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Influence of Structure on the Thermophisical Properties of Thin Walled Castings

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Abstract

This study addresses the effect of the cooling rate and of titanium additions on the thermophysical parameters of thin-walled compacted graphite iron (TWCGI) castings. Various molding materials were used (silica sand and insulating sand LDASC- Low-Density Alumina-Silicate Ceramic) to achieve different cooling rates. Different titanium additions were caused by various amount of Ferro Titanium. The research work was conducted for thin-walled iron castings with a 3-mm wall thickness. The tested material represents the occurrence of graphite in the shape of flakes (C and D types, according to the ISO Standard), nodules or compacted graphite with a percent of nodularity and different shape factor. Thermal conductivity has been determined by the laser flash technique in a temperature range of 22-600°C. The results show that the cooling rates together with the titanium content largely influence the graphite morphology and finally thermal conductivity of thin walled iron castings.

Keywords: Solidification Process, Thin-Walled Iron Castings, Graphite morphology, Thermal diffusivity, Specific heat, Thermal conductivity

1. Introduction

Good thermophysical properties of CGI are of high importance, especially in thin wall castings which are simultaneously, thermally and mechanically loaded, such as cylinder blocks, heads and brake systems [1-4].

Thermophysical properties of thin walled compacted graphite iron castings are strongly influenced by a graphite fraction, its morphology, eutectic grains, and metallic matrix [5-8]. A ferrite metallic matrix has a higher thermal conductivity then a pearlitic one. The thermal conductivity of graphite is strongly anisotropic and along hexagonal planes, the conductivity is very high. At room temperature, thermal conductivity of graphite can be as high as 500 W/(m·K) [5]. In the case of white cast iron, the carbon present in the form of cementite reduces thermal conductivity (about 8 W/(m·K)).

Compacted graphite cast iron may have a complex microstructure, especially in a thin sections. This is due to the fact that 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 [9, 10]. With increasing cooling rates in thin-walled CGI castings, thermal undercooling increases and graphite gradually becomes nodular, resulting in an increased nodule count and lower compact graphite ratio. Therefore, the production of thin-walled compacted iron castings is more difficult than that of thicker section iron [11]. The presence of flake graphite, which has the biggest impact on thermophysical properties, is unacceptable. Surface-active chemical elements (oxygen, sulfur) in the liquid metal significantly affects the morphology of crystallizing graphite and thus on cast iron thermal properties. These surface-active chemical elements may also be in the mould and these create the conditions for a degenerated graphite zone near the surface layer of cast iron, which is characterized by different properties relative to the base material [12,13]. The graphite degradation in the surface layer is the most critical for thin wall castings.

The literature provides limited data [14,15] on the relation of high cooling rate, structure and thermophysical properties of thin wall compacted graphite cast iron. In this work we consider the occurrence of graphite in the shape of nodules, flakes (types C and D) and compacted graphite with a different shape factor and percent of nodularity relative to the thermal conductivity at ambient and elevated temperatures in thin wall castings with a wall thickness of 3 mm.

2. Experimental procedure

2.1. Alloys preparation

The melts were produced in an electrical induction furnace of medium frequency with a 15 kg capacity crucible. The furnace charge consisted of Sorelmetal, steel scrap, technically pure silica, and Fe-Mn. After melting the liquid metal was hold in the temperature 1490°C by several minutes. Then was carried out vermicularization and inoculation operations using the bell method. For the vermicularization process Fe-Si-Mg (6% Mg), as well as Fe-Ti (in alloys II-IV) were used to obtain differential titanium concentrations. The Fe-Si alloy (75% Si, 0.75-1.25% Ca, 0.75-1.25% Ba, 0.75-1.25% Al) in an amount of 0.6 wt.% was used for inoculation. The chemical composition of the investigated castings is given in Table 1.

Table 1.
Results of chemical analysis

Alloy No.	C	Si	Mn	P	S	Cr	Ti	Mg	Al	Ni	Cu
I	3.63	2.47	0.03	0.026	0.017	0.03	0.009	0.010	0.010	0.00	0.050
II	3.66	2.55	0.04	0.027	0.020	0.03	0.070	0.005	0.010	0.01	0.040
III	3.60	2.57	0.05	0.023	0.018	0.04	0.133	0.021	0.021	0.040	0.060
IV	3.60	2.57	0.05	0.023	0.018	0.04	0.133	0.021	0.021	0.040	0.060
V	3.62	2.43	0.04	0.030	0.014	0.02	0.008	0.014	0.020	0.030	0.010
VI	3.62	2.43	0.04	0.030	0.014	0.02	0.008	0.014	0.020	0.030	0.010
VII	3.60	2.58	0.06	0.028	0.022	0.03	0.009	0.013	0.011	0.030	0.010

The pouring temperature was approximately 1400°C. Experimental castings applied in investigations were test blocks, according to the ASTM A 536-84 Standard, with wall thickness 3 mm. The sand molds (in alloys I, II, III, VI) were made using green moulding sand (silica sand, bentonite (7 wt.%), and water: bentonite ratio is about 0.4 and a granularity was 100-200 μm).

Sand moulds in alloys IV, V, VII were made using LDASC (25-45% Al_2O_3 and 55-75% SiO_2) whose heat transfer properties are reduced approximately 4 times more then silica sands. This sand is characterized by a low density 0.35-0.45 g/cm^3.

Metallographic examinations were conducted according to the procedure described in our previous work [14]. Fig. 1 shows microstructure characteristic namely type of graphite, compacted graphite fraction and also ferrite fraction for all investigated alloys.

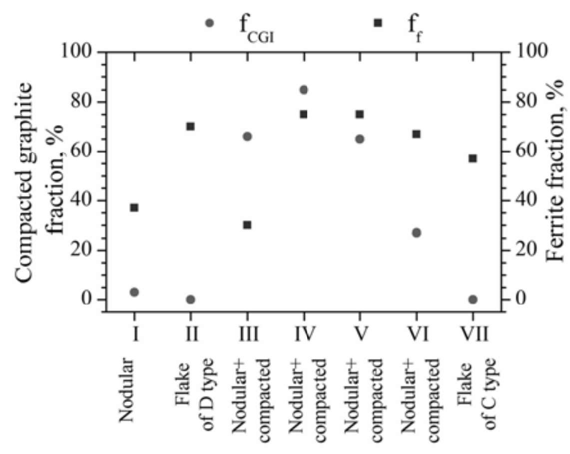

Fig. 1. Compacted graphite (f_{CGI}) and ferrite (f_f) fractions for investigated alloys

2.2. Measurement of thermophisical properties

The specimens for thermophysical parameters measurements had dimensions of 10×10×2 mm and were cut out from the bottom part of each casting. Measurements were carried out in the temperature range 22 - 600°C, at intervals of 100°C. At each temperature were three measurements for statistical purposes.

The thermal conductivity was calculated by using the obtained data together with a bulk density and specific heat:

$$k(T) = \lambda(T) \cdot c_P(T) \cdot \rho(T) \quad (1)$$

where: λ(T) - thermal diffusivity (m^2/s); $c_p(T)$ - specific heat (J/(kg·K)); ρ(T) - material density (kg/m^3).

The thermal diffusivity of cast iron samples was measured using a LFA 427 device using the pulsar laser method (Laser Flash Analysis). The measurement was carried out in a pure argon atmosphere. The thermal diffusivity values were determined using the Cape-Lehmann + pulse correction model with a standard variation of less than 2 %.

The specific heat of the samples was determined using the comparative method with the use of the pulsar laser having a reference sample (Inconel 600). The specific heat value was determined using the following formula:

$$c_p^{sample} = \frac{T_\infty^{ref}}{T_\infty^{sample}} \cdot \frac{Q^{sample}}{Q^{ref}} \cdot \frac{V^{sample}}{V^{ref}} \cdot \frac{\rho^{ref} \cdot D^{ref}}{\rho^{sample} \cdot D^{sample}} \cdot \frac{d_{hole}^{2,sample}}{d_{hole}^{2,ref}} \cdot c_p^{ref} \tag{2}$$

where: c_p - specific heat of sample/reference (J/(kg·K)); T - temperature of sample/reference (K); Q - energy absorbed by sample/reference (J); V - amplitude of signal amplification of sample/reference; ρ - density of the sample/reference (kg/m^3); D - thickness of the material (m); d - diameter of measurement sample/reference (m).

Materials density in a tested temperature range (22-600°C) were determined with DIL 402C Netzsch dilatometer. The measurements were carried out at a scanning rate of 5 K/min within this temperature range.

3. Results and discussion of thermal conductivity measurements

The results of the influence of temperature on thermal diffusivity and specific heat are shown in Fig. 2 for different cast iron types. Figure 2 shows significant differences in thermal diffusivity at a temperature of 22°C and it becomes more similar at elevated temperatures. At a temperature of 22°C, a difference of more than 6.4×10^{-6} m^2/s exists between cast iron with flake graphite type C (alloy VII) and ductile iron (alloy I).

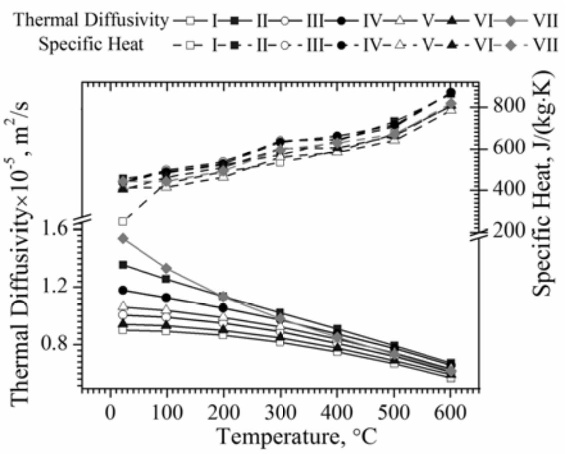

Fig. 2. Thermal diffusivity and specific heat for examined cast irons as a function of temperature

The highest value of thermal conductivity at room temperature, 46.8 W/(m·K) was achieved by alloy VII for gray iron with flake graphite type C (Fig. 3). The lowest value, 15.9 W/(m·K), was attained by alloy I for ductile iron. Thus, a divergence of approximately 30 W/(m·K) at a temperature of 22°C was established, simply as a result of an change of cooling conditions and titanium additions.

In the case of cast iron in which flake graphite is both type D and C, thermal conductivity decreases with a rise in temperature. From a temperature of 200°C, a higher thermal conductivity was obtained in gray cast iron with a D type flake graphite.

This change may be associated with an increase of ferrite fraction in the microstructure. It should also be noted that the cast iron with flake graphite of type D (alloy no. II) shows much smaller differences in thermal conductivity with a examined range of temperatures (Fig. 3).

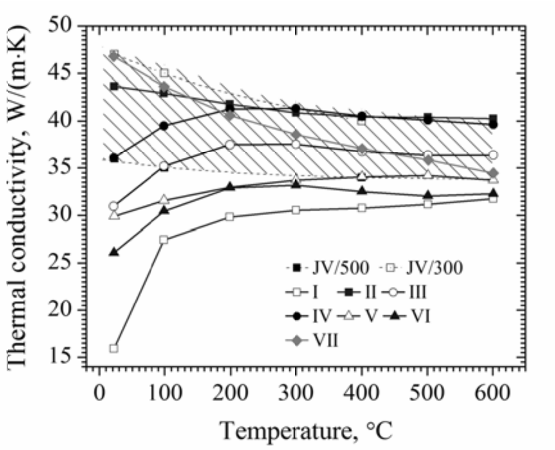

Fig. 3. Dependence of thermal conductivity for examined cast irons and ISO Standard (JV/300, JV/500) as a function of temperature

In the case of cast iron with compacted and nodular graphite, initially from ambient temperature up to a temperature of 200°C, thermal conductivity increases with a rise in temperature. Further increase in temperature causes a slight change in thermal conductivity.

As can be seen in Fig. 3 the difference in thermal conductivity between the examined cast irons decreases at elevated temperatures. Such a tendency of small differences between grey, ductile and compacted graphite iron at increasing temperatures, has been reported in work done [15] for castings with a typical wall thickness.

The effect of the percentage of compacted graphite on thermal conductivity at different temperatures is also shown in Fig. 3. It is clear from this figure, that increasing the percentage of compacted graphite causes an increase in thermal conductivity. The presence of graphite nodules within the microstructure negatively affects the thermal conductivity of compacted graphite cast iron.

It is worth noting that the thin-walled castings of alloy IV are characterized by high thermal conductivity at elevated temperatures (with an effect starting from 200°C), which reaches the level of those obtained for the cast iron with flake graphite. Figure 3 shows also the values of thermal conductivity cast iron with compacted graphite in accordance with the ISO 16112 Standard [16] compared to the value of thermal conductivity of cast iron obtained for all alloys. It can be concluded, that the obtained values of thermal conductivity in thin-walled castings with compacted graphite (alloy no. IV) are within the ISO Standard limits prescribed for CGI.

4. Conclusions

1. The existence of spheroidal graphite within the microstructure negatively affects the thermal conductivity of compacted graphite cast iron in thin sections. It is manifested in the reduction of thermal conductivity as well as an increased sensitivity to change in variable thermally loaded conditions.

2. The thin walled cast iron with compacted graphite have high thermal conductivity at an elevated temperature for example from 200°C, which achieve the level of those obtained for cast iron with flake graphite type C or D.

3. Thin walled cast iron with compacted graphite similar to cast iron with type D flake graphite shows little change in the value of thermal conductivity in the investigated temperature range of (22-600°C) in comparison, especially to ductile iron.

4. Thin walled cast iron with compacted graphite have good mechanical properties [10] and simultaneously high thermophysical properties, which predispose them to work in variable thermally loaded conditions by minimizing the accumulation of thermally induced stress.

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