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Thermophysical Properties of Automotive Metallic Brake Disk Materials

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Abstract The temperature distribution, the thermal deformation, and the thermal stress of automotive brake disks have quite close relations with car safety; therefore, much research in this field has been performed. However, successful and satisfactory results have not been obtained because the temperature-dependent thermophysical properties of brake disk materials are not sufficiently known. In this study, the thermophysical properties (thermal diffusivity, the specific heat, and the coefficient of thermal expansion) of three kinds of iron alloy series brake disk materials, FC250, FC170, and FCD50, and two kinds of aluminum alloy series brake disk materials, Al MMC and A356, were measured in the temperature range from room temperature to 500 °C, and the thermal conductivity was calculated using the measured thermal diffusivity, specific heat capacity, and density. As expected, the results show that the two series have significant differences in respect of the thermophysical properties, and to reduce the thermal deformation of the brake disk, the aluminum alloys with a high thermal conductivity and the iron alloys with low thermal expansion are recommended.

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1 Introduction

The disk and pad of the automotive brake system have become important parts with regard to the safety design of a car because they absorb the dynamic energy of the automobile. The development of brake systems in automobiles aims for high performance, high stability, low noise, and low vibration [1]. The problems occurring in a brake disk, as shown in Fig. 1, are surface temperature rise, cracks induced by the heat, thermal deformation, abnormal vibration, over-abrasion, bending, noise, etc., and these are caused mainly from the disk, pad, caliper, and their combinations. In order to analyze these phenomena, the study of the temperature rise in a disk system caused by friction must be carried out [2,3].

The temperature over-rise caused by long and continuous braking creates an irregular martensitic phase on the disk surface, and this is a source of the abnormal vibration of the brake system. Lots of research in the field of thermal deformation and thermal stress of the brake system have been performed; however, successful and satisfactory results have not been obtained because the temperature-dependent thermophysical properties of brake disk materials are not sufficiently known [2].

In this study, the thermal diffusivity, specific heat capacity, and CTE (coefficient of thermal expansion) of three kinds of iron alloys, FC250, FC170, and FCD50, and two kinds of aluminum alloys, Al MMC and A356, for brake disk materials were measured by the laser-flash, differential scanning calorimeter (DSC), and push-rod dilatometer apparatus, respectively, in the temperature range from room temperature to 500 °C, and the thermal conductivity was calculated using the measured thermal diffusivity, specific heat capacity, and density.

2 Experimental

2.1 Thermal-Diffusivity Measurements

For thermal-diffusivity measurements a laser-flash method (Sinku-Riko, TC-7000 VH/L) was used at temperature up to 500 °C. The thermal diffusivity was analyzed

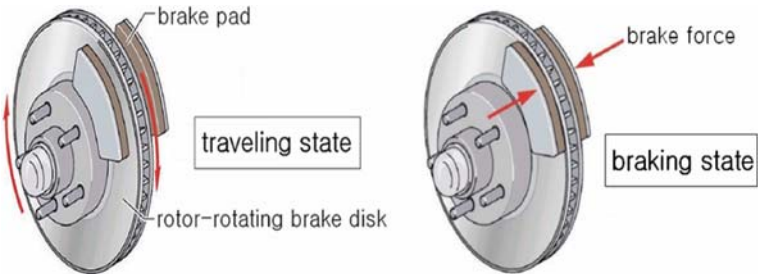

Fig. 1 Traveling state and braking state of the brake disk system

using the Parker method [4]. The results were calculated using the half time of the maximum temperature rise on the back of the sample to obtain the thermal diffusivity. The temperature measurement on the back of the sample was conducted using a HgCdTe infrared sensor. Moreover, the temperature was controlled by using a tungsten mesh heater in vacuum maintained at 10^{-5} torr. For consistent heating energy on the sample, the front and back of the sample were sprayed with graphite. The thermal diffusivity data were corrected by Azumi and Takahashi's method [5] to decrease the effect of a finite pulse width. The mean value was computed from five measurements of the thermal diffusivity. Furthermore, the standard deviation and reproducibility of the thermal-diffusivity measurements were estimated to be approximately 3 % based on measurements on poco-graphite (NIST SRM 8245) from room temperature to 1300 °C.

2.2 Measurements of Specific Heat Capacity [6]

The specific heat capacity (C_p) was measured with a DSC (Perkin-Elmer, Pyris 1) over a temperature range from room temperature to 500 °C. The measurements were carried out with a heating rate of $5\,K \cdot min^{-1}$ in a nitrogen atmosphere with a flow rate of $50\,ml \cdot min^{-1}$. The NIST synthetic sapphire standard reference material, SRM 720, was used as a reference. The standard deviation in measurements of the specific heat capacity is estimated to be 2 %. The process of temperature control is as follows:

- The time interval is determined in the isothermal range for sufficient stabilization of the baseline.
- The initial and final temperatures are determined.
- The increasing rate of temperature change is determined.

The data for the specific heat capacity obtained with the above method were integrated in all the temperature increasing ranges, and the average specific heat capacity was obtained in each range.

2.3 Measurements of Thermal Expansion Coefficient [7]

The thermal expansions of the metallic brake disk materials were measured in the axial direction with a linear variable differential transformer (LVDT) transducer in the temperature range from room temperature to 500 °C by a push-rod-type dilatometer (DIL 402C, Netzsch). The measurements were carried out at a constant heating rate of $5\ K \cdot min^{-1}$ in a vacuum. The standard deviation in the measurements with the dilatometer used in the experiment is estimated to be within 3 % for a standard material of Al_2O_3.

3 Results and Discussion

Figure 2 is a photograph of the metallic brake disks where the inner and outer diameters are 192 mm and 314 mm, respectively. The samples for laser-flash measurements

Fig. 2 Photograph of the automotive metallic brake disk

were cut into a disk of 2 mm in thickness and 10 mm in diameter, and for DSC were cut into disks of 2 mm in thickness and 5 mm in diameter. Those for push-rod dilatometer measurements were prepared as 5 mm in diameter and 10 mm in length. Table 1 summarizes the sample materials.

The measured values of the thermal diffusivity for five samples are shown in Fig. 3, and all the data points represent the averages of five measurements. It shows that the thermal diffusivities of all the samples decrease slowly for the increment of sample temperature because the thermal carriers in metals are mostly electrons; therefore, as the temperature increases, the resistance for thermal diffusion also increases. Also, it shows that the values for aluminum alloys are larger by a factor of two to three than those of the iron alloys. Also, it is clearly distinguished that the main components of each alloy is aluminum or iron as shown in Table 1, and the thermal diffusivity of pure aluminum is larger than that of pure iron by a similar factor [8]. The thermal-diffusivity values of FC170 and A356 are larger than those of others in the iron alloy and aluminum alloy series, respectively, and this can be explained by the higher fraction of copper which has a higher thermal diffusivity than the other components and the slight difference in the microstructure of the alloys which affect heat flows. Table 2 lists the thermal diffusivities.

The obtained average specific heat capacities are shown in Fig. 4 and Table 3. As the temperature rises, the value of the specific heat capacity increases and the values for iron alloys are larger than those for aluminum alloys by a factor of two. This result can also be explained by the fact that the specific heat capacity was mainly affected by the major matrix component, either iron or aluminum in the alloys, and the heat capacity of aluminum is larger than that of iron [9]. All the iron alloys show nearly the same values, and the difference in aluminum alloys is not so large. This means that the small quantities of minor materials do not significantly influence the specific-heat-capacity results; therefore, a study of the microstructure of the samples will be needed to explain this result.

Table 1 Typical sample compositions (in mass%)

Sample	Element											
	C	Si	Mn	S	P	Cr	Ti	V	Fe	Cu	Mg	Al
FC250	3.25–3.5	1.3–2.3	0.6–1.0	0.05–0.15	0.2 ↓	0.2–0.45	0.02 ↓	0.015 ↓	BAL[a]	–	–	–
FCD50	3.0–4.0	2.0–3.0	0.2–0.6	0.05 ↓	0.05 ↓	–	–	–	BAL[a]	–	0.015 ↑	–
FC170	3.4–3.8	1.6–2.2	0.7–1.0	0.1 ↓	0.2 ↓	0.4–0.6	–	–	BAL[a]	0.015 ↑	–	–
A356	–	6.5–7.5	0.03 ↓	–	–	–	0.15 ↓	–	0.15 ↓	0.2 ↓	0.1–0.8	BAL[a]
Al MMC	–	8.5–9.5	–	–	–	–	0.2 ↓	–	0.2 ↓	0.03 ↓	0.45–0.65	BAL[a]

[a] BAL = balance

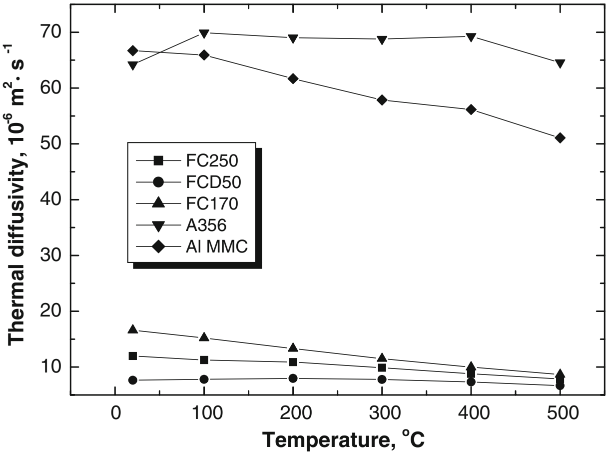

Fig. 3 Measured thermal-diffusivity values of the brake disk materials by laser flash apparatus

Table 2 Measured thermal-diffusivity values (in 10^{-5} $m^2 \cdot s^{-1}$)

T (°C)	Sample				
	FC250	FCD50	FC170	A356	Al MMC
20	11.98	7.63	16.60	64.21	66.71
100	11.26	7.80	15.21	69.92	65.93
200	10.89	7.96	13.31	69.04	61.69
300	9.87	7.77	11.51	68.79	57.87
400	8.79	7.32	9.97	69.29	56.15
500	7.85	6.66	8.66	64.56	51.08

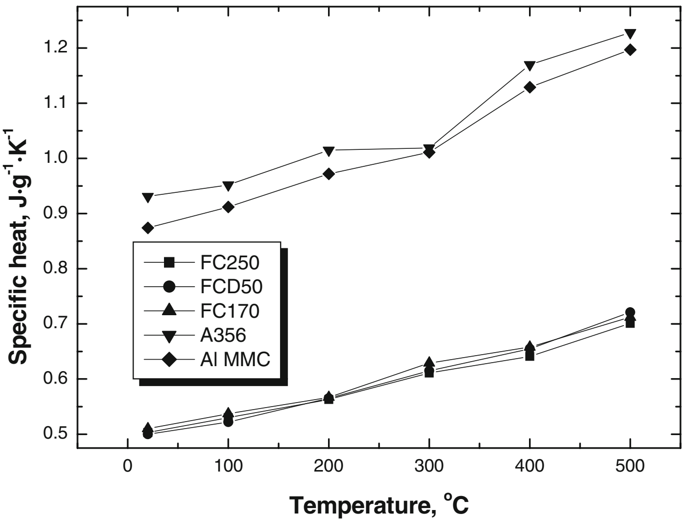

Fig. 4 Measured specific-heat-capacity values of the brake disk materials by DSC apparatus

Table 3 Measured specific-heat-capacity values (in $J{\cdot}g^{-1}{\cdot}K^{-1}$)

T (°C)	Sample				
	FC250	FCD50	FC170	A356	Al MMC
20	0.503	0.500	0.510	0.931	0.874
100	0.530	0.522	0.537	0.952	0.912
200	0.563	0.565	0.567	1.015	0.972
300	0.611	0.615	0.629	1.019	1.011
400	0.641	0.655	0.658	1.170	1.129
500	0.701	0.721	0.712	1.228	1.197

Table 4 Measured density of the samples (in $10^3\ kg \cdot m^{-3}$)

Sample	FC250	FCD50	FC170	A356	Al MMC
Density	7.22	7.04	7.08	2.14	2.73

Table 5 Calculated thermal conductivities (in $W \cdot m^{-1} \cdot K^{-1}$) using the measured thermal diffusivity (a), specific heat capacity at constant pressure (C_p), and the measured density (ρ) of the samples

T (°C)	Sample				
	FC250	FCD50	FC170	A356	Al MMC
20	42.38	26.23	58.36	150.01	155.75
100	43.06	28.64	57.84	169.13	164.06
200	44.23	31.69	53.40	178.76	163.68
300	43.55	33.60	51.23	177.37	159.71
400	40.67	33.73	46.44	205.83	173.02
500	39.72	33.80	43.70	201.39	166.85

The thermal conductivity (k) was calculated by using the measured thermal diffusivity (a), specific heat capacity at constant pressure (C_p), and the measured density (ρ) of the sample [10]. The measured densities of the samples are shown in Table 4 and the densities of iron alloys are larger than those of aluminum by a factor of 2.5.

Figure 5 shows the calculated thermal conductivities of the samples and the recommended thermal-conductivity values of pure aluminum and iron [11]. The variations of the thermal conductivity of the samples with increasing temperature are similar to the thermal diffusivities, and this can also be explained in the same way as shown in Fig. 3. The obtained values are smaller than the recommended values of pure metals because of the addition of small quantities of materials to increase the strength and hardness of the pure metals to be used as the materials of brake disks. In order to prevent the thermal deformation caused by the frictional heating of the brake disk, a higher thermal-conductivity material is more appropriate for fast cooling and heat

Table 6 Measured coefficients of thermal expansion (in $10^{-6}\,K^{-1}$)

T (°C)	Sample				
	FC250	FCD50	FC170	A356	Al MMC
20	4.386	6.608	7.176	17.591	13.902
100	11.653	12.063	12.182	23.306	18.547
200	12.836	14.093	12.743	24.680	21.168
300	13.580	14.626	13.489	28.407	23.587
400	13.578	14.867	13.560	25.385	23.587
500	13.804	15.317	13.972	22.921	17.112

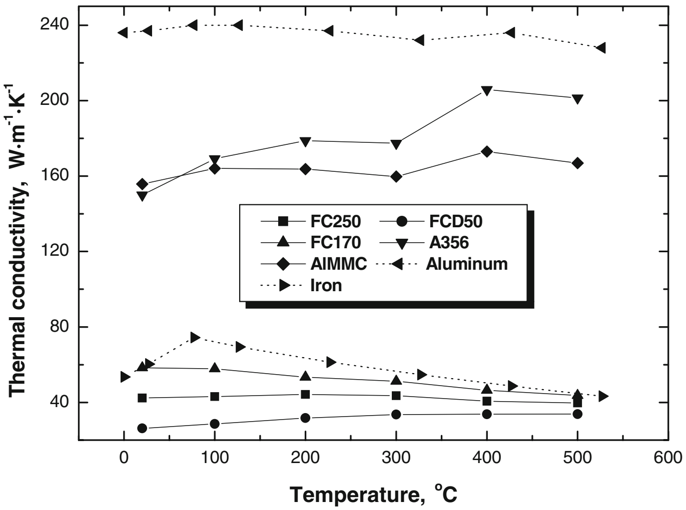

Fig. 5 Thermal-conductivity values calculated using the measured thermal diffusivity, specific heat capacity, and density of the sample

dissipation of a brake disk; therefore, when this is the main factor under consideration, aluminum alloys are recommended for the safe driving of automobiles. (Table 5)

The CTE values experimentally obtained along with the recommended values of pure aluminum and iron are shown in Fig. 6. Similar to the result for the thermal diffusivity, the CTE also shows significant differences between the aluminum and iron alloy series; however, the values are not so different from the values of pure metals. This can also be correlated with the morphology of the microstructure of the samples. In order to reduce the thermal deformation of a brake disk system, a material with lower CTE is appropriate; therefore, when this is the main factor under consideration, iron alloy materials are recommended. (Table 6)

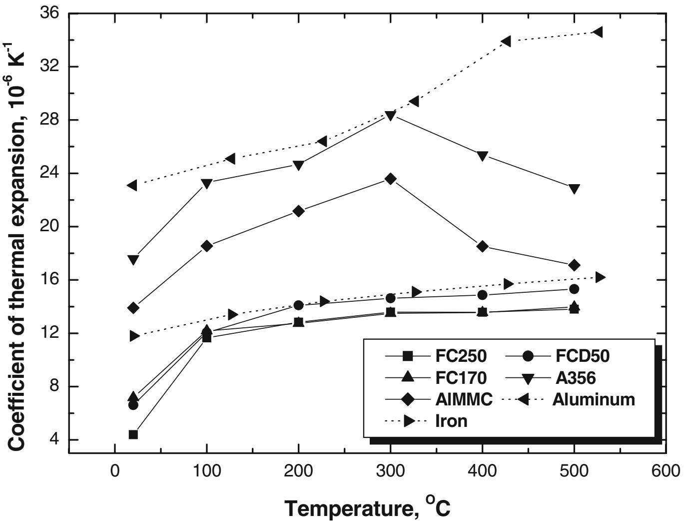

Fig. 6 Coefficient of thermal expansion values experimentally obtained by the push-rod apparatus

4 Conclusion

The thermophysical properties of three kinds of iron alloy series brake disk materials, FC250, FC170, and FCD50, and two kinds of aluminum alloy series brake disk materials, Al MMC and A356, were measured and calculated in the temperature range from room temperature to 500 °C. The experimental results show that the two alloy series have significant differences of thermophysical properties, and to reduce the thermal deformation of the brake disk, the aluminum alloys with a high thermal conductivity and the iron alloys with a low thermal expansion are recommended. The obtained data are applicable as basic input data in the study of the estimation of the temperature distribution and in the thermal analysis of brake disks by using finite element methods.

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