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Effect of Alloying Elements on Thermal Diffusivity of Gray Cast Iron Used in Automotive Brake Disks

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The purpose of this work was to experimentally investigate the thermal diffusivity of four different gray cast iron alloys, regularly used to produce brake disks for automotive vehicles. Thermal diffusivity measurements were performed at temperatures ranging from room temperature to 600 °C. The influence of the thermal conductivity on the thermomechanical fatigue life is also briefly presented. The measurements were sensitive to the influence of the carbon equivalent and alloying elements, such as molybdenum, copper and chromium. Molybdenum, unlike copper, lowered the thermal diffusivity of the gray cast iron, and alloy E (without molybdenum), besides presenting a relatively low carbon equivalent content and an increase in the values of the thermal diffusivity, presented the best performance during the thermomechanical fatigue. The molybdenum present in alloys B and C did not fulfill the expectations of providing the best thermomechanical fatigue behavior. Consequently, its elimination in the gray cast iron alloy for this application will result in a significant economy.

Keywords cast iron, fatigue, thermal conductivity, thermal diffusivity

1. Introduction

Many different parts contribute actively or passively to the enhancement of the required automotive performance. However, the safety is intimately related to the efficiency of the brake system, as can be seen in Fig. 1.

Brake disks are constantly submitted to relatively high thermal and mechanical deformations during braking action. Therefore, it is of fundamental importance to precisely analyze the implication of new technologies and material developments that may be applied for brake systems, especially considering all aspects involving thermal and dynamic behavior (Ref 1).

It is difficult to select effective brake material, because of the large number of competing parameters which often must be satisfied simultaneously. Thus, brake materials should exhibit high thermal capacity and thermal diffusivity and, if possible, low density. Moreover, they have to offer a good friction coefficient and stable mechanical characteristics at high temperatures and/or/in wet environment, as well as high wear resistance.

The thermal diffusivity (α) is a measure of how fast a material can transport heat from a hot source and adjust itself to the surrounding temperature, i.e., it is a material property that allows heat diffusion and dispersion in all directions and it indicates how easy the material withstands temperature variations. The thermal diffusivity can be given by:

$$\alpha = k/c \cdot \rho,$$

where k is the thermal conductivity, c is the specific heat, and ρ the materials density. For example, in the case of steels it is known that the product of density and specific heat ($\rho \cdot c$) is very high while the thermal conductivity is very low. Consequently, brake disks made from steel are able to absorb high amount of thermal energy, but as the steel diffusivity is relatively low, during severe braking action its surface temperature can reach extremely high values.

Therefore, both thermal diffusivity and thermal conductivity are very important parameters in the selection of materials for brake disk application, since the disks must simultaneously conduct and dissipate the heat generated from the transformation of the kinetic to thermal energy.

During severe deceleration due to braking (fraction of seconds), the temperature of the braking system may reach values close to 650 °C and the overheating of the disks may cause serious consequences, thus reducing safety (Ref 2). This temperature variation causes thermal shock and localized heating that changes the material's behavior due to metallurgical transformations, crack formations from plastic flow at the surface, and residual stresses after cooling (Ref 1).

Ideally, the materials used in braking systems should exhibit properties, such as good thermal diffusivity and resistance to corrosion, low weight, long durability, friction stability, low wear ratio, and good rate cost/benefit (Ref 3). The shape and chemical composition of the disks influence the durability, since during the braking action they affect the heat flow, the capacity to dampen vibrations, loss of materials, and noise level (Ref 4, 5).

Among all materials used in brake disks, the gray cast irons are still the most used material, because they have good physical and mechanical properties, easy to produce, and cost effective. One of the main advantages of this material is its high

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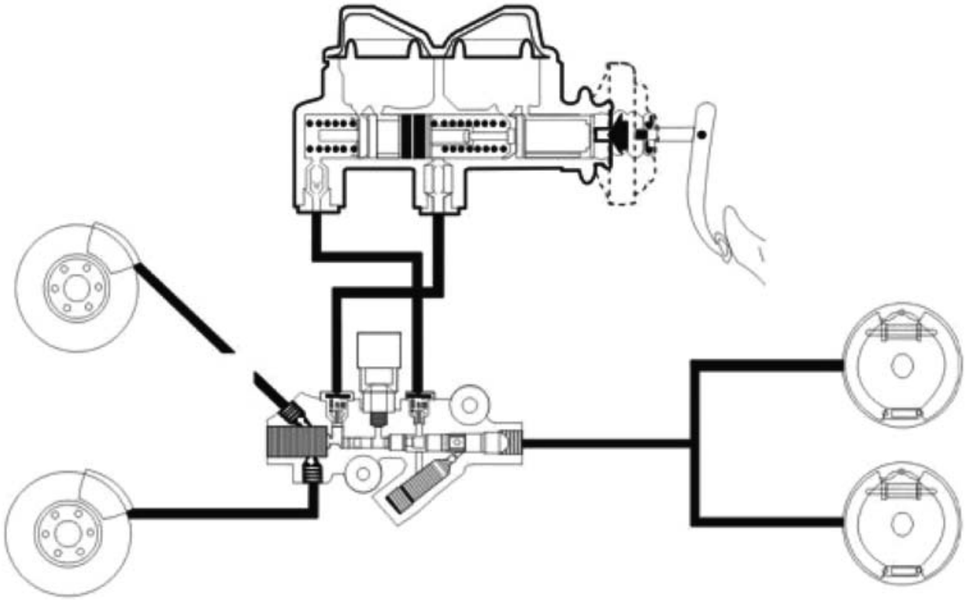

Fig. 1 Brake system

thermal diffusivity, which is directly influenced by the percentage of carbon equivalent (CE) that determines the percentage and the length of graphite (Ref 6-8).

This work aimed to measure the thermal diffusivity behavior of four gray cast iron alloys, regularly used in the automotive industry, from room temperature to 600 °C. The results were analyzed taking into account both the CE and the amount of alloying elements such as molybdenum, copper, and chromium, associating these values obtained with the thermomechanical fatigue results.

2. Materials and Methods

Table 1 presents the chemical compositions of the four pearlitic gray cast iron alloys, and their respective CEs are presented in Table 2.

The measurements of the variation of the thermal diffusivity, from room temperature up to 600 °C, were carried out according to the ASTM C-1113 standard through a Laser equipment (LFA-427) from NETZSCH. This equipment consists of a laser source that makes possible to control the time and the power of the heating pulse that reaches and heat up one of the specimen's faces that is kept at a chosen constant temperature. At the same time, on the other specimen's face, the increase of temperature with time is measured by an infrared sensor, cooled by liquid nitrogen, which is activated simultaneously with the laser.

From the detector response the transient of temperature with time is obtained, and the diffusivity is calculated taking into account the specimen's thickness and the necessary time to increase the temperature to half of its maximum value on the face where the detector is located. Figure 2 shows the specimen's geometry and dimensions used in the thermal diffusivity tests.

These measurements allowed the verification of the statement made by Hetch et al. (Ref 7) that the thermal diffusivity of gray cast irons is directly dependent on the CE content. The thermomechanical fatigue tests, with thermal cycles' period of

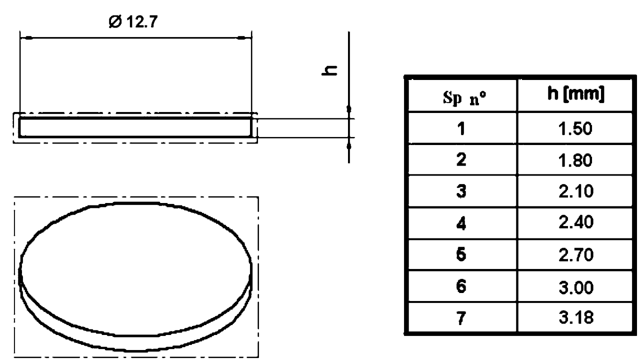

Fig. 2 Sketch of the machining of the group of specimens used in the measurement of the thermal diffusivity

Table 1 Chemical compositions of the four alloys of gray cast iron (wt.%)

	Metallic alloys			
Elements	**A**	**B**	**C**	**E**
C	3.36	3.45	3.71	3.49
Si	2.07	2.11	2.00	1.87
Mn	0.63	0.71	0.69	0.53
P	0.03	0.07	0.06	0.03
S	0.06	0.05	0.05	0.11
Cr	0.16	0.30	0.19	0.29
Mo	0.06	0.41	0.42	…
Cu	0.08	0.10	0.40	0.52

Table 2 Carbon equivalent (CE) of the gray cast irons alloys (wt.%)

	Metallic alloys			
	A	**B**	**C**	**E**
CE	4.05	4.18	4.40	4.12

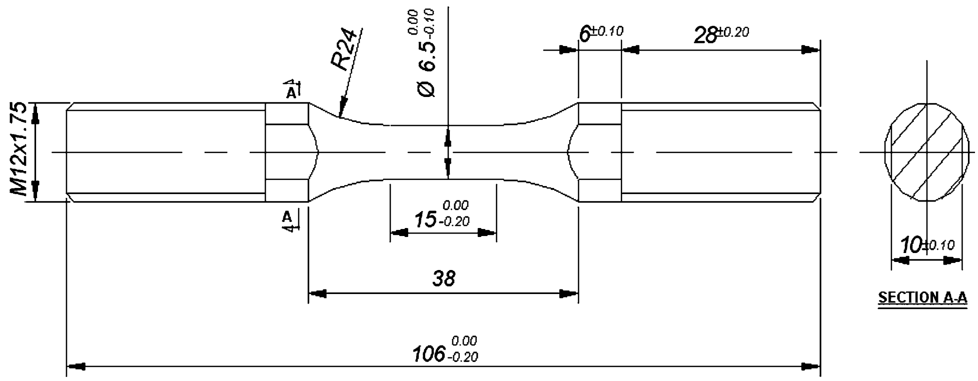

Fig. 3 Schematic drawing of the specimen for the test of thermomechanical fatigue, in mm

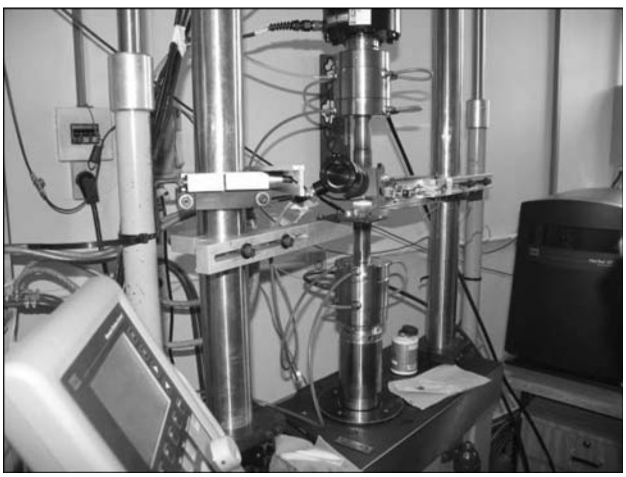

Fig. 4 General view of the thermomechanical test system

120 s, were carried out in temperatures between 300 and 600 °C in a closed-loop, servo-hydraulic machine of 250 kN capacity. The specimens were tested with the mechanical and thermal cycles considered in phase and out of phase, under strain control (0.10, 0.20, 0.30, and 0.40%). The in-phase condition was obtained by making coincident the maximum tensile stress with the maximum temperature and the minimum stress with the lowest temperature, respectively. The out-of-phase condition was obtained when the reverse took place.

Figure 3 shows the thermomechanical fatigue specimens' geometry and dimensions (mm).

After mounting the specimen using hydraulic grips, the heating was performed using an induction furnace with 7.5 kW power and 200 kHz frequency. The temperature control was made by an infrared pyrometer equipped with a laser target. The grips' cooling system, which cools the specimen, is composed of two coils made with copper tubes and two hoses of compressed air coupled to the extremities of the upper and lower grips. Figure 4 presents a general view of this system, assembled for the thermomechanical fatigue tests. Figure 5 shows the details of the specimen coupling region at the hydraulic grips. It shows the furnace heating coil, the auxiliary cooling system, the extensometer with ceramic legs, and the infrared pyrometer.

3. Results and Discussion

The results of the thermal diffusivity test for the studied alloys from room temperature to temperatures slightly higher than 600 °C, graphically presented in Fig. 6, are very important for the development of automotive brake disks.

It may be noticed, as expected (Ref 6, 9, 10), that the thermal diffusivity decreases with the increase of the temperature. It is interesting to observe that the curves of thermal diffusivity of the alloys E and A are relatively apart from each other, and from alloys C and B (that are coincident) until approximately 300 °C, indicating that the chemical composition of the alloys has great influence on the results in this interval of temperature. In this point, the curves start to get together, indicating that above 300 °C all the studied alloys have practically the same value of thermal diffusivity. This is due to the fact that atomic vibration energy is so great that the difference in the crystalline structures of these alloys has no influence. For high temperatures, the atomic vibration is so intense that the difficulty of movement of the conduction electrons is practically the same, regardless of the alloy element present in the crystal structure (e.g., Cu or Mo) (Ref 11).

Molybdenum is generally added in gray cast iron to increase heat resistance. The alloys B and C, in spite of the high CE, presented the worst results. It was due to the fact that not even higher CE, that improves the thermal diffusivity, was sufficient to compensate the deleterious effect that the molybdenum in solid solution has caused on the heat flow.

The best performance was exhibited by alloy E with copper addition (in solid solution), which contributed positively to heat transference, since this element is a good conductor of heat. However, in the case of alloy C, the copper content was not sufficient to neutralize the deleterious effect of molybdenum on the heat conductivity. In the case of alloy A, the thermal diffusivity was not affected since it does not have any alloying element.

The statement made by Callister (Ref 11)—"the higher the percentage of carbon equivalent, the larger is the thermal diffusivity"—was not confirmed for the gray cast iron used in this study. In general, the alloying elements such as molybdenum, copper, and chromium and other impurities act as barriers to electron movement, reducing the efficiency of the transport of heat for the electrons.

Figure 7 presents the results of thermomechanical fatigue realized in specimens of the studied alloys (Ref 12).

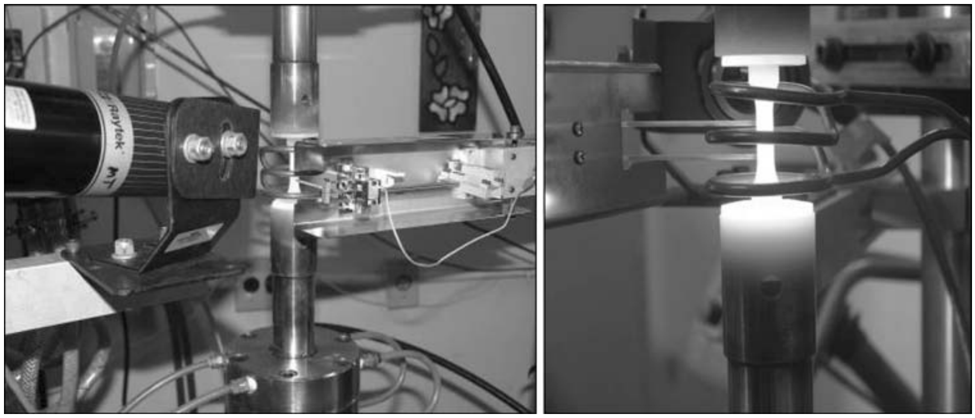

Fig. 5 Details of the region of coupling of the specimen in the hydraulic clutch to high-temperature tests

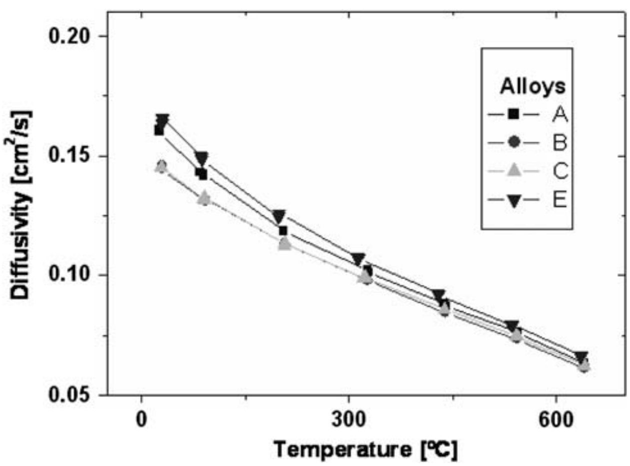

Fig. 6 Thermal diffusivity versus temperature for the alloys A, B, C, and E

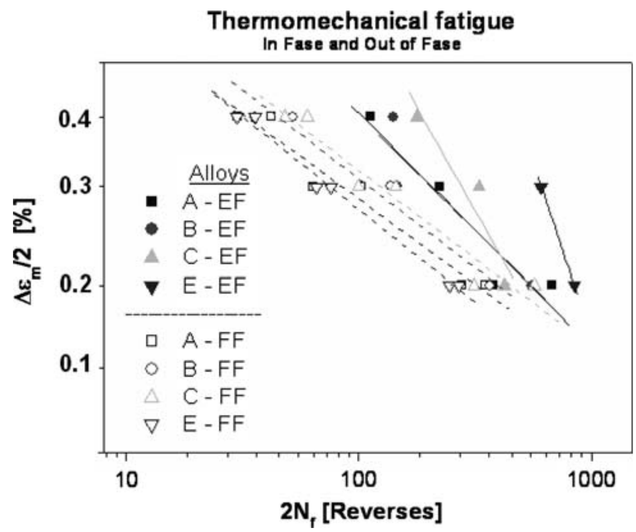

Fig. 7 Thermomechanical fatigue in gray cast iron alloys

It was observed that in the out-of-phase condition the alloys did not present significant differences among themselves in fatigue life, regardless of the mechanical deformation amplitude considered. In the phase condition, the best performance was of the alloy E, followed closely by the others. From the disposition of the curves, the thermomechanical fatigue out of phase was always more critical than that of the in phase, resulting in shorter life span.

It was sufficiently clear that there is an intrinsic relationship between thermal diffusivity and fatigue. Small changes in the values of thermal diffusivity can modify the behavior of the alloys when submitted to isothermal (Ref 13, 14) and thermomechanical tests of fatigue in phase.

4. Conclusion

1. Molybdenum, unlike copper, lowered the thermal diffusivity of the gray cast iron.
2. The gray cast iron alloys studied presented thermal diffusivity significantly different only for temperatures below 300 °C.
3. The alloy E, besides presenting a relatively low CE content and an increase in the values of the thermal diffusivity in all ranges of studied temperature, also presented the best performance during the thermomechanical fatigue tests in the in-phase condition.
4. The molybdenum present in alloys B and C did not fulfill the expectations of providing the best thermomechanical fatigue behavior.
5. The elimination of molybdenum in the gray cast iron alloy used for brake disks will result in a significant economy for the automotive industry.

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