Noncontact Modulated Laser Calorimetry for Liquid Austenitic Stainless Steel in dc Magnetic Field

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A newly developed noncontact modulated laser calorimetry method was attempted to measure the isobaric specific heat capacity and thermal conductivity of liquid austenitic stainless steel (SUS 304: Japanese Industrial Standards). A stainless steel droplet was electromagnetically levitated in a radio frequency coil. A dc magnetic field of 4–5 T was superimposed to the droplet to suppress the convection in the droplet by the Lorentz force. The specific heat capacity of the liquid SUS 304 was successfully measured at temperatures ranging from 1750 to 1970 K. No clear temperature dependence was observed. The mean value over the whole temperature range is $794 \pm 76 \text{ J} \cdot \text{kg}^{-1} \cdot \text{K}^{-1}$.

The lower thermal conductivity of the liquid SUS 304 was obtained at higher dc magnetic field, which indicates that convection in the droplet was reduced by dc magnetic field. The thermal conductivity was measured as $60 \pm 9 \text{ W} \cdot \text{m}^{-1} \cdot \text{K}^{-1}$ at 5 T in the same temperature range. For the thermal conductivity measurement, it is necessary to verify the effect of suppression of the convection by conducting the calorimetry at higher dc magnetic field.

KEY WORDS: laser calorimetry; stainless steel; dc magnetic field; heat capacity; thermal conductivity; electromagnetic levitation; welding.

1. Introduction

Recently, a computer-aided welding system has been developed for improving welding processes for stainless steels.¹⁾ Thermophysical properties such as heat capacity, thermal conductivity, density and heat of fusion are required for a heat conduction model. Furthermore, surface tension is needed for a welding pool shape modeling. Accurate knowledge of thermophysical properties of stainless steel is necessary in the simulation. However, the thermophysical property data are scarce for high-temperature stainless steel melts because of the experimental difficulty arising from the contamination from the contact materials and the convections in the melt.

Fecht and co-workers^{2–5)} have developed the modulation calorimetry for electromagnetically levitated metallic melts to measure the heat capacity, thermal conductivity and hemispherical total emissivity. However, the thermal conductivity can not be measured because the convection still remained in the melt. Yasuda *et al.*⁶⁾ have reported that an electromagnetically levitated droplet behaves as a hard body in a dc magnetic field. The oscillation and convections of the droplet were effectively suppressed by the Lorentz force in a dc magnetic field. Based on the studies described above,^{2–6)} the present authors have newly developed a non-contact modulated laser calorimetry for metallic melts in a

dc magnetic field.^{7–9)} An electromagnetic levitator is equipped in a superconducting magnet to hold a droplet statically. The high-temperature droplet is heated sinusoidally by laser irradiation on the top; then, the temperature response is measured at the bottom of the droplet to determine the heat capacity, thermal conductivity and emissivity of the droplet. Tsukada *et al.*¹⁰⁾ described the theory and validity of this technique using numerical simulation. In addition, the experimental principle was verified using a solid platinum sphere as a reference.⁷⁾ Moreover, we successfully measured the heat capacity, thermal conductivity and hemispherical total emissivity of liquid Si.^{8,9)} Here, we attempted to apply this method for measuring the heat capacity and thermal conductivity of liquid austenitic stainless steel (SUS 304: Japanese Industrial Standards).

2. Principle of Noncontact Modulated Laser Calorimetry

2.1. Heat Capacity

The experimental principle is similar to that explained by the present authors.^{7–10)} Here, a brief outline is described. **Figure 1** presents a heat flow model of noncontact modulated laser calorimetry in a gas stream. The top surface of the droplet levitated in a radio frequency (rf) coil is heated with angular frequency ω ($\text{rad} \cdot \text{s}^{-1}$) using a modulated laser

Fig. 1. Heat flow model for noncontact modulated laser calorimetry in a gas stream.

with a form of $p_o(1 + \cos \omega t)$ ($\text{W} \cdot \text{m}^{-2}$). The temperature response at the bottom surface of the droplet is measured using a pyrometer. The heat balances in this system are as follows.

The heat balance at laser-irradiated part is

$$V_h C_p \frac{dT_h}{dt} = Q_h + \alpha S_h A p_o (1 + \cos \omega t) - S_h A \varepsilon \sigma (T_h^4 - T_\infty^4) - S_h A h (T_h - T_\infty) - K_c (T_h - T_l) \quad \dots\dots\dots(1)$$

that at the laser-nonirradiated part is

$$(1 - V_h) C_p \frac{dT_l}{dt} = Q_l - (1 - S_h) A \varepsilon \sigma (T_l^4 - T_\infty^4) - (1 - S_h) A h (T_l - T_\infty) + K_c (T_h - T_l) \quad \dots\dots\dots(2)$$

In those equations, S_h is the fraction of the irradiated surface area that is heated by the laser, V_h denotes the volume fraction corresponding to S_h , C_p ($\text{J} \cdot \text{K}^{-1}$) represents the isobaric heat capacity, T (K) is the absolute temperature, Q (W) is the power input from the rf coil, α is the absorptivity, A (m^2) is the surface area of the droplet, h ($\text{W} \cdot \text{m}^{-2} \cdot \text{K}^{-1}$) is the forced convection heat transfer coefficient of a gas surrounding the sample droplet, K_c ($\text{W} \cdot \text{K}^{-1}$) is the thermal conductance for conductive heat transfer from the laser irradiated part to the nonirradiated part, K_r ($\text{W} \cdot \text{K}^{-1}$) is the thermal conductance for radiative heat transfer from the sample surface to the heat reservoir in vacuum, ε is the hemispherical total emissivity, and σ ($\text{W} \cdot \text{m}^{-2} \cdot \text{K}^{-4}$) is the Stefan-Boltzmann constant. Subscripts h and l , respectively, denote the laser-irradiated part and nonirradiated part. The sample temperature is expressed as the sum of the initial temperature T_o , the average increase in temperature ΔT_{dc} (dc component), and the modulation amplitude $\Delta T_{ac} \cos(\omega t - \phi)$ (ac component) as

$$T = T_o + \Delta T_{dc} + \Delta T_{ac} \cos(\omega t - \phi) \quad \dots\dots\dots(3)$$

By solving Eqs. (1) and (2) under the condition of $K_r/K_c \leq 0.01$, where $K_r = A(4\varepsilon\sigma T_o^3 + h)$, the temperature amplitude ΔT_{ac} and the phase difference ϕ between the laser signal and temperature response are expressed as follows⁽⁷⁻⁹⁾:

$$\Delta T_{ac} = \frac{\alpha S_h A p_o}{\omega C_p} \left\{ 1 + \frac{1}{\omega^2 \tau_r^2} + \omega^2 \tau_c^2 \right\}^{-1/2} \quad \dots\dots\dots(4)$$

$$\cos \phi = \frac{\tau_c}{\omega} \left\{ \frac{1}{\tau_c \tau_r} - \omega^2 \right\} \left\{ 1 + \frac{1}{\omega^2 \tau_r^2} + \omega^2 \tau_c^2 \right\}^{-1/2} \quad \dots\dots\dots(5)$$

Therein, τ_r (s) is the external thermal relaxation time attributable to the radiative heat transfer and τ_c (s) is the internal thermal relaxation time attributable to the conductive heat transfer in the droplet. These relaxation times are defined as

$$\tau_r = \frac{C_p}{K_r} = \frac{C_p}{A(4\varepsilon\sigma T_o^3 + h)} \quad \dots\dots\dots(6)$$

$$\tau_c = \frac{C_p}{K_c} V_h (1 - V_h) \quad \dots\dots\dots(7)$$

The term $\alpha S_h A p_o$ in Eq. (4) is evaluated quantitatively using the products of the laser power and the normal spectral emissivity at a laser wavelength of the droplet. Assuming Kirchhoff's law, the normal spectral emissivity is used as the absorptivity. For this study, the value of the normal spectral emissivity of liquid stainless steel (SUS 304) is 0.32 ± 0.005 at the laser wavelength (807 nm) measured at 1803 K.⁽¹¹⁾ The distribution of the laser intensity is Gaussian; the e^{-2} radius of the laser beam is 2 mm for the droplet of 3.5 mm radius. Effects of the sample curvature on the absorptivity were ignored.

The correction function f is defined as

$$f = \left\{ 1 + \frac{1}{\omega^2 \tau_r^2} + \omega^2 \tau_c^2 \right\}^{-1/2} \quad \dots\dots\dots(8)$$

The correction function f , i.e. the function $\omega \Delta T_{ac}$, has a maximum value against the modulation frequency as expressed in Eqs. (4) and (8). In general, the condition $\omega^2 \tau_r^2 \gg 1 \gg \omega^2 \tau_c^2$, which satisfies $f \approx 1$, should be achieved by a proper choice of the modulation frequency to determine the heat capacity from Eq. (4). However, in this study, the correction function must be taken into account because of the lower value of f . The lower f value is caused by shorter value of τ_r ; i.e. larger value of K_r . The forced convection heat transfer of a gas surrounding the droplet is attributable to the larger K_r value. The value of f is estimated by using both τ_r and τ_c obtained through the curve fitting of Eq. (5) to the experimental phase difference over the whole frequency range.

2.2. Thermal Conductivity

The relation between ϕ and ω as a function of the thermal conductivity, the hemispherical total emissivity of the droplet and the forced convection heat transfer of a gas surrounding the droplet is obtainable by solving the following unsteady heat conduction equation using finite element analysis⁽⁷⁻¹⁰⁾:

$$\rho C_p \frac{\partial T}{\partial t} = \kappa \left[\frac{1}{r^2} \frac{\partial}{\partial r} \left(r^2 \frac{\partial T}{\partial r} \right) + \frac{1}{r^2 \sin \theta} \frac{\partial}{\partial \theta} \left(\sin \theta \frac{\partial T}{\partial \theta} \right) \right] + Q(r, \theta) \quad \dots\dots\dots(9)$$

In this equation, ρ ($\text{kg} \cdot \text{m}^{-3}$) is the density, c_p ($\text{J} \cdot \text{kg}^{-1} \cdot \text{K}^{-1}$) is the isobaric specific heat capacity, κ ($\text{W} \cdot \text{m}^{-1} \cdot \text{K}^{-1}$) is the thermal conductivity, $Q(r, \theta)$ ($\text{W} \cdot \text{m}^{-3}$) is the heat generation rate attributable to electromagnetic induction heating. r (m) and θ (rad) respectively denote the radial distance and polar angle in the spherical coordinate system.

The following assumptions are made to apply this unsteady heat conduction equation to our experimental condition: (1) the system is axially symmetric; (2) the thermophysical properties are constant within the temperature variation during the calorimetry measurement; (3) laser power is absorbed on the liquid surface depending on its absorptivity; (4) the distribution of laser intensity is Gaussian; (5) the heat transfer in the droplet is governed by conduction.

Boundary conditions (i) of the laser-irradiated area, (ii) of the non-laser-irradiated area, and (iii) of the centerline of the droplet are given as

$$(i) \quad -\kappa \frac{\partial T}{\partial n} = \sigma \epsilon (T^4 - T_\infty^4) + h(T - T_\infty) - \frac{2\alpha P}{\pi r_{\text{laser}}^2} \exp\left[-\frac{2R^2 \sin^2 \theta}{r_{\text{laser}}^2}\right] (-\mathbf{n} \cdot \mathbf{e}_{\text{laser}}) \quad (10)$$

$$(ii) \quad -\kappa \frac{\partial T}{\partial n} = \sigma \epsilon (T^4 - T_\infty^4) + h(T - T_\infty) \quad (11)$$

and

$$(iii) \quad -\kappa \frac{\partial T}{\partial \theta} = 0 \quad (12)$$

where P (W) is the laser power, R (m) is the radius of the sample, $\mathbf{n}$ is the normal unit vector, and r_{laser} (m) and $\mathbf{e}_{\text{laser}}$ respectively, denote the e^{-2} radius and unit vector of the laser. Solving the heat conduction Eq. (9) with the boundary conditions, the phase difference is expressed as

$$\phi = \tan^{-1} \left(\frac{\text{average}(\Delta T_{\text{ac}}^{\text{out}})}{\text{average}(\Delta T_{\text{ac}}^{\text{in}})} \right) \quad (13)$$

$$\text{average}(\Delta T_{\text{ac}}^{\text{in}}) = \frac{1}{S_{\text{pyrometer}}} \int_S \Delta T_{\text{ac}}^{\text{in}}(r, \theta) r \sin \theta ds \quad (14)$$

and

$$\text{average}(\Delta T_{\text{ac}}^{\text{out}}) = \frac{1}{S_{\text{pyrometer}}} \int_S \Delta T_{\text{ac}}^{\text{out}}(r, \theta) r \sin \theta ds \quad (15)$$

where $\Delta T_{\text{ac}}^{\text{in}}$ and $\Delta T_{\text{ac}}^{\text{out}}$, respectively, denote the in-phase and out-of-phase of the temperature amplitude and $S_{\text{pyrometer}}$ is the spot area of the pyrometer.

The variation in ϕ with modulation frequency obtained from the above numerical analysis is fitted to the experimental results using a nonlinear least-squares method. In principle, the numerical parameters including the thermal conductivity and emissivity of the droplet can be deter-

mined from the fitting process over the entire frequency range. However, in the present study, the heat loss from the droplet surface is not radiation alone; emissivity value is therefore affected by the forced convection heat transfer of the gas. The phase difference at a higher modulation frequency is controlled predominantly by thermal conductivity, although the phase difference at a lower frequency is controlled mainly by both radiation and forced convection heat transfer. Thus, only thermal conductivity was determined in this study.

The heat capacity and density of liquid stainless steel (SUS 304) are required to obtain the thermal conductivity as seen in Eq. (9). The heat capacity determined in the present study and the density measured by Matsumoto *et al.* (ρ ($\text{kg} \cdot \text{m}^{-3}$) = $-0.616T + 8.11 \times 10^3$)¹²⁾ were used.

3. Experimental

Figure 2 presents a schematic illustration of the experimental apparatus. Typical austenitic stainless steel (SUS 304: Japanese Industrial Standards) was used as a sample. The sample was held at the center of an rf coil (max. 15 kW, 200 kHz), and the coil was equipped at the center of a superconducting magnet with 220 mm bore (6T220-CSM, SHI, Japan). Chemical compositions of the stainless steel before and after modulation experiment are presented in Table 1. A mixed Ar-5% H_2 gas with addition of He gas was flowed to prevent the oxidation and the overheating of the sample. The initial temperature of the liquid SUS 304 was controlled using the electric power supply to the rf coil and gas flow rate. The flow rates were 2–4 L/min for Ar-5% H_2 gas and 2–3 L/min for He gas. The heating and levitation of the sample was done using the rf-coil. The superconducting magnet imposed the dc magnetic field of 4–5 T to suppress the convection in the droplet. The top

Fig. 2. Schematic illustration for the modulated laser calorimetry of the liquid stainless steel droplet.

Table 1. An example of chemical compositional change of the stainless steel (SUS 304) before and after modulation calorimetry experiment.

	(mass %)								
	C	Si	Mn	P	S	Ni	Cr	Mo	Cu
Before Exp.	0.04	0.31	1.31	0.029	0.006	9.92	18.1	0.18	0.32
After Exp.	0.008	0.34	<0.01	0.027	0.003	10.5	17.8	0.18	0.03

surface of the levitated liquid SUS 304 was heated sinusoidally using a semiconductor laser through a function generator. The modulation frequency varied from 0.04 to 0.3 Hz. A laser apparatus (wavelength = 807 ± 3 nm, NBT-S140-mk II; JENOPTIK Laser diode Japan Co., Ltd., Tokyo, Japan) was used with a fiber-coupling type cw laser diode. The amplitude of laser power was 31.5–40.1 W. A calibrated laser power meter (Field Mate; Coherent, Inc., Portland, OR, USA) evaluated the net laser power through the optical system, which consisted of an optical fiber and a corrective lens within a standard uncertainty of 1.3%. The temperature response was measured at the bottom of the sample through a gas nozzle with inner diameter of 6 mm using a two-color pyrometer (IR-CAQ3CS; Chino Corp., Tokyo, Japan) with the emissivity ratio of two wavelengths (1350 and 900 nm). The signals from the function generator and the pyrometer were recorded with a sampling interval of 20 ms.

4. Results

4.1. Temperature Response

Figure 3 shows an example of the temperature response of the noncontact modulated laser calorimetry for the electromagnetically levitated liquid SUS 304. Initially, the droplet temperature was maintained at T_0 with balancing between the rf induction heating and heat loss caused by radiation and forced convection heat transfer of gas. Then the droplet was heated sinusoidally using the laser. The droplet's temperature gradually increased by ΔT_{dc} from T_0 , subsequently, the temperature reached an ac steady state.

An example of the temperature response in the ac steady state is shown in Fig. 4 for the modulation frequency of 0.1 Hz ($0.628 \text{ rad} \cdot \text{s}^{-1}$). The temperature amplitude and the phase difference were measured by changing the modulation frequency to obtain both the ϕ – ω and the $\omega\Delta T_{ac}$ – ω relation.

Figure 5 shows both the ϕ – ω and the $\omega\Delta T_{ac}$ – ω relation obtained from a series of modulation heating. The value of $\omega\Delta T_{ac}$ has a maximum at a modulation frequency of 0.08 Hz; simultaneously, the phase difference satisfies the requirement that ϕ is equal to -90° at the frequency, as predicted by the principle of modulation calorimetry. The relaxation times τ_r and τ_c were determined to be 6.6 s and 0.6 s, respectively by fitting the phase difference to the Eq. (5). Thus, the correction function f was evaluated as a function of frequency using Eq. (8) with two relaxation times, and the maximum value of f was determined to be 0.92 at a frequency of 0.08 Hz. The heat capacity of the liquid SUS 304 was determined from Eq. (4) using the maximum values of $\omega\Delta T_{ac}$ and f .

The experimental frequency dependence of the phase difference designated by an open diamond was well reproduced by the numerical analysis, as designated by a dashed line shown over the whole frequency range. From least-squares fitting, the thermal conductivity of liquid SUS 304 was determined in the manner described in Sec. 2.2.

4.2. Specific Heat Capacity

The results of specific heat capacity and thermal conductivity are summarized in Table 2. From the maximum value

Fig. 3. An example of time dependence of the laser power (left-hand ordinate) and the temperature response (right-hand ordinate) of liquid stainless steel during modulated laser calorimetry.

Fig. 4. Temperature response in an ac steady state with modulation frequency of 0.10 Hz.

Fig. 5. $\omega\Delta T_{ac}$ as a function of ω is shown on the left-hand ordinate (open squares). ϕ is shown on the right-hand ordinate (open diamond), the dashed line shows fitting to the experimental data using the numerical analysis explained in Sec. 2.2.

of $\omega\Delta T_{ac}$ against the modulation frequency as shown in Fig. 5, the specific heat capacity is determined using Eq. (4) and the value of the absorptivity of liquid SUS 304. Figure 6 shows the temperature dependence of the specific heat capacity of SUS 304. A clear temperature or dc magnetic field dependence of the heat capacity was not observed.

The mean specific heat capacity of liquid SUS 304 is $794 \pm 76 \text{ J} \cdot \text{kg}^{-1} \cdot \text{K}^{-1}$ at temperatures of 1750–1970 K. The experimental uncertainty presented in the above value is double the standard deviation for all the present data. The present results show good agreement with the reference data of Fe and Cr¹³⁾ within experimental uncertainty. In the solid state, there are two data reported by Cezairliyan and

Table 2. Experimental conditions and results for the modulation calorimetry.

Sample No.	Ar+H ₂	He	rf-coil current	Laser power	Sample mass		T_{ave}	τ_r	τ_c	f_{max}	α	c_p	κ
	L·min ⁻¹	L·min ⁻¹	A	W	Before exp.	After exp.							
					g	g	K	s	s			J·kg ⁻¹ ·K ⁻¹	W·m ⁻¹ ·K ⁻¹
Magnetic field 5T													
SUS304-080304b	2.0	2.5	641	31.5	1.475	1.431	1826	6.61	0.60	0.92	0.32	826	63
SUS304-080304c	2.0	3.0	641	31.5	1.521	1.483	1801	6.34	0.63	0.91	0.32	804	64
SUS304-080304d	2.0	2.0	622	31.5	1.515	1.429	1900	5.80	0.68	0.90	0.32	822	55
SUS304-080305b	2.0	2.0	680	31.5	1.538	1.483	1860	6.50	0.68	0.91	0.32	810	57
SUS304-080305c	2.0	2.5	680	31.5	1.442	1.400	1782	5.90	0.66	0.90	0.32	840	65
SUS304-080305d	2.0	3.0	680	31.5	1.555	1.527	1744	6.91	0.63	0.92	0.32	811	62
SUS304-080306a	2.0	2.0	641	31.5	1.504	1.424	1969	6.00	0.75	0.89	0.32	754	52
SUS304-080306b	2.0	2.0	680	31.5	1.585	1.533	1824	6.80	0.70	0.91	0.32	790	60
Magnetic field 4T													
SUS304-070320c	3.9	2.0	720	40.1	1.425	1.386	1892	7.30	0.48	0.94	0.32	797	80
SUS304-070322b	3.9	2.0	699	40.1	1.425	1.384	1868	6.80	0.55	0.93	0.32	806	74
SUS304-070322c	2.9	2.0	699	40.1	1.425	1.388	1912	6.80	0.45	0.94	0.32	786	86
SUS304-070322d	3.9	2.0	710	40.1	1.425	1.392	1847	7.00	0.60	0.92	0.32	828	69
SUS304-070323a	2.9	2.0	699	40.1	1.425	1.379	1933	7.00	0.52	0.93	0.32	696	78
SUS304-070323b	3.3	2.0	699	40.1	1.425	1.389	1908	7.20	0.48	0.94	0.32	751	84

Fig. 6. Isobaric specific heat capacity of the liquid stainless steel (SUS 304) measured in a dc magnetic field at 4 T (open circles) and 5 T (solid circles) with data from literature.^{13–15} The bold line shows the mean value of our experimental data. **Fig. 7.** Thermal conductivity of the liquid stainless steel (SUS 304) measured in a dc magnetic field at 4 T (open circles) and 5 T (solid circles) together with data from literature. The bold line shows the mean value of our experimental data obtained at 5 T.

Miiller,¹⁴⁾ and Zacharia *et al.*,¹⁵⁾ however, no experimental data are available in the liquid state except of the present data. The details of the experimental uncertainty will be discussed in Sec. 5.2.

4.3. Thermal Conductivity

Figure 7 shows the temperature dependence of the thermal conductivity of liquid SUS 304 together with the previous results reported by other investigators.^{14–16)} The thermal conductivity depends on the dc magnetic field. The thermal conductivity of liquid SUS 304 was decreased with increasing the strength of the static magnetic field. This phenomenon is caused by the suppression of the convection in the droplet by the dc magnetic force. Thus, the data approach the true value with increasing dc magnetic field. However, the present experimental apparatus limits a magnetic field as high as 5 T. In the future work, it is necessary to verify the effect of suppression of the convection by conducting the experiment at higher dc magnetic field and also by the numerical simulation.

The mean thermal conductivity of liquid SUS 304 is $60 \pm 9 \text{ W} \cdot \text{m}^{-1} \cdot \text{K}^{-1}$ under 5 T at temperatures ranging from 1750 to 1970 K, which is designated by the bold line. The experimental uncertainty presented in the above value is double the standard deviation for all the present data at 5 T.

The thermal conductivities of Fe, Ni and Cr in the liquid state were also presented at their melting points in Fig. 7 for

comparison. These are recommended values by Mills *et al.*¹⁶⁾ The recommended value for liquid Fe is based on the experimental results obtained using the plane temperature wave technique by Zinovyev *et al.*^{16,17)} The present data at 5 T are much higher than that of liquid Fe. No experimental data on liquid SUS 304 are available except of the present data.

The results of the solid SUS 304 were reported by Cezairliyan and Miiller,¹⁴⁾ and Zacharia *et al.*¹⁵⁾ The data from Cezairliyan and Miiller¹⁴⁾ were calculated from the electric conductivity values assuming the Wiedemann–Franz law.

5. Discussion

5.1. Biot Number and Correction Function

In the heat flow model explained in the preceding Sec. 2.1, the forced convection heat transfer coefficient, h , is derived from Eq. (6) as,

$$h = \frac{C_p}{4\pi R^2 \tau_r} - 4\epsilon\sigma T_0^3 \dots\dots\dots (16)$$

The value of h was calculated using the above equation with the hemispherical total emissivity value of 0.27 for liquid SUS 304,¹¹⁾ and was tabulated in **Table 3**. The Biot number relevant to the value of K_r/K_c is defined as follows:

$$Bi = \frac{4\varepsilon\sigma T_0^3 + h}{\kappa/R} \dots\dots\dots(17)$$

The estimated Biot number varies from 0.04 to 0.08 under the present experimental conditions as shown in Table 3. Thus, a quasi-adiabatic condition (*i.e.* $K_r/K_c \leq 0.01$) is not satisfied well for the modulation calorimetry. Therefore, the correction function f given by Eq. (8) is necessary for determining the heat capacity of the liquid SUS 304 as explained in the Sec. 2.1. The maximum value of f varies from 0.89 to 0.94 depending on the experimental condition as shown in Table 2. All specific heat capacity was corrected using the maximum value of f .

5.2. Uncertainty of Heat Capacity

The uncertainty in the specific heat capacity was evaluated based on the Guide to the expression of uncertainty in measurement (GUM).¹⁸⁾ The specific heat capacity is derived from Eq. (4) as follows:

$$c_p = \frac{\alpha P}{\omega \Delta T_{ac}} f_{\max} \times \frac{1}{m} \dots\dots\dots(18)$$

The combined standard uncertainty in the specific heat capacity, $u(c_p)$, is expressed using the following law of propagation of uncertainties:

$$u^2(c_p) = \left(\frac{\partial c_p}{\partial \alpha} u(\alpha) \right)^2 + \left(\frac{\partial c_p}{\partial P} u(P) \right)^2 + \left(\frac{\partial c_p}{\partial \omega} u(\omega) \right)^2 + \left(\frac{\partial c_p}{\partial \Delta T_{ac}} u(\Delta T_{ac}) \right)^2 + \left(\frac{\partial c_p}{\partial m} u(m) \right)^2 \dots\dots(19)$$

The respective contributions of uncertainty components in the specific heat capacity are listed in **Table 4**. The sources of uncertainties in P , ω and ΔT_{ac} were based upon the limited resolution of the laser power meter, function generator and pyrometer used in this study. The uncertainty in the sample mass was caused by evaporation during the modulation calorimetry. The uncertainty in the absorptivity was evaluated from the original published data.¹¹⁾ The table shows that uncertainties in α , ΔT_{ac} and m are a major contribution. The combined standard uncertainty is evaluated as $34 \text{ J} \cdot \text{kg}^{-1} \cdot \text{K}^{-1}$. The expanded uncertainty at the 95% level of confidence (coverage factor=2) in the heat capacity is therefore $68 \text{ J} \cdot \text{kg}^{-1} \cdot \text{K}^{-1}$.

Table 4. List of uncertainty components of the specific heat capacity for the experimental condition of SUS304-080304b given in Table 2.

Component	Standard uncertainty	Sensitivity coefficient	Contribution $\text{J} \cdot \text{kg}^{-1} \cdot \text{K}^{-1}$
α	$u(\alpha) = 0.005$	$\partial c_p / \partial \alpha = 2.58 \times 10^3 \text{ J} \cdot \text{kg}^{-1} \cdot \text{K}^{-1}$	13
P	$u(P) = 0.4 \text{ W}$	$\partial c_p / \partial P = 26 \text{ s} \cdot \text{kg}^{-1} \cdot \text{K}^{-1}$	10
ω	$u(\omega) = 0.00001 \text{ rad} \cdot \text{s}^{-1}$	$\partial c_p / \partial \omega = -1.64 \times 10^3 \text{ J} \cdot \text{kg}^{-1} \cdot \text{K}^{-1} \cdot \text{rad}^{-1} \cdot \text{s}$	-0.016
ΔT_{ac}	$u(\Delta T_{ac}) = 0.5 \text{ K}$	$\partial c_p / \partial \Delta T_{ac} = 54 \text{ J} \cdot \text{kg}^{-1} \cdot \text{K}^{-2}$	27
m	$u(m) = 0.022 \times 10^{-3} \text{ kg}$	$\partial c_p / \partial m = -568 \times 10^3 \text{ J} \cdot \text{kg}^{-2} \cdot \text{K}^{-1}$	-13
Combined standard uncertainty			34

5.3. Effect of dc Magnetic Field on Thermal Conductivity Measurement

The thermal conductivity of the liquid SUS 304 was measured at dc magnetic fields of 4 T and 5 T. The thermal conductivity depends on the dc magnetic field, and the lower thermal conductivity was obtained at 5 T as shown in Fig. 7. This means that the Lorenz force suppressed the convection in the droplet more effectively at 5 T than at 4 T. The results should be verified experimentally or using numerical simulation.

Tsukada¹⁹⁾ demonstrated, using numerical analysis, that the maximum flow rate in the electromagnetically levitated liquid Si is significantly reduced with increasing strength of the dc magnetic field. In numerical simulation, the electromagnetic field in the system was first computed to obtain the electromagnetic force and the distribution of heat generation rate in the droplet, and then the flow and temperature fields in the droplet were calculated, under the assumptions that the droplet shape is spherical and the system is axisymmetric. Here, the magnetohydrodynamic (MHD) convection was considered as well as the buoyancy and Marangoni convection in the droplet. Moreover, the modulation calorimetry for measuring thermal conductivity was numerically simulated, taking into account the flow field in the droplet. Applying the dc magnetic field of 4 T is enough to measure the thermal conductivity of liquid Si. However, the magnetic field should be at least 10 T for measuring the thermal conductivity of liquid Fe. The Prandtl number of liquid Fe is approximately 10 times larger than that of liquid Si, which contributes the difference. Another possible

Table 3. Evaluation of the forced convection heat transfer coefficient and Biot number for the modulation calorimetry.

Sample No.	T_0	R	ε	h	Bi
	K	m		$\text{W} \cdot \text{m}^{-2} \cdot \text{K}^{-1}$	
Magnetic field 5T					
SUS304-080304b	1726	0.0037	0.27	754	0.06
SUS304-080304c	1701	0.0037	0.27	799	0.06
SUS304-080304d	1800	0.0037	0.27	856	0.08
SUS304-080305b	1760	0.0037	0.27	744	0.07
SUS304-080305c	1682	0.0036	0.27	921	0.07
SUS304-080305d	1644	0.0037	0.27	758	0.06
SUS304-080306a	1869	0.0037	0.27	669	0.08
SUS304-080306b	1724	0.0038	0.27	705	0.06
Magnetic field 4T					
SUS304-070320c	1792	0.0036	0.27	569	0.04
SUS304-070322b	1768	0.0036	0.27	662	0.05
SUS304-070322c	1813	0.0036	0.27	609	0.04
SUS304-070322d	1747	0.0036	0.27	674	0.05
SUS304-070323a	1833	0.0036	0.27	458	0.04
SUS304-070323b	1808	0.0036	0.27	517	0.04

reason is that the larger rf-power was required to levitate liquid Fe than liquid Si. The details of the numerical simulation will be separately reported. Furthermore, the modulation calorimetry will be conducted to measure the thermal conductivity at higher dc magnetic field.

6. Conclusion

The newly developed noncontact modulated laser calorimetry method was attempted to measure the specific heat capacity and thermal conductivity of liquid austenitic stainless steel (SUS 304). The specific heat capacity of the liquid SUS 304 was successfully measured as $794 \pm 76 \text{ J} \cdot \text{kg}^{-1} \cdot \text{K}^{-1}$ at temperatures ranging from 1750 to 1970 K. The uncertainty in the specific heat capacity was evaluated according to the GUM (Guide to the Expression of Uncertainty in Measurement).

The thermal conductivity was measured as $60 \pm 9 \text{ W} \cdot \text{m}^{-1} \cdot \text{K}^{-1}$ at 5 T in the same temperature range. For the thermal conductivity measurement, it is necessary to verify the effect of suppression of the convection by conducting the calorimetry at higher dc magnetic field.

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