	15.05%	62.66%
4th stair	18.24%	11.25%	45.21%
5th stair	24.89%	09.57%	40.00%

stairs 1 to 3 because of increase, in the amount of bainite phase, the hardness of bainite phase increases and from stairs 4 to 5, because of decrease in the amount of this phase, the hardness decreases. About martensite phase, from stairs 1 to

3 the hardness decreases because of decrease in the amount of this phase which is the result of decrease in cooling rate. From stairs 4 to 5, the hardness increases because of the resulted segregation during solidification which leads to increase of carbon in the retained austenite which makes martensite coarser.

4. Conclusions

- (1) By increasing the thickness of stairs, the graphite type changes from type E to A.
- (2) By increasing the thickness of stairs from stairs 1 to 3, the hardness decreases because of decrease in cooling rate which leads to increase in bainite and decrease in martensite.

FIGURE 3: (a) The STM picture of upper bainite and (b) the 3D picture of this phase related to third stair.

TABLE 3: The result of hardness test.

Stair number	BH	Micro hardness	
		Martensite	Bainite
1st stair	330	692	239
2nd stair	297	649	286
3rd stair	273	598	292
4th stair	287	617	247
5th stair	302	625	213

- (3) By increasing the thickness of stairs from stairs 4 to 5, the solidification time increases and consequently alloy element segregation such as Ni and Mo occurs which leads to decreasing bainite and coarsening martensite and increasing hardness.
- (4) By increasing the thickness of stairs, the upper feathery bainite becomes coarser.
- (5) The third stair detected as optimum stair.

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