ARCHIVES of FOUNDRY ENGINEERING

Published quarterly as the organ of the Foundry Commission of the Polish Academy of Sciences

ISSN (1897-3310)
Volume 14
Special Issue
1/2014
139-142

28/1

Effect of Cooling Rate on Microstructure of Thin-Walled Vermicular Graphite Iron Castings

M. Górny [a*], M. Kawalec [a], G. Sikora [a]
[a] AGH University of Science and Technology, Reymonta 23, 30-059 Cracow, Poland
*Corresponding author. E-mail address: mgorny@agh.edu.p

Received 12.03.2014; accepted in revised form 31.03.2014

Abstract

This article addresses the effect of cooling rate and of titanium additions on the microstructure of thin-walled vermicular graphite iron (TWCI) castings as determined by changing molding media, section size and *Ferro Titanium.* The research work was carried out on TWCI castings and reference castings of 2-5 mm and 13-mm wall thickness, respectively. Various molding materials were employed (silica sand and insulating sand ''LDASC'') to achieve different cooling rates. Thermal analysis was implemented for determinations of the actual cooling rates at the onset of solidification. This study shows that the cooling rates exhibited in the TWCI castings varies widely (70-14°C/s) when the wall thickness is changed from 2 to 5 mm. In turn, this is accompanied by a significant variation in the vermicular graphite fraction. The resultant cooling rates were effectively reduced by applying an insulating sand in order to obtain the desired vermicular graphite shape. In addition, good agreement was found between the theoretical predictions of the solidification process and the experimental outcome. Ti additions in combination with LDASC sand molds were highly effective in promoting the development of over 80 % vermicular graphite in castings with wall thicknesses of 2 and 3 mm as evidenced by quantitative metallographic analyses.

Słowa kluczowe: Innovative Foundry Technologies and Materials Vermicular Graphite Iron, Cooling Rate, Thermal Analysis, Microstructure.

1. Introduction

Current trends in the casting market are driving the need for strong cast irons with reduced weight when compared with gray iron parts. These cast irons must possess improved machinability, thermal-fatigue resistance, high damping capacity, improved casting mold yield and castability. In this sense, thin-walled Vermicular Graphite Iron (TWCI) castings provide a cost-effective solution to meet these challenges. Vermicular Graphite Cast Iron is a still modern engineering alloy with attractive features that enable its use in the diverse application [1-6]. In Vermicular Graphite Cast Iron, graphite exhibits an intermediate shape from the view point of compactness between flake graphite and spheroidal graphite.

The microstructure is influenced by a large number of factors like chemical composition, cooling rate, liquid treatment, and heat treatment. During the solidification process [7-8] the cooling rates exhibited by a given casting are primarily a function of the section size, pouring temperature, and the material mold ability to absorb heat. Increasing cooling rates have a strong effect on the graphite morphology and hence on the resultant mechanical properties. In particular, high cooling rates lead to an increase in the chilling tendency which is manifested as a high hardness and brittleness including poor machinability.

The challenge of producing sound thin-walled vermicular graphite iron castings is not a simple one since it is closely related to the strong effect of a wide range of cooling rates upon solidification [9]. Moreover, there is limited data on cooling rate-microstructure relationships in thin-walled castings, which is crucial for predictions of TWCI castings [10-11]. Hence, this work is aimed at investigating the effect of wall thickness on the exhibited cooling rates and on the resultant microstructures. In addition, the effect of Ti additions and the use of low thermal conductivity sand molds is considered in this work.

2. Experimental

The experimental melts were produced in an electric induction furnace of intermediate frequency and a 15 kg capacity crucible. The furnace charge consisted of Sorelmetal, technically pure silica, Fe-Mn, and steel scrap. Melting was carried out at 1490°C, with the bath held at temperature for 2 min. This was followed by vermicularization and inoculation operations using a bell method. For the vermicularization process, Fe-Si-Mg (6% Mg), as well as Fe-Ti were used, while a Fe-Si alloy (75% Si, 0.75-1.25% Ca, 0.75-1.25% Ba, 0.75-1.25% Al) was used for inoculation. The inoculant added in an amount of 0.6 wt.%. The chemical composition of the investigated ductile iron is given in Table 1. The CGI was poured at 1400°C on plate like castings with section sizes of 2, 3, 5 and 13 mm, respectively. The sand molds were made using conventional green molding sand consisting of silica sand, bentonite (7 wt.%), water/bentonite ratio of 0.4% and a granularity of 100-200 μm. In addition, sand molds were made using Low-Density Alumina-Silicate Ceramic (LDASC, composition 25%-45 % Al_2O_3 and 55%-75 % SiO_2) whose heat transfer properties are drastically reduced (approx. by 4 fold) when compared with those of silica sands [11]. Moreover, the sand is characterized by a low density 0.35-0.45 $g{\cdot}cm^{-3}$.

The molds were instrumented with Pt/PtRh10 thermocouples of 0.3 mm diameter and with their tips located in the geometrical center of each mold cavity. An Agilent 34970A electronic module was employed for temperature recording.

Metallographic characterization was made using a Leica MEF 4M microscope and a QWin v3.5 quantitative analyzer at various magnifications in order to determine the graphite and matrix morphologies. The analysis was based on line scans of the measuring area for measurements of the arithmetical average of graphite nodule fractions in the microstructure. At least five areas in the central part of the sample were used for these measurements. In addition, the fractured surfaces were examined by a JEOL JSM-5500LV Scanning Electron Microscope (SEM) operated at 20 kV.

3. Results and Discussion

3.1 Thermal Analysis

It is well known that the section sensitivity of vermicular graphite iron is lower than for gray iron, which in turn contributes to the homogeneity of the casting structure. Yet, in thin-walled castings, the section sensitivity of vermicular graphite iron should be taken into account due to the high cooling rate ranges involved. In this case, there is a vast tendency for defect formation, particularly structural inhomogeneities including the development of chilled iron. As a first approximation, in sand castings it can be assumed that heat transfer is mainly determined by the properties of the sand mold. From a heat balance for the heat flux in the casting, the cooling rate can be expressed as [12].

$$Q = \frac{8 T_s a^2}{\pi \; c^2 s^2 \ln \frac{T_i}{T_s}} \tag{1}$$

where: a - material mold ability to absorb heat, c - specific heat of the cast iron, s – wall thickness of the casting and T_i – initial temperature of the metal in the mold cavity just after pouring.

Figure 1 shows the cooling rates estimated using Eq. (1) as well as the experimental data obtained from the thermal analysis curves. Notice from this figure that there is good agreement between the theoretical predictions and the experimental outcome.

Table 1. Chemistry of GGI castings

Heat No.	Chemical composition											
	C	Si	Mn	P	S	Cr	Ni	Cu	V	Al	Ti	Mg
	Wt. %											
I	3.63	2.47	0.03	0.026	0.017	0.03	0.004	0.045	0.007	0.010	0.009	0.010
II	3.66	2.55	0.04	0.027	0.020	0.03	0.005	0.044	0.011	0.010	0.070	0.005
III	3.65	2.53	0.05	0.030	0.010	0.03	0.030	0.010	0.010	0.010	0.095	0.020
IV	3.60	2.55	0.05	0.023	0.018	0.04	0.040	0.060	0.010	0.021	0.133	0.021
V	3.63	2.56	0.04	0.030	0.018	0.03	0.040	0.050	0.010	0.020	0.135	0.022

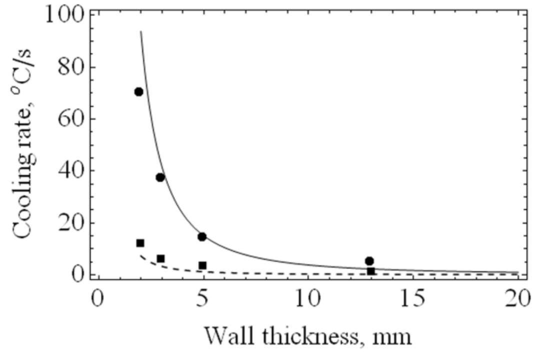


Fig. 1. Effect of wall thickness on the cooling rate of the experimental castings: Solid curve – melt No. IV (calculations made for c = 5.95 J $cm^{-3o}C^{-1}$; T_e = 1167 °C; T_i = 1400°C; a = 0.1 J/($cm^{2o}C$ $s^{1/2}$)), dotted curve - melt No. V (calculations made for c = 5.95 J cm^oC^{-1}; T_e = 1167°C; T_i = 1400°C; a = 0.025 J/($cm^{2o}C$ $s^{1/2}$)); ● – experimental points for green molding sand, ■ – experimental points for LDASC sand molds.

From the theoretical analysis (Eq. 1), it is shown that the cooling rate (except for the wall thickness of the casting) is mainly affected by the mold heat transfer properties (a) and by T_i. In particular, molding materials with a low ability to absorb heat (e.g., LDASC sand) have a significant effect in reducing the cooling rates. Notice that when LDASC sand is used as casting molds (a≈0.025 J^oC^{-1} cm^{-2} $s^{-1/2}$) instead of silica sand (a≈0.10 J^oC^{-1} cm^{-2} $s^{-1/2}$), the cooling rates experienced by a TWCI with a 2 mm wall thickness decrease by over 5 fold (see Fig. 1).

In addition, it is found that the cooling rates exhibited in TWCI with a wall thickness of 3 mm are similar to those obtained in conventional castings of 13 mm wall thickness when produced using silica sand (Fig. 2). Hence, the use of LDASC sand materials in the foundry process can dramatically improve metal flow, reduce misruns in thin sections, and slow down solidification rates in TWCI. In a related work, Showman and Aufderheid [11] reported that casting design is plausible by the use of insulating molding materials, other than conventional sand mold castings. Hence, the development of insulating sand materials which provide a significant reduction in the heat absorption thermal properties can be highly valuable for the production of sound TWCI castings.

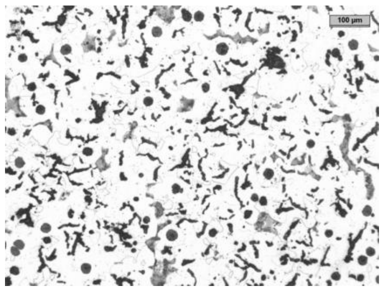
3.2. Microstructure

Metallographic examinations (Table 2) revealed a significant effect of Ti additions on the vermicular graphite, particularly in thin walled castings. However, the addition of Ti requires the addition of extra magnesium to avoid any risks for graphite flake formation. Thus, it is common to set a limit of 20% nodularity in order to meet Polish Standard specification [13]. In the case of thin-walled castings, the natural tendency of vermicular graphite cast iron is to solidify with a higher nodularity in thin outer walls (<4-5 mm) with up to 50% nodularity [6]. Studies show that in TWCI castings with a wall thickness of 5 mm, additions of 0.13% Ti result in reductions in the graphite nodule fraction to below 20% thus satisfying the Polish Standard [13]. In this work, for TWCI castings with a wall thickness of 3 mm, the nodular graphite fraction was reduced from 73% for the base iron down to 34% through the addition of 0.13% Ti.

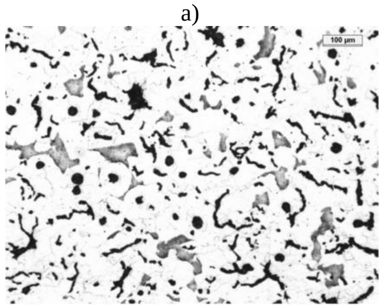
Notice that in castings with wall thicknesses of 2 and 3 mm, Ti additions as an anti-nodularizing element do not allow to meet the Polish specification of a required vermicular graphite fraction above 80 %. In contrast, metallographic evaluations clearly show that the use of LDASC sand significantly reduces the cooling rates (Fig. 1). In turn, this causes a significant increase in the vermicular graphite fraction exhibited in the TWCI castings. When LDASC sands are employed in castings with wall thicknesses of 2 and 3 mm the vermicular graphite fraction exceeds 90%. Thus, it satisfies the Polish Standard concerning a *minimum* volume *fraction* of at least 80%. In particular, notice that the vermicular graphite fraction, as well as the graphite size in TWCI with a wall thickness of 3 mm using LDASC sands is similar to that found in castings with thick wall thicknesses of approx. 13 mm obtained using silica sand molds.

SEM investigations show that titanium carbides are created in the form of faceted crystals which are evenly distributed in iron matrix. From metallographic observations result that their maximum size does not exceed 5 μm and their volume fraction is much lower than 1%.

Hence, from this work, it is evident that there is a wide range of possibilities for vermicular cast iron production unattainable through the use of ordinary foundry sands, Accordingly, novel applications are envisaged such as in the design of diesel engine blocks, exhaust manifolds, gearbox housings, brake discs for high-speed trains, flywheels [5-6], and other. Accordingly, TWCI provides increasing potential for applications which conventional materials cannot offer such as in the design of 'compound' iron-plus-aluminum blocks.



a)



b)

Fig. 2. Microstructure of cast iron in castings with wall thicknesses of (a) 3 mm (using LDASC sand) and (b) 13 mm (using silica sand). Nital etched samples.

Table 2. Effect of Ti on the Nodular Graphite Fraction in TWCI Castings

Heat No.	Ti additions [%]	Wall thickness [mm]	Graphite nodule fraction %	Ferrite fraction %
I	0.00	2	92	28
III	0.09	2	64	23
IV	0.13	2	50	26
V	0.13	2	10	84
I	0.09	3	73	40
III	0.09	3	46	40
IV	0.13	3	34	30
V	0.13	3	7	87
I	0.00	5	47	65
III	0.09	5	29	74
IV	0.13	5	17	56

4. Conclusions

1. In TWCI castings with wall thicknesses of 2 -3 mm using an insulating sand, LDASC, the cooling rates exhibited and the graphite fraction were found to be at the level typically achieved in castings with a wall thickness of the order of 13 mm when using silica sand molds. Also, a homogeneous structure free from chills was obtained despite the high cooling rates expected in thin-walled castings.
2. Theoretical calculations were made and then compared with the experimental outcome on the effect of casting cooling rates at the onset of solidification in TWCI. It was found that the predictions of the theoretical analysis are in a good agreement with the experimental results.
3. The cooling rates were found to vary between 70 and 14^{o}C/s in TWCI castings when the wall thickness was changed from 2 to 5 mm. This was accompanied by a significant change in the vermicular graphite fraction. The fraction of vermicular graphite was effectively reduced by employing an insulating LDASC molding sand. In turn, a structure in the vermicular graphite iron having more than 80 % vermicular graphite fraction was obtained, thus meeting the Polish Standard specifications.

Acknowledgements

This work was supported by Polish NCN Project No. 2013/09/B/ST8/00210.

References

[1] Qiu, H. & Chen, Z. (2007). The forty years of vermicular graphite cast iron development in China (Part III). *China Foundry*. 4, 261–269.

[2] Guesser, W.. Schroeder, T. & Dawson, S. (2001). Production experience with compacted graphite iron automotive components, *AFS Trans*. 109, 1–11.

[3] Kopyciński, D., Guzik, E., Nowak, A., Ronduda, M. & Sokolnicki, M. (2012). Prepation Vermicular Graphite in Thin and Thick Wall Iron Castings. *Archives of Foundry Engineering*. 12, 41–44.

[4] Murthy, V., Kishore, S. & Seashan, S. (1985). Vermicular graphite cast iron-current state of the art. *Sadhana*. 8, 361–372.

[5] Tittenson, D. (2011). Process control requirements for the consistent production of compacted graphite irons. *Foundry Trade Journal*. 6, 176.

[6] Dawson, S. (2011). Compacted graphite iron– a material solution for modern diesel engine cylinder blocks. *Foundry Trade Journal*. 6, 170–172.

[7] Podrzucki, C. (1991). *Structure, properties and application. Cast Iron*. Katowice: ZG STOP.

[8] Sofroni, L., Riposan, I., Chria, I. (1974). Some considerations on the crystallization features of cast irons with intermediate-shaped graphite (vermicular type). In 2nd International Symposium on the Metallurgy of Cast Iron, 29-31 May 1974 (pp. 179–196). Geneva, Switzerland: Institute Battele, Georgi Pub. Co.

[9] Górny, M., Kawalec, M. (2013). Role of titanium in thin wall vermicular graphite iron casting production. *Archives of Foundry Engineering*. 13 (2/2013), 25–28.

[10] Charoenvilaisiri, S., Stefanescu, D.M., Ruxanda, R. & Piwonka, T.S. (2002). Thin wall compacted graphite iron castings, *AFS Trans*. 110, 1113–1130.

[11] Showman, R.E., Aufderheide, R.C. & Yeomans, N. (2006). Ironing out thin-wall casting defects. *Mod Cast*. 96(9), 29–32.

[12] Fraś, E., Górny, M. & Lopez, H.F. (2007). Eutectic cell and nodule count in cast iron - Part II. Theoretical Background. *ISIJ Int*. 47(2), 259–268.

[13] PN-EN 16079:2012, Odlewnictwo – Żeliwo z grafitem zwartym (wermikualrnym).