Thermal Properties of Ultrafine Spheroidal Graphite Iron Castings

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ABSTRACT

The thermophysical properties of ferritic spheroidal graphite iron castings with varying nodule sizes were investigated. Nodule size in the sample castings was controlled by utilizing sand molds and permanent molds. Carbon and silicon contents were adjusted to target ranges of 3.40–3.70% and 1.30–3.20%, respectively. The results revealed that smaller nodule sizes enhanced thermal conductivity in castings with lower silicon content. However, this effect was negligible when the silicon content exceeded 2.30%.

Keywords: ultrafine spheroidal graphite cast iron, SGI, thermal properties, compacted vermicular graphite, CV graphite, flake graphite

INTRODUCTION

Spheroidal graphite cast iron is a composite material comprising a matrix and graphite structures. The thermal conductivity of graphite is over four times higher than that of the matrix. As heat transfer primarily occurs along the a-axis of graphite's crystal structure, the morphology and distribution of graphite significantly influence the thermophysical properties of cast iron.

For instance, flake graphite cast iron exhibits higher thermal conductivity compared to spheroidal graphite cast iron, as reported in prior studies. This difference arises due to the heat transfer mechanisms inherent to their respective graphite structures. In gray cast iron, flake graphite forms an interconnected three-dimensional network within the eutectic cell, facilitating efficient heat transfer. In contrast, in spheroidal graphite cast iron, the graphite nodules are isolated and separated, which hinders thermal conductivity. Walton[1] and Noguchi[2] observed that increasing silicon content reduces thermal conductivity. Nevertheless, we hypothesized that ultrafine spheroidal graphite nodules with reduced inter-nodule distances could improve thermal conductivity, even in high-silicon spheroidal graphite iron. In this study, the thermophysical properties of ultrafine spheroidal graphite iron castings with nodule sizes of 10 µm or smaller using permanent molds were evaluated and compared with conventional sand mold castings having larger nodule sizes.

DESIGN OF EXPERIMENTS

1. PREPARATION OF SAMPLE

Figure 1(a) shows the shape of the sand mold casting and the sample extraction area. Samples were taken from the bottom portion of the section measuring 50 mm wide x 50 mm high x 180 mm long, located beneath the casting riser. Sand molds were made using reclaimed silica sand, furan resin, and a catalyst. A magnesium oxide-based alcohol coating was applied to the mold, which was then air-dried for 24 hours.

Figure 1(b) shows the design of the permanent mold. Samples were extracted from the cylindrical portion, measuring 20 mm in diameter x 160 mm in length. The mold was fabricated using S50C steel and coated with acetylene soot and a 0.4 mm-thick diatomite layer. The sand mold and permanent mold were maintained at room temperature and 350C (662F), respectively. Thermophysical property samples were extracted from the central portion of the castings.

Figure 2 shows the melting and pouring conditions. A 30-kg high-frequency induction furnace was used for melting. The chemical composition was adjusted after melting, and the molten metal was heated to over 1500C (2732F) and held for 5 minutes. For sand mold castings, spheroidizing and inoculation were performed using the sandwich method in the ladle. For permanent mold castings, spheroidizing was carried out with a plunger inside the furnace, and the inoculant was added directly to the melt surface during pouring. A Fe-73%Si-1.3%Ca-1.7%Al alloy served as the inoculant, while a Fe-44%Si-4%Mg-0.8%Ca-1.1%Ce-0.6%La-0.4%Al-1.9%C alloy was used for spheroidizing. The carbon content was set to 3.50%, while silicon content varied across three levels: 1.30%, 2.30%, and 3.00%.

Heat treatment conditions are shown in Figure 3. Samples were heat-treated at 920C (1688F) for 3 hours to promote a fully ferritic matrix.

2. MEASUREMENT OF THERMOPHYSICAL PROPERTIES

Thermal diffusivity and specific heat capacity were measured across a temperature range from room temperature (RT) to 600°C (1112°F) using the RASER flash method and differential scanning calorimetry (DSC), respectively.

Density was determined at RT using the underwater suspension method. Thermal conductivity was then calculated from thermal diffusivity, specific heat capacity, and density.

3. CHEMICAL COMPOSITION AND MICROSTRUCTURE

Chemical compositions were analyzed using solid-state emission spectroscopy, while carbon and sulfur were measured through combustion gas analysis. Graphite nodules smaller than 1 µm were excluded from nodule count measurements. Nodularity was assessed according to JIS G 5502, excluding nodule size. Ferrite ratio was measured post-heat treatment, with samples etched using 5% Nital. Graphite morphology was analyzed using image analysis software, as shown in Figure 4.

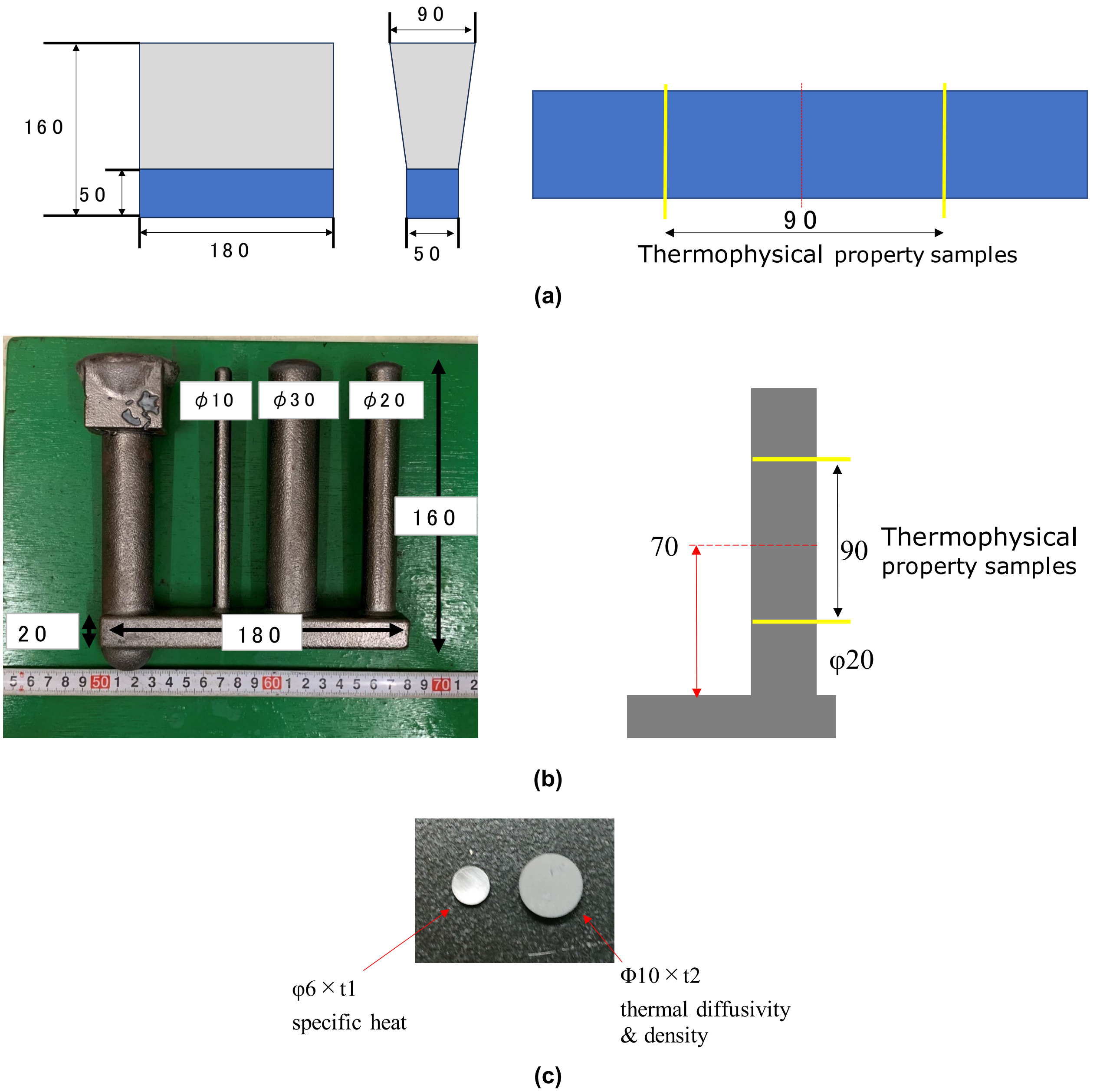
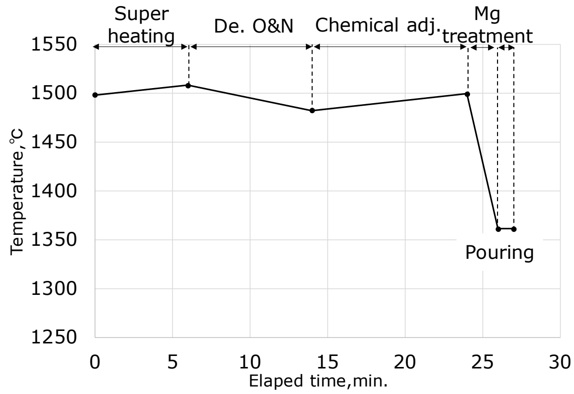
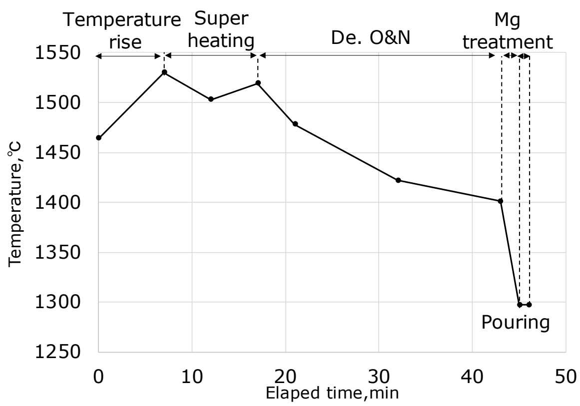


Figure 1. Dimension of castings and sampling position for thermal test pieces. (a)Sand mold, (b)Permanent mold, (c)Test pieces. (Units = mm)



(a)



(b)

Figure 2. Time-temperature schedule from melting to pouring. (a)Sand mold, (b)Permanent mold.

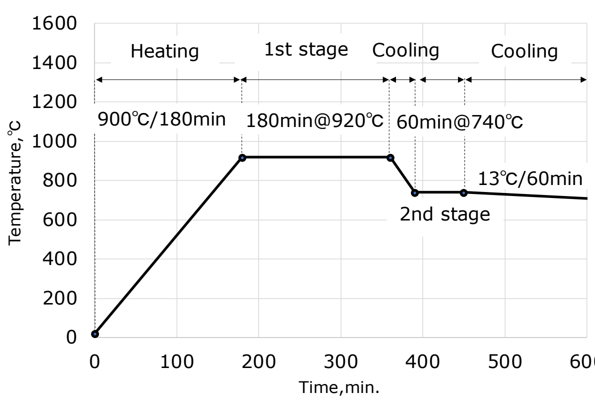


Figure 3. Condition for graphitization heat treatment.

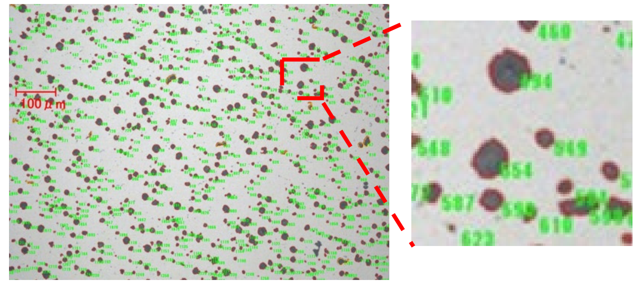


Figure 4. Example of image analysis for spheroidal graphite.

RESULTS AND DISCUSSION

Table 1 shows the chemical composition and microstructural analysis results. Carbon contents ranged from 3.36% to 3.72%, with silicon contents targeted at 1.30%, 2.30%, and 3.00%. While the manganese content varied slightly, phosphorus levels remained consistent, except for two samples. Higher phosphorus levels in these samples had no discernible effect on microstructure or thermal properties, a finding to be verified in future studies.

The microstructures of the sample castings are shown in Figure 5. Sand mold castings exhibited residual pearlite, whereas permanent mold castings were predominantly ferritic. Graphite nodule sizes were under 10 µm for all permanent mold castings, except one (13.8 µm). Thermophysical properties were evaluated and compared among the three Si content groups (1.30%, 2.30% and 3.00%) as described above.

1. THERMAL CONDUCTIVITY

Figure 6 shows thermal conductivity measurements. Thermal conductivity decreased with increasing silicon content in both mold types. Permanent mold castings with 1.30% silicon displayed higher thermal conductivity due to finer graphite particle sizes. At 2.30% silicon, sand mold castings exhibited slightly higher conductivity, with no difference observed at 3.00%.

2. THERMAL DIFFUSIVITY

Thermal diffusivity trends, shown in Figure 7, mirrored those of thermal conductivity. Permanent mold castings had higher diffusivity at 1.30% silicon, with differences diminishing at higher silicon levels.

3. SPECIFIC HEAT

Figure 8 shows specific heat capacity measurements. No significant differences were observed between mold types or silicon levels. Specific heat capacity increased with temperature.

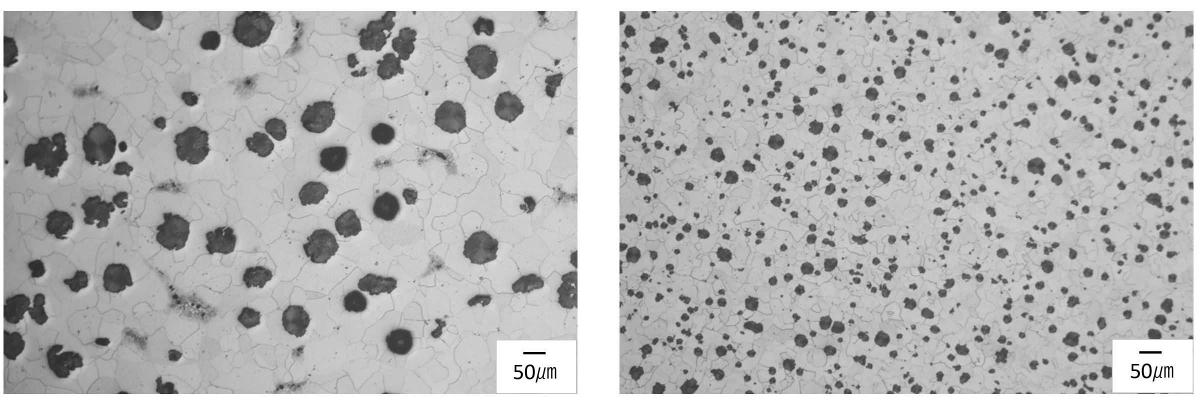
4. DENSITY

Density measurements are shown in Table 2. Mold type and silicon level had negligible effects on densit

Table 1. Chemical Composition & Microstructure of Sample Castings

NO.	Mold	Chemical Composition(mass%)									Graphite				Matrix
		C	Si	Mn	P	S	FMg	TMg	Ce	CE	Nodule number (N/mm2)	Nodule diameter Ave. (μm)	Nodularity (%)	Area (%)	Ferrite ratio (%)
1	Sand	3.49	1.34	0.07	0.020	0.010	0.026	0.034	0.013	3.94	57	56.5	85	11	97.9※
2		3.44	2.30	0.09	0.019	0.006	0.036	0.044	0.016	4.21	84	44.9	88	11	97.4※
3		3.39	3.00	0.19	0.103	0.010	0.023	0.030	0.011	4.39	79	46.2	96	13	100
Ⅰ	PM	3.54	1.30	0.06	0.021	0.010	0.024	0.032	0.012	3.97	620	13.8	96	10	99
Ⅱ		3.45	2.25	0.05	0.020	0.012	0.020	0.027	0.009	4.2	1210	9.6	98	9	99
Ⅲ		3.53	3.10	0.18	0.118	0.010	0.025	0.032	0.011	4.56	1722	7.8	99	9	100
Ⅳ		3.36	3.20	0.06	0.021	0.012	0.022	0.029	0.012	4.43	1347	6.5	95	5	99
Ⅴ		3.72	3.42	0.09	0.019	0.009	0.028	0.035	0.011	4.86	1668	7.3	98	8	98

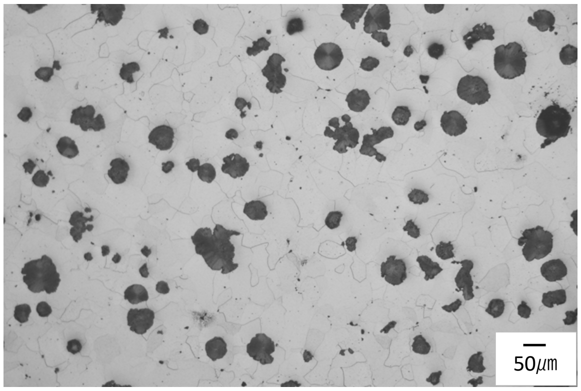
※Pearlite and Cementite residues present.



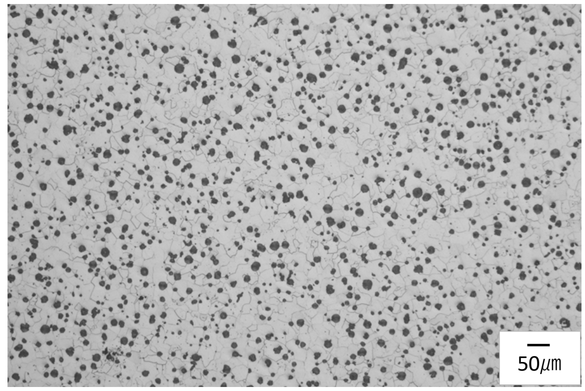
(1) Sand 1.34%Si

(I) PM 1.30%Si

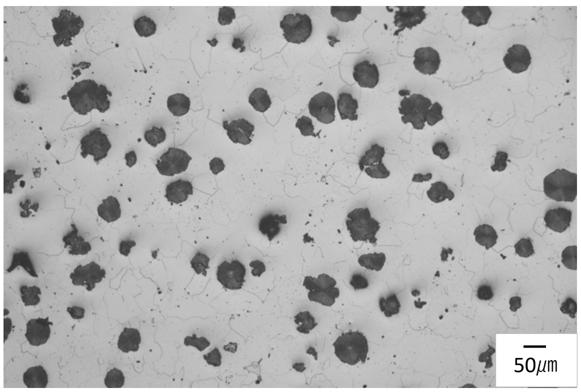
Figure 5. Microstructure of sample castings, 5% Nital etched. (Cont'd on next page)



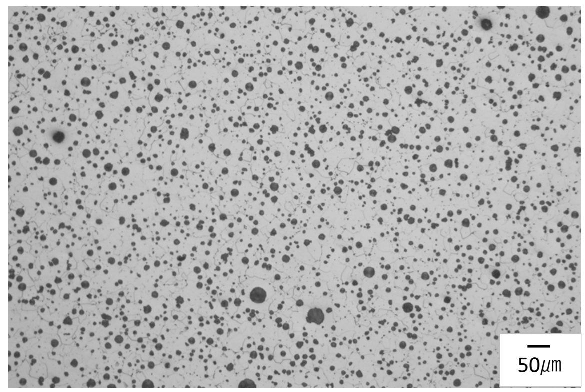
(2) Sand 2.30%Si



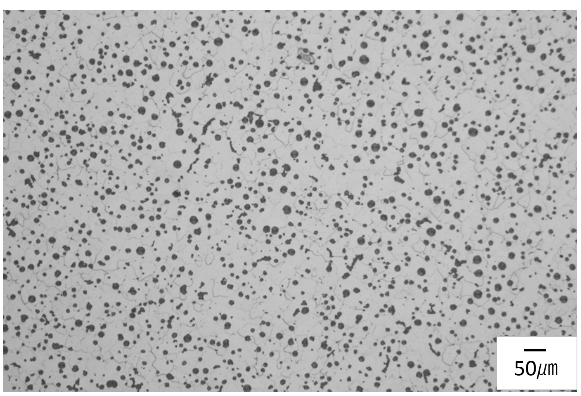
(II) PM 2.25%Si



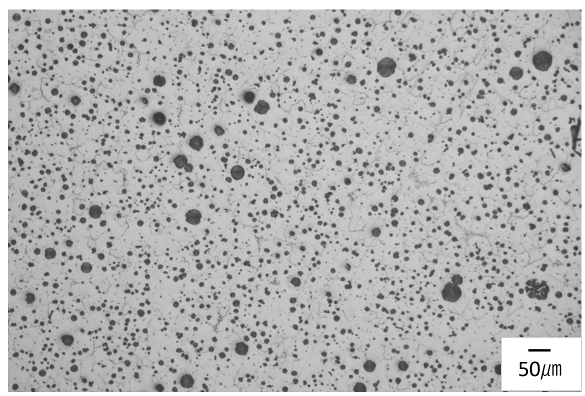
(3) Sand 3.00%Si



(III) PM 3.10%Si



(IV) PM 3.20%Si



(V) PM 3.42%Si

Figure 5. (Cont'd from previous page）Microstructure of sample castings, 5% Nital etched.

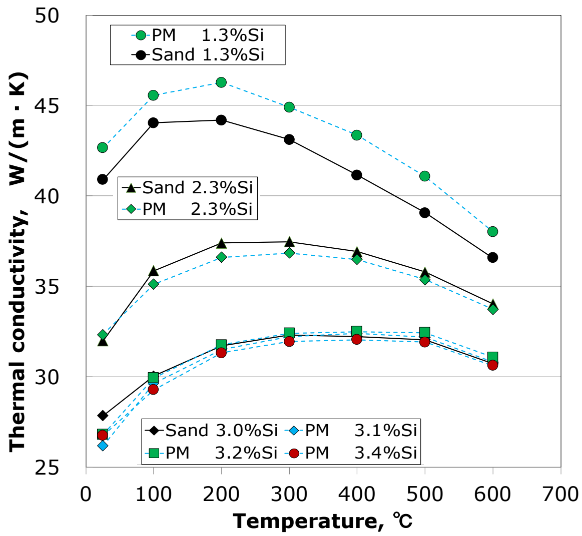


Figure 6. Results of thermal conductivity measurement.

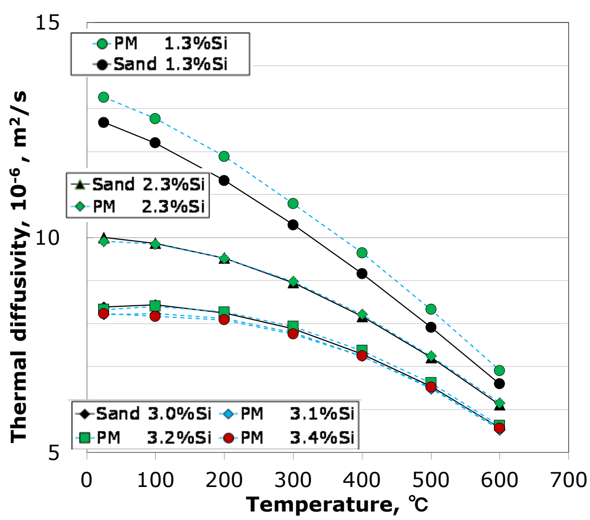


Figure 7. Results of thermal diffusivity measurement.

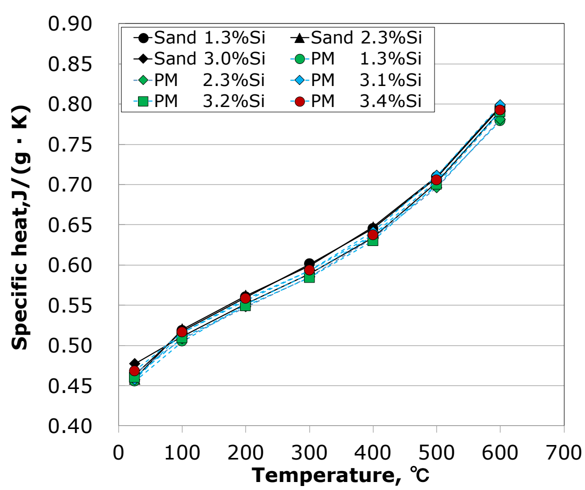


Figure 8. Results of specific heat measurement.

Table 2. Density Measurements

No.	Mold	Chemical Composition (mass%)		Density
		C	Si	(g/cm³)
1	Sand	3.49	1.34	6.97
2		3.44	2.30	6.99
3		3.39	3.00	6.97
I	PM	3.54	1.30	7.07
II		3.45	2.25	7.02
III		3.53	3.10	6.98
IV		3.36	3.20	7.00
V		3.72	3.42	6.95

CONCLUSION

The thermophysical properties of ultrafine spheroidal graphite iron castings were systematically investigated, leading to the following conclusions:

1. Smaller graphite nodule sizes effectively enhance thermal conductivity in castings with low silicon content. However, this effect diminishes as silicon content increases.
2. Higher silicon content shifts the thermal conductivity peak to higher temperatures.
3. The influence of graphite nodule size on thermal conductivity and diffusivity is negligible when silicon content exceeds 2.30%.

Permanent mold castings allow for higher carbon equivalent values without forming graphite dross, enabling increased ultrafine graphite content and superior thermal conductivity.

REFERENCES

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2. Noguchi, T., Matsumoto, Y., Nagaoka, K.; "Bulletin of the Faculty of Engineering," Hokkaido University, No. 87, pp. 57-65 (1978).