Microstructures and formation mechanism of hypoeutectic white cast iron by isothermal electromagnetic rheocast process

Zhang Wanning[1], Song Dan[2], Zhang Hongbing[2], Li Deyuan[2], Yuan Xiaoguang[2], and *Qiu Keqiang[2]

(1. Shenyang Government Investment Project Evaluation Center, Shenyang 1100141, China; 2. School of Materials Science and Engineering, Shenyang University of Technology, Shenyang 110870, China)

Abstract: An investigation was made on the evolution of microstructures of hypoeutectic white cast iron slurry containing 2.5wt.%C and 1.8wt.%Si produced by rheocasting in which the solidifying alloy was vigorously agitated by electromagnetic stirrer during isothermal cooling processes. The results indicated that under the proper agitating temperatures and speeds applied, the dendrite structures in white cast iron slurry were gradually evolved into spherical structures during a certain agitating time. It also revealed that the bent dendrites were formed by either convection force or by the growth of the dendrites themselves in the bending direction; then, as they were in solidifying, they were gradually being alternated into separated particles and into more spherical structures at the end of the isothermal cooling process. Especially, the dendrites were granulated as the bending process proceeding, which suggested that they were caused by unwanted elements such as sulfur and phosphor usually contained in engineering cast iron. Convective flow of the melt caused corrosion on the dendritic segments where they were weaker in strength and lower in melting temperature because of higher concentration of sulfur or phosphor. And the granulation process for such dendrites formed in the melt became possible under the condition. Certainly, dendrite fragments are another factors considerable to function for spherical particles formation. A new mechanism, regarding to the rheocast structure formation of white cast iron, was suggested based on the structural evolution observed in the study.

Key words: white cast iron; rheocasting; structural evolution; structures formation mechanism

CLC number: TG143.1/249.9 Document code: A Article ID: 1672-6421(2010)02-113-04

The initial work on the processing of semi-solid alloys was proposed by Flemings[1,2] many years ago, which represented an initial stage of rheocasting process that focused on technological consideration to the semi-solid zone at the solidification front. The main theme of his works was in control of microstructures of alloys. When liquid metal alloys were subjected to vigorous agitation during the early stage of solidification, the dendritic structures normally occurred were enable to transform into a structure of nearly spherical solid particles suspended in a liquid matrix, although irregular crystal grains such as rosette-type primary crystals could be observable in the microstructures because of insufficient agitation during the solidification [3]. Utilization of such slurries, so-called semi-solid alloys, in the high-pressure die-casting process has inherent advantages over superheated molten metals as discussed previously [4]. Up to now, many light weight metals, such as Al- [5-7] and Mg-based [8] alloys developed by using of such methods. Unfortunately, few research works on semi-solid processing for iron and steel [9] have been published so far.

In the present work, an investigation was made on the evolution of microstructures of hypoeutectic white cast iron ingots containing 2.5wt.%C and 1.8wt.%Si produced by rheocasting in which the solidifying alloy was vigorously agitated by electromagnetic stirrer during isothermal cooling processes.

***Qiu Keqiang**

Male, born in 1962, Professor and doctor supervisor. His research interests mainly focus on metal alloys and their forming technology, especially on amorphous alloys, semi-solid alloys and processing, metal composites. Now he has published over 100 papers and 60% of them have been indexed by SCI and EI.

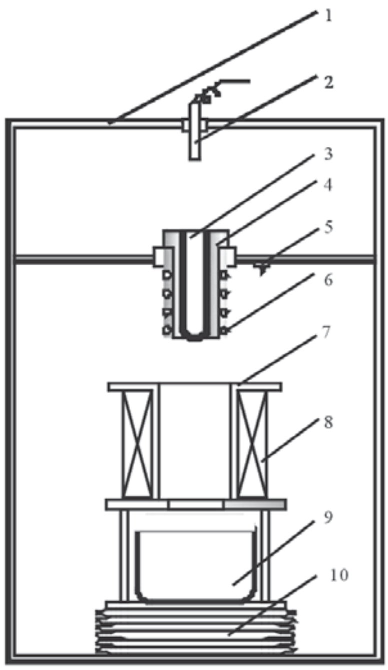
E-mail: kqqiu@163.com.

Received: 2009-11-22; Accepted: 2010-02-02

1 Experimental procedures

A cross-sectional view of semi-solid casting apparatus used for the semi-solid processing in the study is shown in Fig.1. The alloy composition (by weight percent) with 2.5%C, 1.8%Si, 0.5%Mn, 0.008%Bi, S≤0.025%, P≤0.085 and

Fe, the balance, was used in this investigation. Based on the measurement results on the liquid metal in heating and cooling at the rate of 10 K/min by differential thermal analysis (DTA), it indicated that the liquidus temperature of the alloy is at 1,543 K and the solidus temperature is at 1,429 K, respectively. The temperature range of the liquid-solid zone is 134 K in which two stages of isothermal agitating processes were conducted. The first stage is at a temperature of 1,523 K, which is 20 K lower than the liquidus temperature and, the second stage is at 1,483 K which is 54 K higher than the solidus temperature. The temperature was monitored by radiation pyrometer within accuracy of ± 2 K. In order to reveal the microstructure evolution of the alloy, the agitation was operated with various isothermal holding time intervals and then cooled naturally. The sample size was 30 mm in diameter and 70 mm in length. Microstructures on the cross sections of samples were observed under an optical microscopy (OM).



1. Chamber; 2. Radiation pyrometer; 3. Quartz crucible; 4. Graphite crucible; 5. Touching switch; 6. Induction coils; 7. Water cooler; 8. Electromagnetic stirrer; 9. Melt collector or quenching basin; 10. Elevating mechanism

Fig.1:Schematic illustration of the experimental apparatus for semi-solid alloys

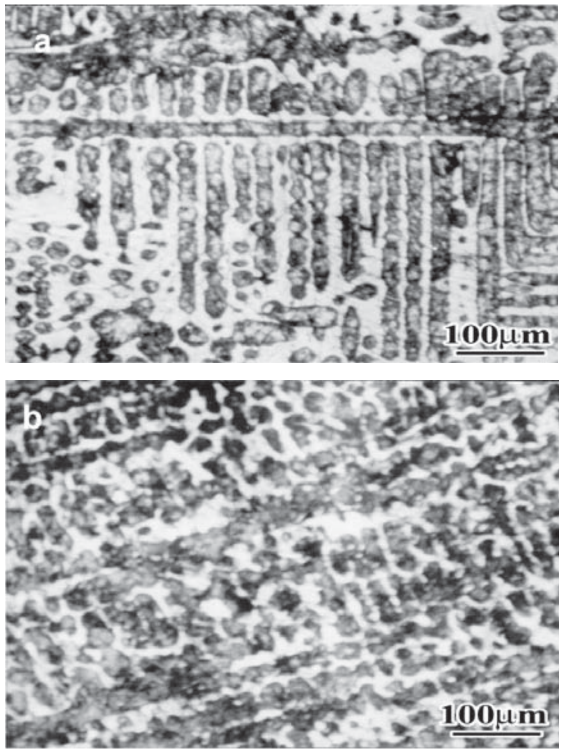


Fig.2: Microstructures taken from (a) boundary and (b) internal of white as-cast iron ingots

2 Microstructure evolution and discussion

Figure 2 shows the as-cast microstructures of the white cast iron without being agitated by electromagnetic stirrer. The Fig.2 (a) presents the microstructure of the field approaching to the outer edge of the sample where there is a larger cooling rate than the inner area. Meanwhile, the microstructure for the inner area is shown in Fig.2 (b). Primary austenite dendrites in Fig.2 (a) characterize significantly directional array like fish bone in shape, but a little difference appears in Fig.2 (b), which is more like dendrite structures existed at the area. In each case, however, the knob dendrites, i.e., the dendrites consisted of knob-like particles, are observed. These knob dendrites are essentially caused by undercooling as a result of the constituents with lower melting point, especially S and P, saturated at the front of the liquid-solid interfaces of molten metal when it solidifies. The connected segments of the knobs are the thin parts and therefore the weaker locations in strength. The knob dendrites are therefore easy to be separated from each other at the weaker locations with convective flow of the liquid metal when stirred by electromagnetic force.

Figure 3(a) through Fig.3(d) demonstrate the microstructural evolution of white cast iron with various isothermal agitating times. All the images in the figure were in the same magnification and the stirring direction is marked with an arrow in Fig.3(a). Figure 3 (a) shows the structure changes after 5 seconds of agitating in the electromagnetic field, which indicates that the growing direction of the dendrites, as showing a bending tendency under the convection of liquid metal, is not quite clear, yet. However, some of the secondary dendrites got separated from their primary arms and some of others were approaching each other. With time proceeding, greater bending stress will be concentrated on the neck of the dendrites [10] due to the collision between dendrite particles or/and corrosion from liquid as well as the convection of heat or mass transfer. Therefore, a greater degree of bending can be happened at the weaker segments of dendrites where accumulated more impurities, at the primary and/or secondary dendrites. Thus, the weaker parts are possibly becoming

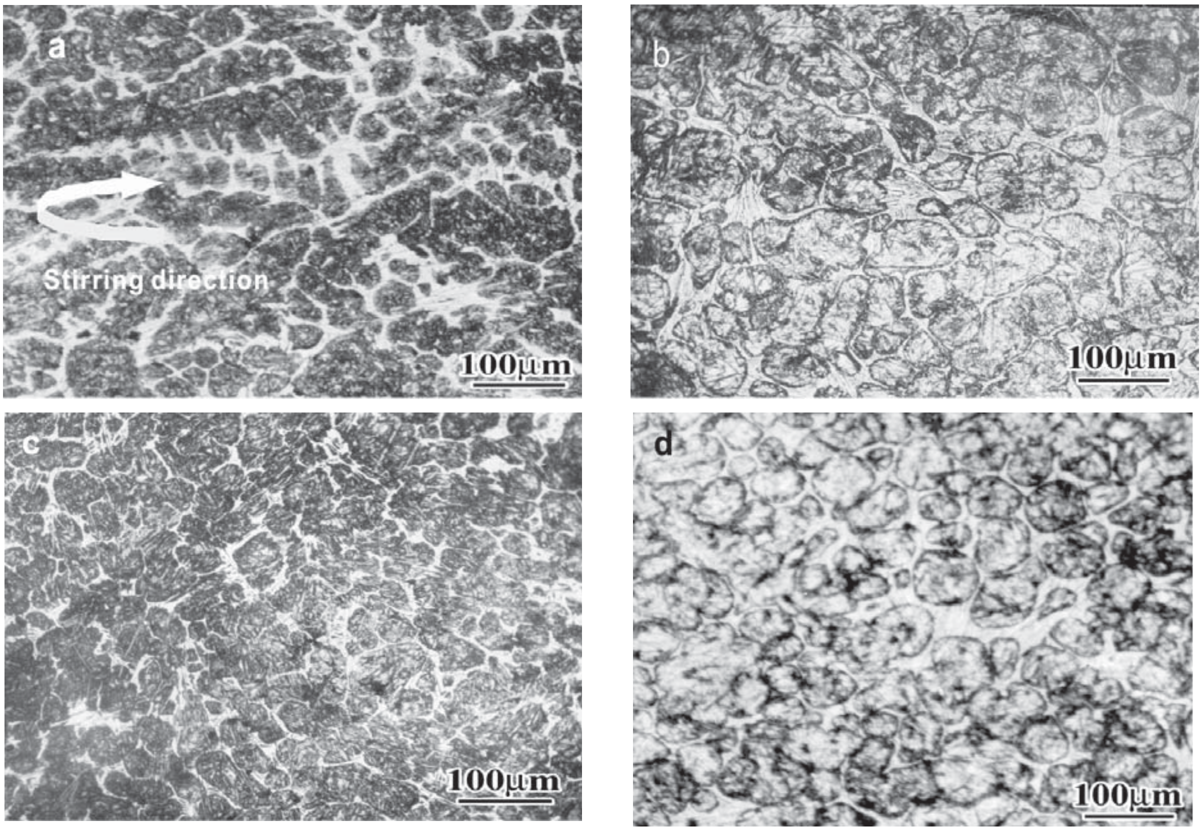


Fig.3: Evolution of microstructure morphologies in white cast iron ingots solidified after stirring for 5 s (a), 15 s (b), 120 s (c) and 240 s (d)

narrower and narrower. As a result, these dendrites gradually evolve into separated particles. From Fig.3 (b), it can be seen that some of the dendrites had been alternated into separated particles although some of them are still in incompletely separated forms. At least, the morphology presents a nearly non-dendritic structure plus a trace of rotation that resulted from the agitating of electromagnetic field, which has not been reported heretofore. At the first stage of isothermal agitating, both agitation and crystallization are exothermal processes. The processes as well as the higher temperature of the first stage of agitating make the solidifying crystals tend to be remelted due to the agitating energy released. These factors cause the dendrites lower in strength and higher in ductile, so it is possible for the dendrites to bend with agitating. Furthermore the bent structures are easily to be corroded by liquid convection at the weaker locations of connected knobs. When agitating time reached 120 s, the nearly non-dendritic particles were formed with almost same size, but lacking the degree of roundness, as seen in Fig.3(c). There exists certain fraction of solid for given temperature, then the fraction of solid increases with decreasing isothermal temperature. Figure 3 (d) shows the result of microstructural evolution of the melt stirred for 120 s during the second isothermal stage, i.e., 240 s in total, after accounting for the time agitated during the first isothermal stage. A nearly spherical structure was formed at the stage. It is necessary to increase the electric current of electromagnetic stirrer when the fraction of solid increases with decrease of the agitating temperature or else it is difficult to achieve proper non-dendrite particles. Especially, because of the agitating temperature drop from the first stage to the second one, resulting in the increase in the fraction of solid and viscosity and the decrease in shear rate, a lot of agglomeration of grains can be formed in the melt. This evidence will be given in a separated paper. It should be pointed out here that the semi-solid casting apparatus used in the study is not a standard one, therefore the electric current applied by the electromagnetic stirrer is not given here, too.

The dendrite arm bending plays an important role in the microstructural evolution process. It may be the case of the growth of the dendrites in the bending direction or the case they were bent under the convection of flowing of heat/mass. The case more frequently happened is both of them coexisted. Granulation is, however, a more important process than the spherical particles formation alone. Flowing liquid convection can cause corrosion at the dendritic segments that were weaker in strength and lower in melting temperature because of higher concentration of S or P. And such a granulation process from dendrites becomes possible in the melt where knob like dendrites existed. Certainly, dendrite fragments are another factor to influence spherical particles formation. The above explanation can be described in Fig.4. From Fig.4, we can see that the dendrites granulation mechanism is as followings: First, the dendrites are bent due to melt flowing caused by agitating force; second, the corrosion occurs at the weaker locations due to liquid convection. The coexisting of such two processes is the dendrites granulation mechanism.

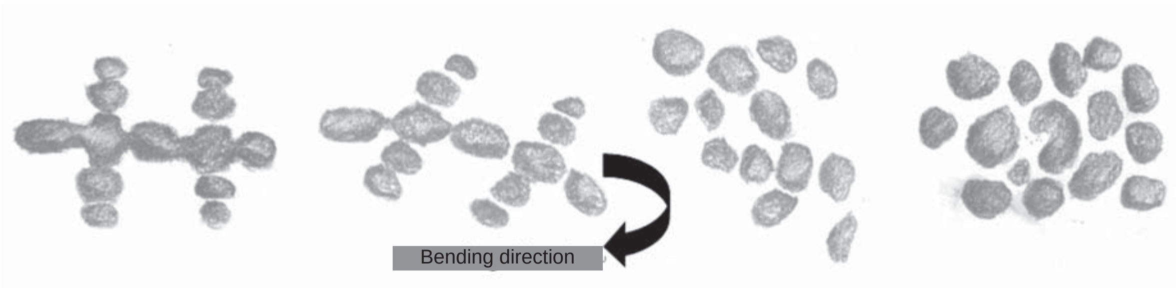


Fig.4: Schematic illustration of microstructural evolution of white cast ingots agitated by electromagnetic field during isothermal stirring

3 Summary

An investigation was made on the evolution of microstructures of hypoeutectic white cast iron slurry containing 2.5wt%C and 1.8wt%Si produced by rheocasting in which the solidifying alloy was vigorously agitated by electromagnetic stirrer during isothermal cooling processes. The intrinsic nature of dendrites with knob-like structure has endowed them with the semi-solid processing properties during agitating. The dendrites bending due to melt flowing caused by agitating force plays an important role. The corrosion at the weak locations due to liquid convection will accelerate the knob-like dendrites separation process. The coexisting of such two processes is the dendrites granulation mechanism.

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This work is financially supported by the Liaoning Education Bureau of China under grants No. 20061010.