

THERMAL CONDUCTIVITY OF GRAY IRON AND COMPACTED GRAPHITE IRON USED FOR CYLINDER HEADS

W. L. Guesser, I. Masiero, E. Melleras, C. S. Cabezas - UDESC and Tupy Fundições

Abstract

It is presented an experimental study about thermal conductivity in gray iron and compacted graphite iron. Thermal conductivity of the specimen is measured by a comparative method with stationary axial heat flow according to ASTM E 1225. The investigated specimen is put in a stack in tight thermal contact with two reference materials of same diameter. The upper reference specimen is coupled to a heat source, the lower reference to a heat sink. A guard heater and other experimental setup minimize radial heat losses. Reference material is electrolytic iron with certified thermal conductivity. It was tested 2 gray irons, the first alloyed with CuSnCr and the second with CuSnCrMo. Two grades of compacted graphite iron were also tested, CGI 350 and CGI 450. The tests were conducted up to 400 C.

The results show that thermal conductivity decreases in the following sequence: CuSnCr gray iron, CuSnCrMo gray iron, CGI 350, CGI 450. The thermal conductivity results of the gray iron samples decrease with increasing temperatures, and are almost constant for the CGI samples. The results show the potential of using CGI 350 for applications like engine cylinder heads.

Key words: Thermal conductivity, cast irons, compacted graphite iron, gray iron, cylinder heads.

1) Introduction

Thermal conductivity is, in some applications, the main reason for the material selection, in special in the automotive industry, for internal combustion engine components and brake systems. Cast irons have been used for such components (cylinder heads, pistons, brake drums and disks), combining good mechanical and friction properties with thermal conductivity.

The recent use of compacted graphite iron (CGI) for cylinder heads has demanded the study of properties of this material, in special the thermal conductivity. In comparison with gray iron, CGI shows lower values of thermal conductivity, and this is the main reason of the designer objection regarding CGI for such applications, in spite of its higher mechanical properties. However, one point is the comparison between the CGI not with the regular gray iron, but with alloyed gray irons (Cu, Sn, Cr, Mo), nowadays used for diesel cylinder heads. In a general way the alloying elements tend to decrease thermal conductivity, so those alloyed gray irons must present thermal conductivity values lower than the regular gray irons.

After that, this paper presents a thermal conductivity comparison study between compacted graphite irons and alloyed gray irons.

2) Literature Review

Thermal conductivity values of metallographic phases of cast irons are presented in Table 1. It can be seen that ferrite has higher thermal conductivity than pearlite and also that cementite can lower the cast iron thermal conductivity. 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. This is the case of gray iron, as can be seen in figure 1 (Hasse, 1996).

The amount of graphite also affects thermal conductivity, specially in gray irons, as shown in figure 2 (Silva Neto, 1978). In this figure theoretical models were plotted considering nodular graphite as perfect spheres and flake graphite as discs. The model for nodular graphite showed good agreement with the experimental results, while for flake graphite this agreement is poor.

Typical values of thermal conductivity of different gray and ductile irons grades can be seen in tables 2 and 3 for increasing temperatures. For gray irons thermal conductivity decreases with temperature. This trend is observed in many reports (Angus-1960, BCIRA Broadsheet-1981, Konstruiren+Giessen-2000, Stefanescu-2003), although there is no discussion on the cause of this behavior. The effect of the temperature in reducing

thermal conductivity is higher for gray irons with high carbon content (Angus-1960, BCIRA Broadsheet-1981).

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). In table IV the effects of alloying elements are presented. In this table it can be seen the significant effect of silicon, which is always present in high amounts in cast irons.

The thermal conductivity of CGI is compared to an unalloyed gray irons in figure 3. It is shown that, in CGI high nodularity decreases thermal conductivity, while increasing temperatures have little effect in this property. Additional results are presented in Figure 4, where it can be seen that higher nodularity decreases thermal conductivity (Monroe & Bates, 1982).

A practical consequence of the differences between gray and compacted graphite iron's thermal conductivity was verified by Cueva et al, establishing the temperature during the restrain of break discs (figure 5). It is observed that gray iron break discs are better heat conductors than CGI, causing the CGI casting to reach higher temperatures in service.

In the following experimental work thermal conductivities of two alloyed gray irons used for cylinder heads for heavy diesel engines and two classes of CGI were determined.

3) Experimental Procedures

Table V shows the chemical composition of the tested materials. Copper and tin are used in CGI to obtain the necessary amount of pearlite for each grade. In gray iron, copper, tin, chromium and molybdenum are used as alloying elements to obtain the high strength grades.

Gray iron samples were obtained from bars with 30 mm diameter, and CGI samples were machined from keel blocks of 25 mm, casted in chemically bonded sand moulds. Those are standards samples for tensile tests.

Thermal conductivity was measured by a comparative method with stationary axial heat flow according to ASTM E 1225-99. The investigated specimen is put in a stack in tight thermal contact with two reference materials of the same diameter. The upper reference specimen is coupled to a heat source, the lower reference to a heat sink. Radial heat losses are minimized by a guard heater and other experimental setup. Reference material is electrolytic iron with certified thermal conductivity.

The temperature drop along the specimen ΔT_P and the references ΔT_{R1} , ΔT_{R2} as well as the distances between the temperature sensors Δx_P , Δx_{R1} and Δx_{R2} are measured. With known thermal conductivity as function of temperature of the reference material λ_{R1} and λ_{R2} , following equation gives the thermal conductivity of the specimen λ_P

$$\lambda_P = \frac{1}{2} \frac{\Delta x_P}{\Delta T_P} \left[\left(\lambda_{R1} \frac{\Delta T_{R1}}{\Delta x_{R1}} \right) + \left(\lambda_{R2} \frac{\Delta T_{R2}}{\Delta x_{R2}} \right) \right]. \quad (1)$$

An apparatus of Dynatech Co., Cambridge, MA, USA, Type TCFCM was used for the measurements. Temperature was measured by Ni-CrNi thermocouples, thermo-voltages were measured by a data acquisition system Philips, Type PM 8237A, which automatically references to ice point and linearizes the signal. A traveling microscope measured the distances of the drillings of the specimen, where the thermocouples are placed.

The temperature difference in the specimen is approx. 10°C. The average value of the two temperature values measured along the specimen is considered as specimen temperature.

The tests were conducted at the labs of Österreichisches Giesserei-Institut, Leoben, Austria.

4) Results and Discussion:

Table VII and figure 6 show the results obtained. The numbers are the average of 2 measurements.

The results show that gray iron presents always higher thermal conductivity than CGI. The differences decrease with increasing temperature, because for gray iron thermal conductivity results decrease with

increasing temperature, while for CGI the results do not show a significant variation with the temperature. The highly alloyed Gray Iron Grade 300, used for cylinder heads of heavy diesel engines, presents lower thermal conductivity than the Gray Iron Grade 250. This is caused by the lower carbon content and by the alloying elements, reducing thermal conductivity.

Comparing with the results on Table II, the effect of temperature, reducing the thermal conductivity of gray irons, is much higher in the results we obtained (figure 6). One possible reason for that is that the carbon content from our samples (3,3-3,5) is higher than the usual carbon contents of gray iron (3,2-3,4), resulting in higher amount of graphite (lamellar).

Comparing the two grades of CGI (figure 6), one can observe that the CGI Grade 350 should be consider a candidate material for cylinder heads, because of the higher thermal conductivity compared to the CGI Grade 450. In this case, the larger amount of ferrite in the CGI Grade 350 resulted in increasing thermal conductivity.

5) Conclusions:

- Gray iron always presents higher thermal conductivity comparing with compacted graphite iron, due to the graphite form;
- Increasing the temperature and adding alloying elements, thermal conductivity decreases for gray irons;
- CGI 350 presents higher thermal conductivity comparing with CGI 450, due to the higher ferrite content.

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Table I – Thermal conductivity of main metallographic phases in cast irons at room temperature (Stefanescu, 2003).

| Metallographic constituent | Thermal conductivity, $W\ m^{-1}\ ^\circ C^{-1}$ | | |
|------------------------------|--|----------|---------|
| | 0 – 100 °C | 500 °C | 1000 °C |
| Ferrite | 71 – 80 | 42 | 29 |
| Pearlite | 50 | 44 | 40 |
| Cementite | 7 – 8 | - | - |
| Graphite | - | - | - |
| Parallel to basal plane | 293 - 419 | 84 – 126 | 42 – 63 |
| Perpendicular to basal plane | 84 | - | - |

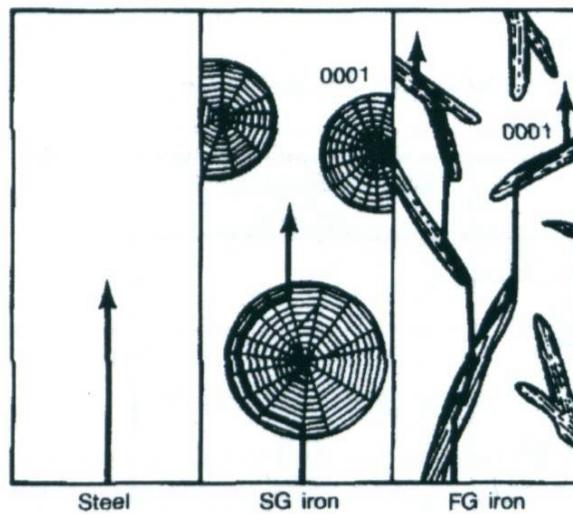


Figure 1 – The thermal conductivity of graphite parallel to basal plane is higher than perpendicular (Hasse, 1996).

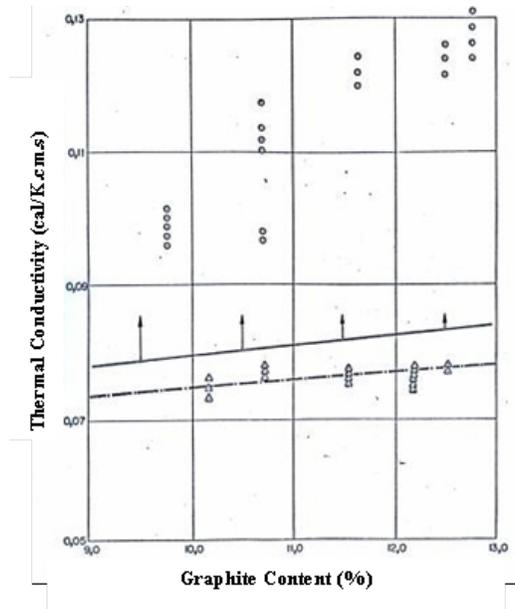


Figure 2 – Effect of graphite amount on the thermal conductivity, for gray iron (O) and ductile iron (Δ), with ferritic matrix (Silva Neto, 1978)

Table II - Results of thermal conductivity for different grades of gray Iron (Konstruiren + Giessen-2000).

| Temperature (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 III – Results of thermal conductivity for ductile irons (Konstruiren + Giessen-1988)

| | GGG-35.3 | GGG-40 | GGG-50 | GGG-60 | GGG-70 | 4 Si-Mo |
|--------|----------|--------|--------|--------|--------|---------|
| 100 °C | 40.2 | 38.5 | 36.0 | 32.9 | 29.8 | 25.1 |
| 200 °C | 43.3 | 41.5 | 38.8 | 35.4 | 32.0 | 27.2 |
| 300 °C | 41.5 | 39.8 | 37.4 | 34.2 | 31.0 | 28.1 |
| 400 °C | 38.8 | 37.4 | 35.3 | 32.8 | 30.3 | 28.6 |
| 500 °C | 36.0 | 35.0 | 33.5 | 31.6 | 29.8 | 28.9 |

Table IV – Change in Thermal Conductivity of Gray Iron Upon Addition of 1%Alloying Element (Stefanescu, 2003).

| Element | Experimental range % | Change in k, % |
|------------|----------------------------|----------------|
| Silicon | 1 – 6 | -6 |
| | 0.65 – 4.15 (ductile iron) | -14.7 |
| Manganese | 0 – 1.5 | -2.2 |
| Phosphorus | ? | -6 |
| Chromium | 0 – 0.39 | +21 |
| | 0 – 0.5 | -30 |
| Copper | 0 – 1.58 | -4.7 |
| Nickel | 0 – 0.74 | -14.5 |
| Molybdenum | 0 – 0.58 | -12 |
| Tungsten | 0 – 0.475 | -5.2 |
| Vanadium | 0 – 0.12 | 0 |

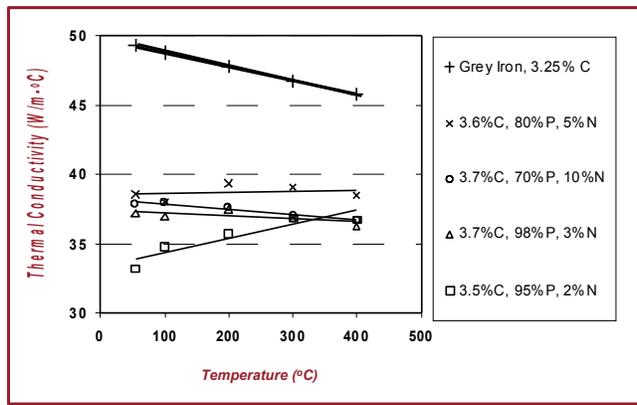


Figure 3 – Thermal conductivity results of compacted graphite iron, compared to a gray iron (Shao-1997).

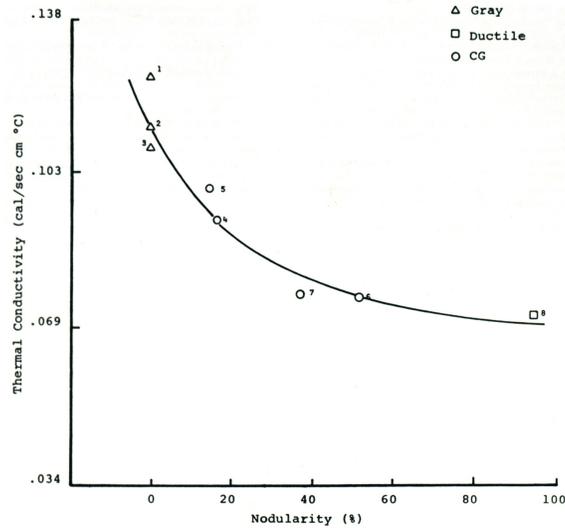


Figure 4 – Effect of nodularity on the thermal conductivity of cast irons (Monroe & Bates, 1982)

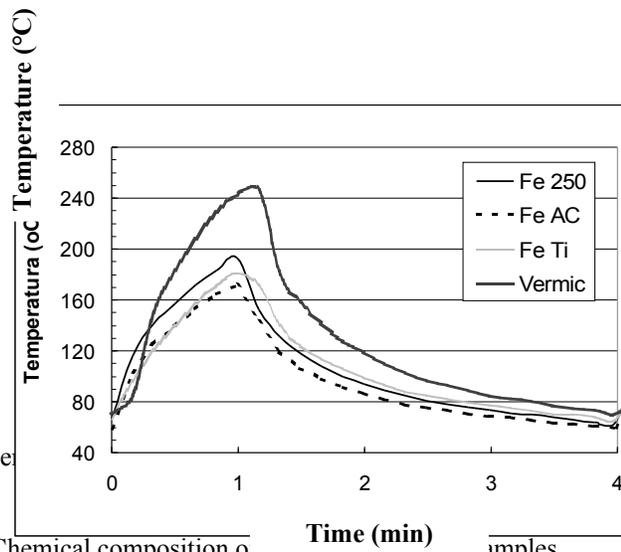


Figure 5 – Temperature vs. Time for different iron samples (Lueva, 2000)

Table V - Chemical composition of different iron samples.

| Elements | CGI 350 | CGI 450 | Gray Iron 250 | Gray Iron 300 |
|----------|---------|---------|---------------|---------------|
| C (%) | 3,65 | 3,62 | 3,43 | 3,30 |
| Si (%) | 2,45 | 2,41 | 2,07 | 2,05 |
| Mn (%) | 0,37 | 0,37 | 0,55 | 0,56 |
| Cu (%) | 0,41 | 1,17 | 1,00 | 1,20 |
| Sn (%) | 0,031 | 0,064 | 0,10 | 0,11 |
| Cr (%) | 0,029 | 0,029 | 0,20 | 0,24 |
| Mo (%) | - | - | - | 0,30 |

Table VI - Microstructure and mechanical properties of the CGI samples.

| | CGI 350 | CGI 450 | Gray Iron 250 | Gray Iron 300 |
|----------------|----------------|----------------|----------------------|----------------------|
| Ferrite (%) | 48 | 2 | 0 | 0 |
| Graphite shape | 4% nodularly | 7% nodularity | A, size 4 | A, size 4 |
| UTS (MPa) | 371 | 498 | 270 | 317 |
| YS (MPa) | 292 | 443 | - | - |
| E (%) | 2,5 | 1,4 | - | - |

Table VII - Thermal conductivity results

| Temperature (C) | Thermal conductivity (W/K.m) | | | |
|----------------------|------------------------------|---------|---------------|---------------|
| | CGI 350 | CGI 450 | Gray Iron 250 | Gray Iron 300 |
| 100 | 37,0 | 33,6 | 50,0 | 45,5 |
| 200 | 37,4 | 34,2 | 46,6 | 43,15 |
| 300 | 37,2 | 34,3 | 43,6 | 41,2 |
| 400 | 36,5 | 33,9 | 40,9 | 39,7 |

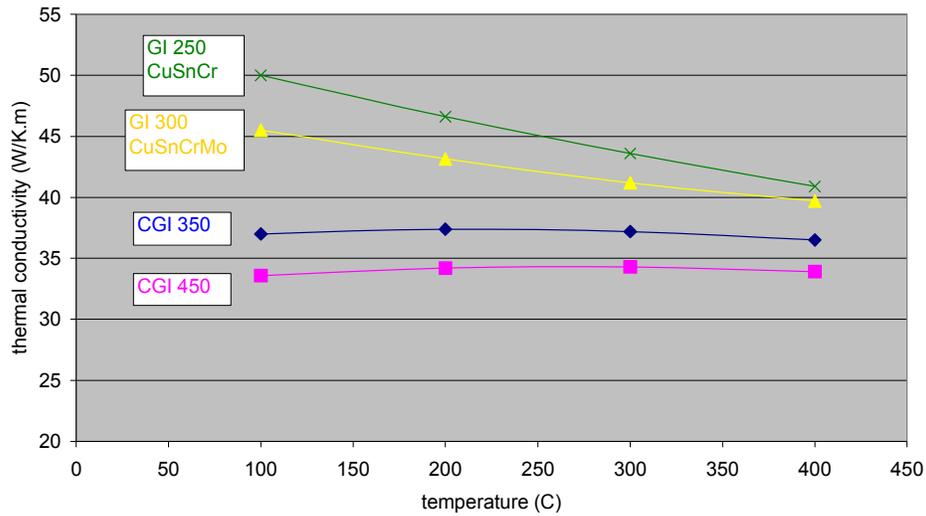


Figure 6 - Thermal conductivity results of CGI and Gray Iron.