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Ultrasonic Testing of Vermicular Cast Iron Microstructure

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Abstract

The paper presents results of a study on the effect of passage of time on magnesium content in iron alloys and the effect of magnesium content on the number of vermicular graphite precipitations per unit surface area and value of the longitudinal ultrasonic wave velocity for two different vermicularization methods. The study was carried out with the use of inspection bar castings. For specific production conditions, it has been found that in case of application of both the cored wire injection method and the method of pouring liquid metal over magnesium master alloy on ladle bottom, the satisfactory level of magnesium content in the bottom-pour ladle, for which it was still possible to obtain castings with vermicular graphite, was 0.018% Mg. In case of the cored wire injection method, the “time window” available to a pouring station at which castings of vermicular cast iron are expected to be obtained, was about 5 minutes. This corresponds to the longitudinal ultrasonic wave velocity values exceeding 5500 m/s and the number of graphite precipitations per unit surface area above 320 mm^{-2}. In case of the master alloy method, the respective “time window” allowing to obtain castings of vermicular cast iron was only about 3 minutes long. This corresponds to the longitudinal ultrasonic wave velocity value above 5400 m/s and the number of graphite precipitations per unit surface area above 380 mm^{-2}.

Keywords: Vermicular cast iron, Vermiculatization method, Microstructure, Graphite precipitation surface density, Longitudinal ultrasonic wave velocity

1. Introduction

Values of parameters characterizing a process of fabrication of vermicular iron castings developed for a specific casting shop are useless for another iron foundry. This is a result of differences in the course of the kinetics of “assimilation” of magnesium and the time interval for which the content of the element is maintained necessary to obtain the vermicular cast iron. It is a well known fact that the process is affected by, among other things, the way magnesium is introduced to the liquid metal and the method of achieving its target content, temperature of the liquid metal, capacity and the ratio of slenderness of the used casting ladles, and the way and frequency of transfers of magnesium-containing liquid metal. In the foundry practice, two ways of introducing magnesium to liquid metal are used most commonly: the cored wire injection method or the method in which liquid metal is poured over magnesium master alloy placed on bottom of a treatment ladle [1]. This follows from the possibility to assess effectiveness of the vermicularization process in liquid metal remaining still in a casting ladle which in turn offers the option to adjust the magnesium content before making the decision to start pouring the liquid metal into casting molds.

To take decision whether the vermicular cast iron fabrication process should be carried out with either the cored wire injection method or by pouring the parent metal over magnesium master alloy placed on ladle bottom (hereinafter in short, “the master alloy method”), it is necessary to establish quantitative relationships expressing the effect of the passage of time from the end of the vermicularization and modification process on magnesium content and microstructure of the cast iron.

From 1980s onwards, continuously increasing recognition of ultrasonic methods used to inspect microstructure of castings is observed both in the United States and the European Union [2-6]. Evaluation of the longitudinal ultrasonic wave velocity was widely accepted as the most useful diagnostic tool in examination of the cast-iron spheroidization degree. Results of several studies confirm that in conditions prevailing in a specific casting shop there exists a relationship, typically linear, between the degree of cast iron spheroidization and the longitudinal ultrasonic wave velocity value. Such relationship was also found between microstructure and the longitudinal ultrasonic wave velocity [3, 6]. Therefore, the use of ultrasonic inspection for the purpose of assessing microstructure of vermicular iron castings seems to be justified in view of similarity between the two production processes.

The objective of the present study was to establish the effect of the used vermicularization method on the number of vermicular graphite precipitations and longitudinal ultrasonic wave velocity values when either the cored wire injection method or the master alloy method was used in conditions prevailing in a newly established foundry shop.

2. Experimental

The liquid metal constituting the parent material for the vermicularization process was prepared in Inductotherm induction furnace with capacity of 5 tons. The metal charge was based on 1200 kgs of Pig-Nod casting pig iron with chemical composition including 4.32% C, 1.05% Si, 0.16% Mn, 0.01% S, and 0.09% P. Once the metal was melt, about 3 kg of SAS slag coagulating agent was added onto the liquid metal surface to remove slag. The liquid metal, temperature of which in the furnace was 1498°C, constituted the parent material for the vermicularization treatment with the use of either the cored wire injection method or the master alloy method. Chemical composition of the parent liquid metal subjected to the vermicularization process is summarized in Table 1.

Table 1.
Chemical composition of parent metal subjected then to vermicularization treatment with the use of either the cored wire injection method or the master alloy method

Element content, % wt.				
C	**Mn**	**Si**	**S**	**P**
4.21	0.15	1.02	0.01	0.08

It has been assumed that the magnesium content to be achieved in the cast iron after vermicularization treatment carried out with the use of either of the two tested method s should be 0.020–0.022% Mg.

In case of vermicularization with the use of the cored wire injection method, to obtain the assumed magnesium content on the level of 0.020–0.022% Mg, CEDIFIL NCF 4800 cored wire was use in the proportion of 4.5 meters per 350 kg of liquid metal. Next, a slender ladle was preheated and a portion of 350 kg of the liquid metal was poured into it while MB10 inoculant was added onto the stream of liquid metal and a sample for analysis of chemical composition was taken. The ladle was then transported to the station on which the vermicularization treatment was carried out. After completion of the vermicularization process and sweeping slag from the liquid metal surface, ladle with liquid metal was moved to the mold pouring station where the metal was transferred to a bottom-pour ladle. During the transfer, MB10 inoculant was applied onto the liquid metal stream. Just before and in the course of pouring production molds, liquid metal samples were taken to cast inspection rods [3] for examination of microstructure, evaluation of the lingitudinal ultrasonic wave velocity, and analysys of chemical composition.

The process of vermicularization with the use of the master alloy method, 3 kg of Lamet inoculant (Elkem) was used per 350 kg of liquid metal. Once the magnesium master alloy was poured onto the bottom of the slender ladle, the latter was filled with liquid metal to start the process and at the same time, powdered MB10 inoculant was added onto the stream of transferred metal. Next, after sweeping the slag off, the ladle with liquid metal was transported to the pouring station where the metal was transferred to a bottom-pour ladle. Immediately before and in the course of pouring production molds, liquid metal samples were taken to cast inspection rods [3] for examination of microstructure, evaluation of the longitudinal ultrasonic wave velocity, and analysys of chemical composition. The assessment of effectiveness of the vermicularization treatment with the use of either the cored wire injection method or the master alloy method was carried out based on results of measurements of the longitudinal ultrasonic wave velocity in combination with outcomes of metallographic examination.

The longitudinal ultrasonic wave velocity measurements were carried out on a portion of the inspection rods with dimensions 20 mm × 20 mm × 30 mm isolated for that purpose. The used apparatus was ECHOMETER gauge (Karl Deutsch) equipped with DSE 18/25 P 2 probe.

Microstructure of cast bar samples and specimens taken from test castings of fireplace insert plates was assessed on unetched metallographic sections, observed with the use of Neophot 2 optical microscope at ×100 and ×300 magnification and Multiscan v. 18.03 software dedicated for image analysis. In the course of the measurements, graphite precipitates with size less than 10 µm were not taken into account. It was also assumed that a graphite precipitate is categorized as vermicular one when the ratio of its length to maximum thickness is greater than 2.0.

Metallographic sections were used to evaluate the number of graphite precipitations per unit surface area N_A. 50 measurements were taken for each sample. The presented results are mean values. The number of vermicular graphite precipitations per unit surface area N_A was determined from the formula

$$N_A = L / S, \qquad (1)$$

where L is the number of observed graphite precipitates, and S is the surface area of the analyzed image, mm^2.

3. Research results

Results of measurements of the longitudinal ultrasonic wave velocity c_L and the number of vermicular graphite precipitations per unit surface area N_A in bar samples cast with the passage of time counted from completion of the vermicularization treatment with the use of the cored wire method are summarized in Table 2.

Results of microstructure examination of bar samples cast with the passage of time τ counted from completion of the vermicularization treatment with the use of the cored wire injection method are presented in Figures 1–5.

Table 2
Results of measurements of the longitudinal ultrasonic wave velocity c_L and the number of graphite precipitations per unit surface area N_A in bar samples cast with the passage of time τ counted from completion of the vermicularization treatment with the use of the cored wire injection method

Sample	D1	D2	D3	D4	D5
τ, min	0,57	2,28	3,63	5,00	6,93
Mg, %wt.	0,022	0,021	0,020	0,018	0,015
c_L, m/s	5572	5556	5515	5510	4486
N_A, mm^{-2}	425	400	392	323	–
D5 – no vermicular graphite precipitates					

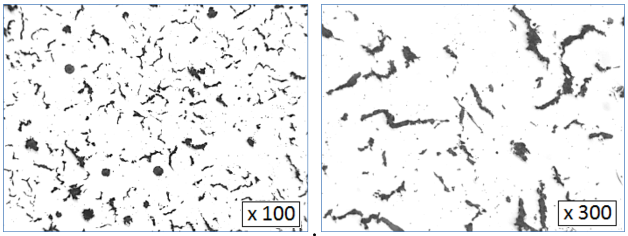

Fig. 1. Microstructure of bar sample D1
(τ = 0.57 min, 0.022% Mg, c_L = 5572 m/s, N_A = 425 mm^{-2})

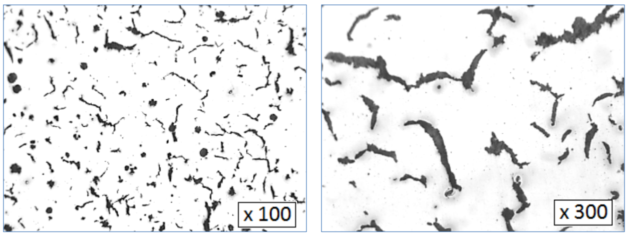

Fig. 2. Microstructure of bar sample D2
(τ = 2.28 min, 0.021% Mg, c_L = 5556 m/s, N_A = 400 mm^{-2})

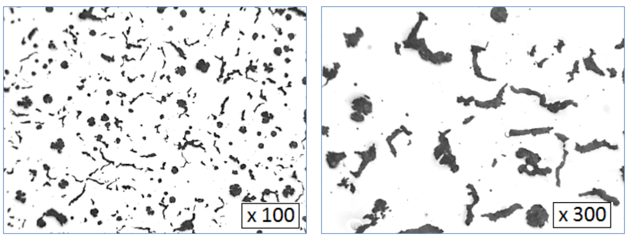

Fig. 3. Microstructure of bar sample D3
(τ = 3.63 min, 0.020% Mg, c_L = 5515 m/s, N_A = 392 mm^{-2})

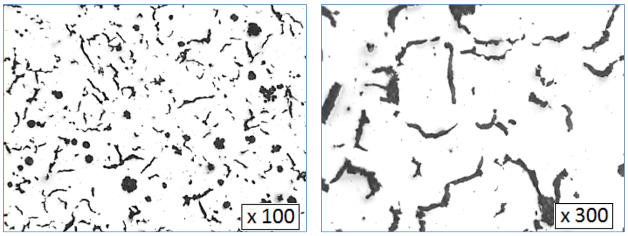

Fig. 4. Microstructure of bar sample D4
(τ = 5.00 min, 0.018% Mg, c_L = 5510 m/s, N_A = 323 mm^{-2})

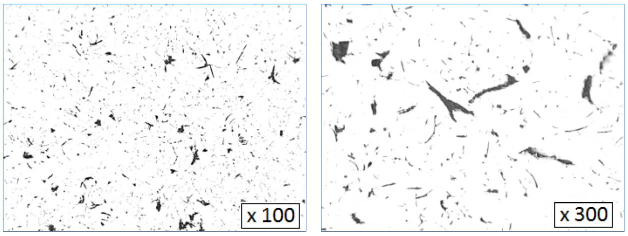

Fig. 5. Microstructure of bar sample D5
(τ = 6.93 min, 0.015% Mg, c_L = 4486 m/s)

The obtained results of the study indicate that in case of the cored wire injection method, the desired microstructure was demonstrated by samples cast at about 6 minutes from the end of the process of introducing magnesium and inoculant to liquid metal. The analyzed samples D1–D4 were characterized with the longitudinal ultrasonic wave velocity value c_L = 5572–5510 m/s. Extension of the liquid metal holding time to about 7 minutes resulted in disappearance of the vermicularization effect. The analyzed sample D5 was characterized with values of the longitudinal ultrasonic wave velocity below 5000 m/s (4486 m/s). It has been found that disappearance of the graphite vermicularization process was caused by decrease of magnesium content to the level of 0.015% Mg.

Results of measurement of the longitudinal ultrasonic wave velocity c_L and the number of vermicular graphite precipitations per unit surface area N_A on bar samples cast one by one with the passage of time τ from the end of the cast iron vermicularization process with the use of the master alloy method are presented in Table 3.

Table 3.
Results of measurement of the longitudinal ultrasonic wave velocity c_L and the number of graphite precipitations per unit surface area N_A on bar samples cast with the passage of time τ from the end of the cast iron vermicularization process with the use of the master alloy method

Sample	Z1	Z2	Z3	Z4	Z5
τ, min	0.37	1.87	3.23	4.67	5.83
Mg, % wt.	0.020	0.019	0.018	0.015	0.014
c_L, m/s	5497	5449	5443	4895	4777
N_A, mm^{-2}	436	405	383	-	-
Samples Z4–Z5 — microstructure significantly diversified					

Example microstructures of bar samples cast with the passage of time τ from the end of the cast iron vermicularization process carried out with the use of the master alloy method are presented in Figures 6–11.

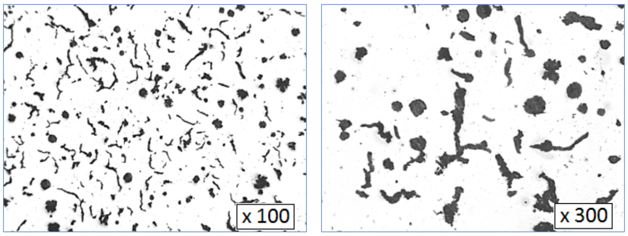

Fig. 6. Microstructure of bar sample Z1
(τ = 0.37 min, 0.020% Mg, c_L = 5497 m/s, N_A = 436 mm^{-2})

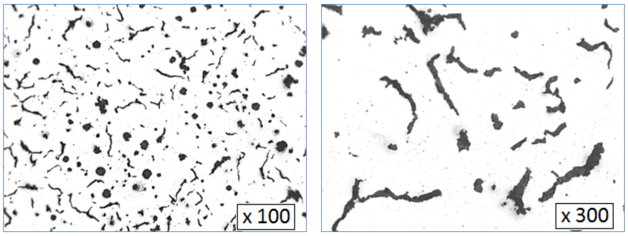

Fig. 7. Microstructure of bar sample Z2
(τ = 1.87 min, 0.019% Mg, c_L = 5449 m/s, N_A = 405 mm^{-2})

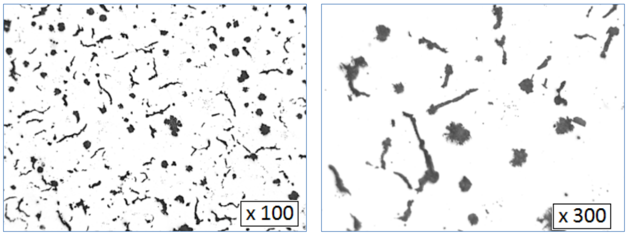

Fig. 8. Microstructure of bar sample Z3
(τ = 3.23 min, 0.018% Mg, c_L = 5443 m/s, N_A = 383 mm^{-2})

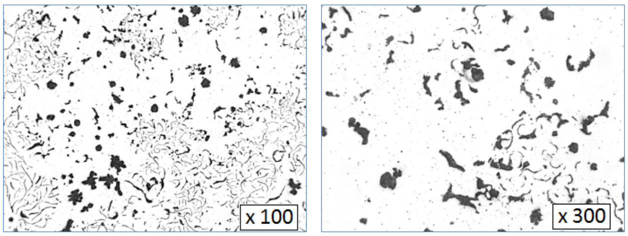

Fig. 9. Microstructure of bar sample Z4
(τ = 4.67 min, 0.015% Mg, c_L = 4895 m/s)

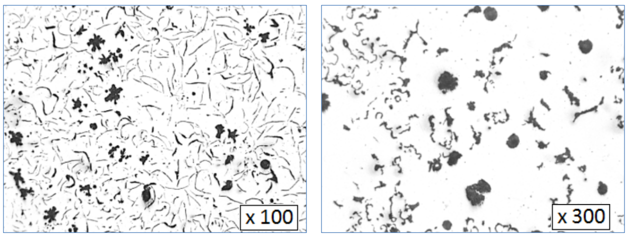

Fig. 10. Microstructure of bar sample Z5
(τ = 5.83 min, 0.014% Mg, c_L = 4777 m/s)

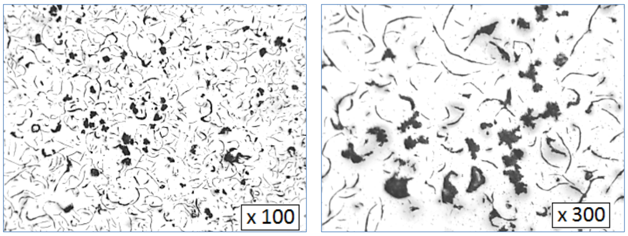

Fig. 11. Microstructure of bar sample Z6
(τ = 7.12 min, 0.011% Mg, c_L = 4715 m/s)

The obtained results indicate that in case of the master alloy method, satisfactory microstructure characterized those samples which were cast within up to about 3 minutes from the moment of introducing magnesium and inoculant to the liquid metal. Samples Z1–Z3 were characterized with the longitudinal ultrasonic wave velocity values c_L = 5443–5497 m/s. Extension of the liquid metal holding time up to 4.67 minutes resulted in disappearance of the graphite vermicularization effect. Samples Z4 and Z5 demonstrated values of the longitudinal ultrasonic wave velocity below 5000 m/s (4895–4715 m/s). It has been found that disappearance of the graphite vermicularization effect was caused by the magnesium level dropping below 0.015% Mg.

4. Conclusions

The results of the study allow to claim that in case of both the cored wire injection method and the master alloy method, the quantity of magnesium introduced to the liquid metal should be at least 0.022–0.020% Mg, while the magnesium content level in the bottom-pour ladle which still made possible to obtain vermicular iron castings was about 0.018% Mg.

It has been found that when the input magnesium content in the bottom-pour ladle could be secured on the level of 0.022–0.020% Mg, the “time window” which was available to the pouring station allowing to obtain castings of vermicular cast iron, was about 5 minutes in case of the cored wire injection method which corresponds to longitudinal ultrasonic wave velocity values above 5500 m/s and the number of graphite precipitations per unit surface area above 320 mm^{-2}. In case of the master alloy method, the “time window” allowing to obtain castings of vermicular iron was only 3 minutes, which corresponded to the longitudinal ultrasonic wave velocity value above 5400 m/s and the number of graphite precipitations per unit surface area exceeding 380 mm^{-2}.

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