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Role of Titanium in Thin Wall Vermicular Graphite Iron Castings Production

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Abstract

In this paper the effects of titanium addition in an amount up to 0.13 wt.% have been investigated to determine their effect on the microstructure and mechanical properties of Thin Wall Vermicular Graphite Iron Castings (TWVGI). The study was performed for thin-walled iron castings with 3-5 mm wall thickness and for the reference casting with 13 mm. Microstructural changes were evaluated by analyzing quantitative data sets obtained by image analyzer and also using scanning electron microscope (SEM). Metallographic examinations show that in thin-walled castings there is a significant impact of titanium addition to vermicular graphite formation. Thin-walled castings with vermicular graphite have a homogeneous structure, free of chills, and good mechanical properties. It may predispose them as a potential use as substitutes for aluminum alloy castings in diverse applications.

Keywords: Vermicular graphite, Microstructure, Titanium, Thin-walled castings

1. Introduction

Vermicular Graphite Cast Iron (VGCI) also known as the Compacted Graphite Iron (CGI) is an alloy with attractive features that is used in the automotive industry [1-5]. Brake discs and brake drums, exhaust manifolds, engine heads, and diesel engine blocks, and is traditionally manufactured from gray cast iron. Vermicular graphite cast iron allows the manufacture of diesel engines with better combustion and performance. VGCI may be used for light castings with good mechanical properties and performance, with especially good vibration damping capacity and thermal conductivity [6,7], higher pressures, and is relatively low production cost [8,9]. From the point of view of ecology and economics, thin-walled castings of VGCI can compete in terms of mechanical properties with the ‘‘light’’ aluminum alloy castings. The main factors that influence the structure of VGCI castings are chemical composition, cooling rate, liquid treatment, and heat treatment [9,10]. The cooling rate of a casting is primarily a function of its section size, pouring temperature, and the ability of the material mold to absorb the heat. The process of obtaining thin-walled castings is not simple, because it is associated with a wide range of cooling rates at the beginning of graphite eutectic solidification [11,12]. With increasing cooling rates in thin-walled VGCI castings, thermal undercooling increases and graphite gradually becomes nodular, resulting in an increased nodule count and lower vermicular graphite ratio. Therefore, the production of thin-walled vermicular iron castings is more difficult than that of thicker section iron [13]. The formation of vermicular graphite is a difficult process to control with only a narrow margin of residual Mg: too much Mg will give an excess of nodules, whereas too little Mg will lead to the formation of gray iron flake structures [9,13]. From the literature [14], it follows that even at magnesium levels as low as 0.01% it is not possible to obtain acceptable VGCI with wall thicknesses of 4 mm due to excessive graphite nodularity. The treatment of iron with addition of antispheroidizing elements (Al, Bi, Ti, Zr, Sb) has much wider industrial application. The use of titanium as a key alloying elements has advantages and disadvantages. Magnesium-titanium combination helps to extend the working range of magnesium to achieve successful production of VGCI castings [9, 10]. A major concern with regard to titanium additions is contamination of casting returns and reduced machinability [5]. Foundry practice and good production discipline could not be sufficient to maintain the consistency of the desired microstructure without the use of antispheroidizing elements such as titanium. The literature provides limited data [5,14,15] dealing with the influence of titanium addition on high cooling rate-structure relations of VGCI, which is a crucial property in the formation of thin-walled castings. This article presents an analysis of the addition of Ti on the microstructure and mechanical properties of thin-walled castings.

2. Experimental

The experimental melts were done in an electric induction furnace of intermediate frequency in a 15 kg capacity crucible. The furnace charge consisted of the following materials: Sorelmetal, technically pure silicon, Fe-Mn, Fe-S, and steel scrap. After metal heating to a temperature of 1490 ^{o}C, the bath was held for 2 min and then, vermicularization and inoculation operations were performed by a bell method. For the vermicularization, the foundry alloy Fe-Si-Mg (6% Mg) as well as Fe-Ti were used, while the inoculation was done by means of the Fe-Si alloy (75% Si, 0.75-1.25% Ca, 0.75-1.25% Ba, 0.75-1.25% Al) inoculant in an amount of 0.6 wt.%. The pouring temperature was app. 1400 ^{o}C. In this experiment, VGCI plate castings with wall thickness of 3, 5, and 13 mm were produced. The sand mold was prepared using conventional green molding sand made of silica sand, bentonite (7 wt.%), water/bentonite ratio amounts to 0.4%, and a granularity of 0.1-0.2 mm. Chemical compositions are tabulated in Table 1.

Metallographic characterization was made using a Leica MEF 4M microscope and QWin v3.5 quantitative analyzer at various magnifications to observe graphite morphology and matrix. The analysis was based on the use of a line scan of the measuring area. This method counts the number of graphite nodules which have been cut by the line scan. The final result was the arithmetical average of the graphite nodule fraction in the microstructure during the scan of at least five areas of the central part of the sample. In addition, the fractured surfaces were examined by a JEOL JSM-550LV scanning electron microscope (SEM) operated at 20 kV.

Brinell hardness measurements were made in an HPO-250 hardness tester and tensile testing was performed in a universal Zwick/Roell Z050 following the PN-EN ISO 6892-1:2010 Standard.

3. Experimental Results and Analysis

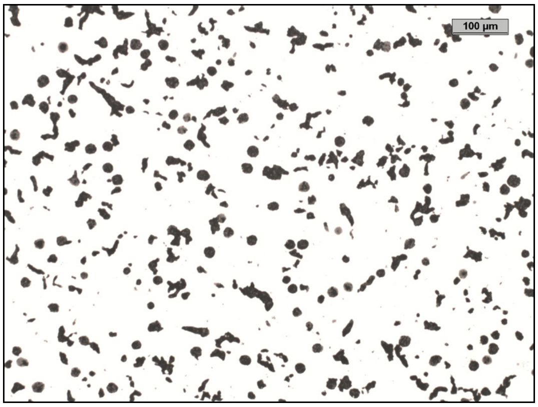
Microstructure

The results of metallographic examination are given in Table 2. Metallographic examination revealed a significant effect of the addition of titanium to vermicular graphite, especially in thinwalled castings. The addition of titanium requires the addition of extra magnesium to stay safely away from the risk of formation of graphite flake structures. Studies show that titanium addition reduces the graphite nodule fraction in cast iron (G = 3 mm) from 73% for the base iron to 34% for cast iron with the addition of 0.13% Ti. It is usual to set a limit of 20% nodularity for VGCI specifications [16,17]. In the case of thin-walled castings, the natural tendency of VGCI is to solidify with higher nodularity, which may result in the thin outer walls (<4-5 mm) having up to 50% nodularity [5]. In the case of thin-walled castings with greater wall thickness (G = 5 mm) after the addition of 0.13% Ti the graphite fraction is reduced to below 20% (Fig. 1), thus meeting standards both the Polish PN and American ASTM. According to the work [15], the addition of 0.15% titanium increases the vermicular graphite fraction in castings with a wall thickness of 30-80 mm only by approximately 10%, and has a negligible impact on the mechanical properties. This study shows that the use of 0.13% Ti in thin-walled castings has a much stronger effect on the solidification of vermicular graphite in comparison with castings with thicker sections. Analysis of the cast iron matrix shows that the addition of Ti slightly decreases the ferrite fraction in the casting (Table 2).

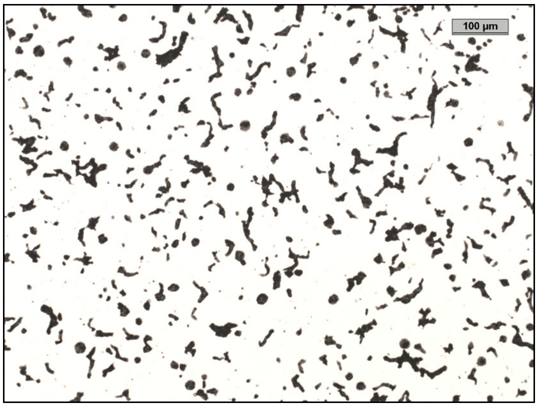
Titanium causes solidification of carbides (TiC) in cast iron. SEM investigations revealed crystals of TiC in the cast iron microstructure. Titanium carbides in the form of faceted crystals are evenly distributed in iron matrix. Metallographic analysis shows that their maximum size is<4 lm, and their fraction is much lower than 1%.

Table 1.
Result of chemical compositions

Heat No.	Chemical compositions											
	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



a)



b)

Fig. 1. Microstructure of castings with wall thickness of 5 mm: (a) heat No. I, (b) heat No. IV

The process of obtaining thin-walled castings is not easy, as it is associated with a high range of cooling rates. This contributes to a greater tendency toward the formation of defects, in particular structural inhomogeneity and the occurrence of chills. Knowledge of the effect of technological factors on the cooling rate and on the physicochemical state of liquid iron is of fundamental importance for the preparation of thin-walled castings with good mechanical properties and performance, and without casting defects. Characteristic features of thin-walled castings are also significant changes of cooling rate during insignificant wall thickness variation. The thermal analysis [12] shows that the change in wall thickness from 5 to 3 mm results in a significant increase in the cooling rate. This causes shortening of the solidification time and the risk of chill occurrence in cast iron. For this purpose, in thin-walled ductile iron or VGCI castings a high degree of inoculation is required [18]. In the case of VGCI, it is particularly disadvantageous in view of the fact that increasing nucleation potential decreases the amount of vermicular graphite and increases the graphite nodule fraction. This study shows that the addition of Ti enables, in thin-walled castings with a high degree of inoculation and solidified under high cooling rate, the obtention of a homogeneous structure of cast iron, free of chills, with a high vermicular graphite fraction.

Table 2.
The results of metallographic examination

Heat No.	Ti additions [%]	Wall thickness [mm]	Graphite nodule fraction %	Ferrite fraction %
I	0	3	73	40
II	0.07	3	-	15
III	0.09	3	46	40
IV	0.13	3	34	30
I	0	5	47	65
II	0.07	5	-	85
III	0.09	5	29	74
IV	0.13	5	17	56
I	0	13	20	90
II	0.07	13	-	90
III	0.09	13	17	85
IV	0.13	13	15	90

Mechanical Properties

The effects of titanium addition and casting size on the mechanical properties of VGCI castings are summarized in table 3. From the results one can see that no significant increase in the hardness occurs for Ti addition up to 0.13%. It can be seen that the tensile strength slightly increases with the addition of Ti up to 0.09% Ti. Further increasing the titanium causes a decrease in both the tensile strength and the elongation of thin-walled iron castings. This is due to an increase in the vermicular graphite fraction in the cast iron microstructure, with a higher length to thickness ratio.

Table 3.
Tensile strengths, elongation, and Brinell hardness as a function of Ti addition and wall thicknesses

Heat No.	Ti additions [%]	Wall thickness [mm]	R_m [MPa]	A_5 [%]	HBW
I	0	3	595	6.04	223
III	0.09	3	622	5.4	232
IV	0.13	3	516	3.7	238
I	0	5	526	9.2	173
III	0.09	5	466	6.1	181
IV	0.13	5	443	6.1	183
I	0	13	378	8.88	155
III	0.09	13	387	6.4	160
IV	0.13	13	363	6.4	154

In the case of reference casting (G = 13 mm), the addition of Ti does not appreciably affect the Rm or HBW, while elongation is lowered to the level of 6.4%. In conclusion, It can be said that the addition of titanium up to 0.13 wt.% effectively increases the vermicular graphite fraction and pearlite percentage, owing to the anti-spheroidising and carbide-forming potential of Ti. Increasing the vermicular graphite fraction reduces ductility, while increasing pearlite percentage strengthens the metallic matrix. These contradictory effects resulted in VGCI castings with added titanium having relatively unchanged tensile strength and hardness. The structural characteristics, including the absence of chills, uniformly distributed TiC, ferritic-pearlitic matrix, and high fraction of vermicular graphite predispose thin-walled VGCI castings for potential use as substitutes for aluminum alloy castings in diverse applications.

4. Conclusions

From the experiments it results that even at Mg levels as low as 0.01% it is not possible to obtain acceptable fraction of vermicular graphite in thin-walled castings because of excessive nodularity. The introduction of titanium in amounts up to 0.13% iron allows a high proportion of vermicular (compacted) graphite in thin-walled castings. A homogeneous structure, free of chills was obtained in thin-walled castings, despite high cooling rates. The addition of titanium results in solidification of titanium carbides in the form of faceted crystals, which are uniformly distributed in the iron matrix. Their maximum size is <4 μm, and their volume fraction does not exceed 1%. The addition of titanium causes no significant deleterious influence on the mechanical properties of thin walled VGCI castings.

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