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Influence of Section Thickness on the Thermal Conductivity of Compacted Graphite Cast Iron at Elevated Temperatures

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ABSTRACT- Cast iron has been used in large applications due to its good mechanical and friction properties with good thermal conductivity. This research studies the influence of section thickness on the thermal conductivity of compacted graphite cast iron at elevated temperatures. Compacted graphite cast iron was produced with different section thicknesses such as 5, 10, 20 and 40mm. The electrical resistance was measured by using a direct resistance technique over a wide range of temperatures varies from 100 - 500 ^{o}C. The thermal conductivity was calculated by using Weidman – Franze - Loranze Law. The results showed that the section thickness is a critical factor in affecting the shape of graphite and consequently it is a critical factor in defining the thermal conductivity. The existence of spheroidal graphite within compacted graphite in the thinnest section should be considered especially in thermally loaded applications.

***Keywords:* Compacted graphite iron, Electrical resistance, Thermal conductivity.**

I. INTRODUCTION

In some applications, such as cylinder heads, pistons, and brake drums, thermal conductivity is the main reason for the material selections. Cast irons have been used in such applications, combining good mechanical and friction property with good thermal conductivity [1]. Compacted graphite iron (CGI) is an alloy with attractive features that is used in the automotive industry for brake discs and brake drums, exhaust manifolds, and engine heads traditionally manufactured from grey cast iron[2], [3]. Also compacted graphite cast iron (CGI) has been increasingly satisfied many other engineering applications especially replacing some of the existing cast iron components such as diesel engines due to its high strength and thermal conductivity [4]. Compacted Graphite Iron can be produced with varying pearlite contents to suit the required application. Exhaust manifolds require more than 95% ferrite to prevent high temperature growth. In contrast, cylinder blocks and heads are typically produced with a predominantly pearlite matrix to maximize the strength and stiffness while simultaneously producing a more consistent matrix structure and hardness to the machining operation. CGI may also be specified with an intermediate ferrite - pearlite matrix. Within the range of 60-80% pearlite, CGI has approximately the same hardness (BHN 190-225) as a conventional fully pearlite gray cast iron [5]. The main factors that influence the structure of CGI castings are chemical composition, cooling rate, liquid treatment, and heat treatment. 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 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 [6]. The investigation of the dependence of the graphite shape on the section exhibited increased amount of spherical graphite in thin sections that rapidly solidified. The thermal conductivity of all cast iron appears to be controlled by the form, amount and distribution of graphite [7]. Because of the different interconnected network of the graphite particles in compacted graphite iron, its thermal conductivity is slightly lower than that of grey iron but much higher than that of ductile iron [8]. Parallel to the graphite basal plane the thermal conductivity is high and in this condition is the phase with highest thermal conductivity. So a graphite shape that eases the thermal conductivity along the basal plane must result in maximum thermal conductivity. With increasing cooling rates in thin-walled CGI castings, thermal under cooling 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 [9]. The thermal analysis shows that the change in wall thickness 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. In thin-walled nodular or CGI castings a high degree of inoculation is required. In the case of CGI, it is particularly disadvantageous in view of the fact that increasing nucleation potential decreases the amount of compacted graphite and increases the graphite nodule fraction [6]. Typical values of thermal conductivity of different grey and ductile irons grades can be seen in Tables 1 and 2 for increasing temperatures for grey irons thermal conductivity decreases with temperature. This trend is observed in many reports [10], 11]. The effect of the temperature in reducing thermal conductivity is higher for gray irons with high carbon content [12]. As for steels, the presence of alloying elements in cast irons decreases thermal conductivity for a given matrix (it should always be considered that alloying elements can affect the amounts of ferrite and pearlite in the matrix).It can also be seen the significant effect of silicon, which is always present in high amounts in cast irons [11]. While the thermal conductivity of CGI was compared to an unalloyed gray irons. It was found that, in CGI high nodularity decreases thermal conductivity, while increasing temperature have little effects in this property. It can be seen that higher nodularity decreases thermal conductivity [13]. The thermal conductivity measurements are not so practical to carry out, finding a simpler way becomes a desired goal. At this point the similarity between the electrical and thermal conductivity is realized, that is the electrical and thermal conductivity are both material characteristic and are both directly proportional to each other, therefore, estimating the thermal conductivity by means of electrical conductivity could be implemented [7]. The measuring of the electrical resistivity can be categorized into two methods. The direct resistance measurements using contact probes and contactless inductive measurements [14]. Relatively, few studies have been reported on the electrical conductivity at elevated temperature, since the measurements are extremely difficult, and it is difficult to measure thermal conductivity of metals and alloys precisely. In this research the results of electrical conductivity of compacted cast iron that was produced at different section thickness were presented. Also the thermal conductivity of this type of cast iron over a wide range of temperatures was calculated.

Table 1. Results of thermal conductivity for different grades of Grey Iron

Temp. [^{o}C]	Thermal Conductivity [W/K.m]					
	GJL 150	GJL 200	GJL 250	GJL 300	GJL 350	GJL 400
100	52.5	50.8	48.8	47.4	45.7	44.0
200	51.5	49.8	47.8	46.4	44.7	43.0
300	50.5	48.8	46.8	45.4	43.7	42.0
400	49.5	47.8	45.8	44.4	42.7	41.0
500	48.5	46.8	44.8	43.4	41.7	40.0

Table 2. Results of thermal conductivity for ductile irons

Temp. [°C]	Thermal Conductivity [W/K.m]				
	GGG 35.3	GGG 40	GGG 50	GGG 60	GGG 70
100	40.2	38.5	36.0	32.9	29.8
200	43.3	41.5	38.8	35.4	32.0
300	41.5	39.8	37.4	34.2	31.0
400	38.8	37.4	35.3	32.8	30.3
500	36.0	35.0	33.5	31.6	29.8

II. EXPERIMENTAL WORK

The compacted graphite irons (CGI) were produced in a step block casting in green sand with 5, 10, 20 and 40 mm thick steps with the calculated and the analyzed chemical composition are shown in Table 3a and Table 3b respectively. Sorely white cast iron and steel scrap were used as basic charge material. FeSiMg - Cermish metal was used as an agent material. Cu and FeSi were used as an alloying element and 0.5% FeSi was used as post inoculation. The chemical composition of these materials is shown in Table 4. Once the charge materials Sorel and Steel scrap, prepared and calculated, they were melted down using a 10-17 kg capacity induction furnace installed with a clay graphite crucible. After having molten metal, alloying materials such as Cu and FeSi were added to the molten charge. In the stage of spheroidzing treatment, FeSiMg Cerium Misch metal was added by plunging method. The treatment temperature varied in the range of ~ 1425 – 1475 ^{0}C. Post inoculation was accomplished by adding 75% foundry grade ferrosilicon (lump size are in between 1-2 mm) from the top of the molten metal in the ladle. The melt was stirred to ensure complete solution and reaction inoculation. The treatment time and post inoculation time was 5 to 7 minute and 1.5 minute respectively. The pouring temperature was in the range of 1400 ^{0}C to 1420 ^{0}C. In order to understand the specimen belongs to which casting, codes were given to the samples. Fig.1 shows the sample codes a, b, c and d which means the 5, 10, 20 and 40 mm section thickness respectively. The metallographic specimen was taken from each sections of stepped block. Specimens were prepared by using abrasive emery papers and polished were on Metaserv universal polisher equipment. The specimens were machined and examined by optical microscope.

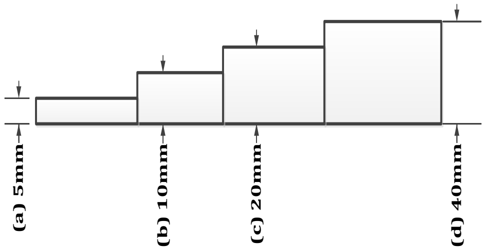

Fig.1. Step block used for compacted graphite cast iron

The microphotographs were taken by Nikon Optiphot; the James Swift Micro scale Image Analyzer System was used to calculate the percentage of compacted graphite iron in each section. Thermal conductivity changes with each specimen and with temperatures gradients ranging from room temperatures to 500 ^{0}C were found via measuring electrical resistance. The direct contact probe measurement technique shown in Fig.2 was used for high temperature measurements. This process set up similar to the one used in **[15],** however, in this set up instead of using Nano voltmeter we used digital voltmeter. This set up consists of 30 cm long and 1.2 cm in diameter alumina tube with close bottom as the main part. Fig.3 shows the scheme of the specimen fixing mechanism used in high temperature resistivity measurements. In this tube there is window close to the bottom as the main part for changing the specimen. Alumina spaghetti in bottom of the tube was fixed by alumina cement. Spaghetti which was able to move up and down was attached to the open end by using a special mechanism made from brass. Samples to be measured were placed between these two spaghettis and a pressure was applied to get better contacts. With this mechanism, it was possible to measure resistance of specimens simply by pumping 1 A constant current through the Pt-Pt/13% Rh wires and detecting the potential drop in the specimen by the digital voltmeter, and then the resistance can be calculated by using ohms law.

III. RESULTS AND DISCUSSION

The compacted graphite irons specimens with different section thickness in the range of 5, 10, 20 and 40 mm were produced by plunger casting technique. Thermal conductivity changes with each specimen and with temperatures gradients ranging from room temperatures to 500 ^{0}C were found via measuring electrical resistance which can be calculated by using ohms law.

Table 3a. The calculated chemical composition of the heat

%Si	%C	%Mg	%Cu	%S	%Mn	%P	%CerMM
2.65	3.84	0.05	1.22	0.01	0.01	0.001	0.075

Table 3b .The analyzed chemical composition of the heat.

%Si	%C	%Mg	%Cu	%S	% Mn	%P	%CerMM
2.88	3.88	0.01	1.26	0.01	0.06	0.03	0.004

Table 4. The chemical analysis of charge material

	Charge Material					
	Sorel white CI	Steel Scrap	FeSiMgCe Misch metal	FeSi	Cu	Post İnoculation
%C	4.3	0.05	------	----	----	----
%Si	0.7	0.01	44-48	75	-----	75
%Mg	0.01	----	5.5-6.5	----	----	------
%Ca	0.01	----	0.2-0.6	0.8	----	-----
%Al	-----	0.03	Max12	----	----	-----
%RE	-----	----	2.5	-----	----	-----
%V	0.2	----	-----	-----	----	-----
%S	0.01	-----	-----	------	----	----
%P	0.01	0.01	-----	-----	----	-----
%Cu	-----	0.03	------	-----	Pure	-----
%Fe	Balance	Balance	Balance	Balance	----	Balance

As it's well known, the free electrons are primarily responsible for the electrical and thermal conductivity of metals and alloys, therefore, the Wiedemann-Franz-Lorenz Law can be applied to relate the thermal conductivity to the electrical resistivity.

$$\frac{\lambda\rho_e}{T} = \frac{\pi^2 K^2}{3\ e^2} = L_0 \qquad (1)$$

Where λ is the thermal conductivity, T is the absolute temperature, ρ_e is the electrical resistivity, K is the Boltzmann constant and e is the electron charge. The constant

$$L_0 = \frac{\pi^2 K^2}{3\ e^2} = 2.445\times10^{-8}\, w\Omega K^{-2} \qquad (2)$$

The electrical resistance (R) and electrical resistivity (ρ_e) are related with the formula

$$R = \frac{\rho_e L}{A} \qquad (3)$$

Where L and A are the length and the cross-section area of specimen respectively, Therefore.

$$\lambda = \frac{2.445\times10^{-8}\times T\times L}{R\times A} \qquad (4)$$

The thermal conductivity can be derived from electrical resistivity data with accuracy $\pm$5% [16]. The compacted graphite cast iron which was attained in the matrix tending to be changed to spheroidal in thin section and compacted in medium and large sections**.** Figs. 4, 5, 6 and 7 show the microphotographs of sections 5, 10, 20 and 40mm respectively. The electrical resistance of each section was measured and the results are shown in Table 5 while Fig.7 shows the variation of the calculated thermal conductivity of a, b, c and d with temperature. It could be observed from Fig. 7 that, the trend of the calculated thermal conductivity of CGI that was produced at different section size increases as the temperature increase. In case of section (a) as the temperature increased from 300 ^{0}k to 800 ^{0}k the thermal conductivity varied from 36 W/cm.^{0}k to 36.9W/cm.^{0}k. For section (b) the thermal conductivity varied from 34.8 W/cm.^{0}k to 36.1 W/cm.^{0}k during the same range of temperature. For section (c) the thermal conductivity varied from 34 W/cm.^{0}k to 35.7 W/cm.^{0}k, while for section (d) the thermal conductivity varied from 32 W/cm.^{0}k to 34 W/cm.^{0}k. At room temperature, the thermal conductivity of the sections a, b, c and d shows approximately 33.9%, 34.3%, 35.06% and 36.93% less than the thermal conductivity of the grey iron. On the other hand the thermal conductivity of CGI is greater than that of spheroid graphite iron at all ranges of temperatures.

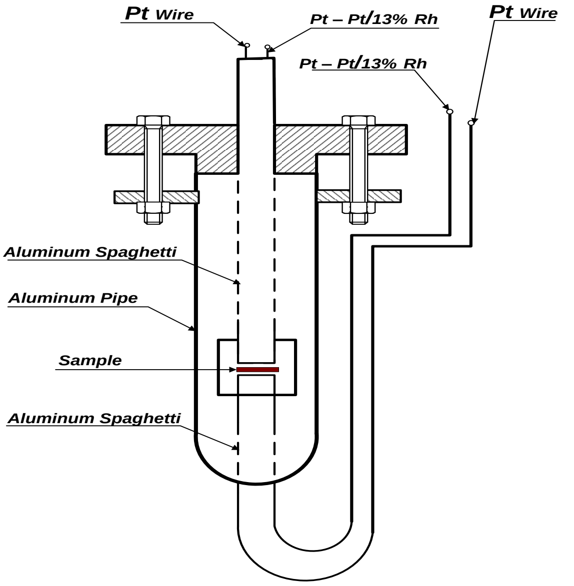

Fig.2. The setup used for electrical resistance measurements

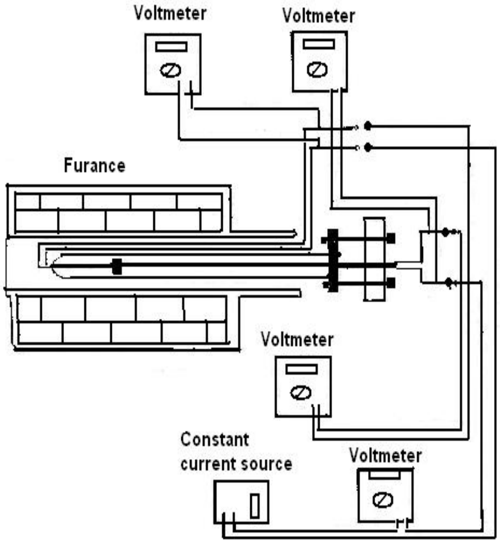

Fig.3.The scheme of the specimen fixing mechanism

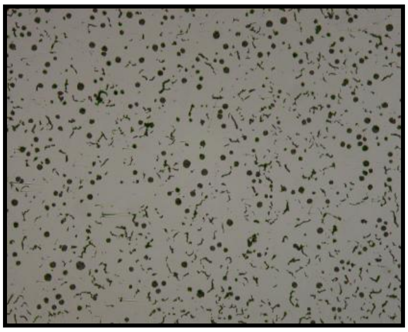

Fig.4. Microstructure of section (a) (~33.9% CGI)

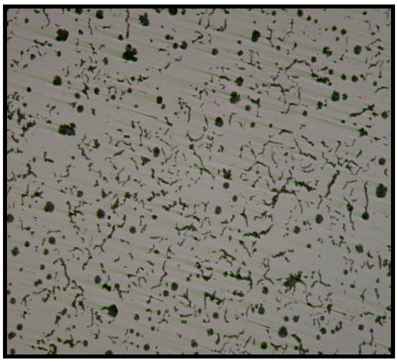

Fig.5. Microstructure of section (b) (~64.5% CGI)

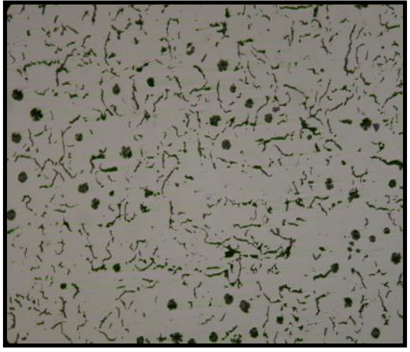

Fig.6. Microstructure of section (c) (~80%CGI)

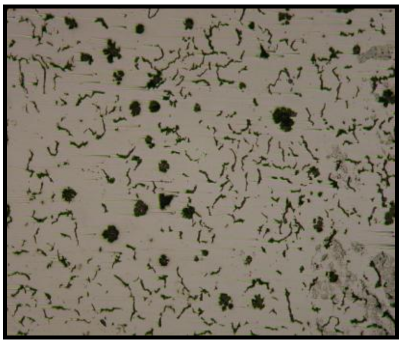

Fig.7. Microstructure of section (d) (~95%CGI)

Table 5. The Electrical resistance of the sections a, b, c and d

	Electrical Resistance of (a)	Electrical Resistance of (b)	Electrical Resistance of (c)	Electrical Resistance
Temp.	x10^{-6} [Ω]	x10^{-6} [Ω]	x10^{-6} [Ω]	of (d)
[^{o}K]				x10^{-6} [Ω]
298	199	171	168	161
323	215	185	181	175
373	235	211	209	200
423	28	241	234	229
473	311	266	264	255
523	333	292	289	28
573	373	319	316	306
623	408	348	341	335
673	428	371	366	36
723	457	400	392	384

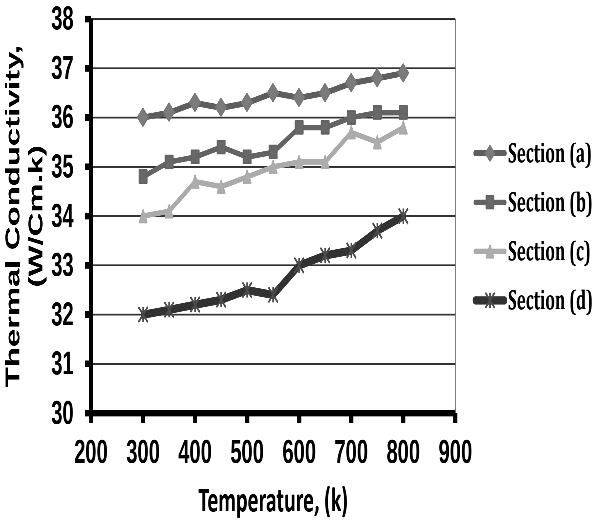

Fig.8. Variation of thermal conductivity versus temperature for sections a, b, c, and d

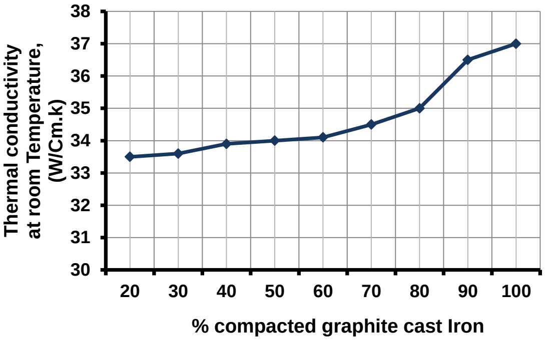

Fig. 9. Variation of thermal conductivity with % of CGI at room temperature

The effect of the percentage of CGI at different section size on the thermal conductivity at room temperature is shown in Fig.8. It is clear from this figure, that increasing the percentage of CGI by 64.3% will increase the thermal conductivity by 8.4%. These results show a good agreement with the results from the literature; however the small variations can be attributed to the contact problem between the samples and the thermocouples. This contact is becoming week especially at high temperatures resulting in increasing the electrical resistance and then decreasing the thermal conductivity.

IV. CONCLUSION

The Direct resistance measurement using probes method was implemented to measure the electrical resistance of different sections of compacted cast irons over a wide range of temperature and the thermal conductivity of this iron was estimated by the Wiedemann-Franze-Loranz Law. The investigations showed that thermal conductivity of the section thickness increases with increasing the temperature. The existence of spheroidal graphite within the thinnest section affects the thermal conductivity of compacted graphite cast iron negatively.

REFERENCES

[1] W. L. Guesser. I. Masiero. E. Melleras. C. S. Cabezas:. “Thermal Conductivity of Gray Iron and Compacted Graphite Iron Used for Cylinder Heads”., UDESC , Revista Material. Vol.10. n. 2. pp. 265 – 272, 2005.

[2] S. Dawson, I. Hollinger, M. Robbins, J. Daeth, U. Reuter, and H. Schultz, “The Effect of Metallurgical Variables on the Machinability of Compacted Graphite Iron”, Society of Automotive Engineers, Inc., 2001.

[3] H. Qiu and Z. Chen, “The Forty Years of Vermicular Graphite Cast Iron Development in China (Part III)”, China Foundry, 4, p 261–269, 2007.

[4] W.L. Guesser, et al, “Compacted graphite cast iron for diesel engine cylinder blocks”, 106th AFS Casting Congress, Kansas City, pp. 4 – 7, May 2002.

[5] AFS Iron Castings Engineering Handbook, AFS, Chapter 6D, pp. 171-193, 2003.

[6] Marcin Gomy and Magdalena Kawalec, “Effects of Titanium Addition on Microstructure and Mechanical Properties of Thin-Walled Compacted Graphite Iron Castings”, Journal of Materials Engineering and Performance, Volume 22 (5), p.p. 1519-1524, 2013.

[7] Gürolhan Yaşar:.”Compacted / Vermicular Graphite Production Techniques and The section Sensitivity of Compacted /Vermicular Graphite.” M.Sc thesis. METU, 1996.

[8] P. James Hrusovsky,” Factors Effecting Graphite Morphology .Matrix Structures and tensile properties of Compacted Graphite Cast Iron”. Ph.D. Thesis., Case Western Reserve University, 1982.

[9] J. Zhou, Color Metallography of Cast Iron, China Foundry, , 8(1), p 154–165, 2011.

[10] Gusseisen mit Kugelgraphit.Konstruiren Giessen. Zentrale fuir Gussvervendung.VDI- Verlag.Dusseldorf, (Translated from Duetch), 1988.

[11] D. Stefanescu:.”Physical properties of Cast iron”.ln; Goodrich.G.M. Iron castings Engineering Handbook.AFS, 2003.

[12] ”Thermal conductivity of Unalloyed cast iron”', .BCIRA Broadsheet 203, 1981.

[13] R.W. Monroe, C.E Bates, “Some Thermal and Mechanical Properties of Compacted Graphite iron”, AFS Transactions. pp. 615, 1982.

[14] S. I. Bakhtiyarov.R .A .Overfelt. S. G. Teodorescu, “Electrical and Thermal Conductivity of A319 and A356 Aluminium Alloys”, Journal of Material Science. Vol.36, pp. 4643– 4648, 2005.

[15] M. AKBAŞ,”Effect of Ni and Ti Substitution on the Superconducting Properties of YBa2Cu307-X System.”M.S thesis. METU, 1991.

[16] R.W. Powell,” The Thermal and Electrical Conductivities of some Magnesium Alloys”. Phil.Mag.Vol.27.p667, 1939.

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