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

Hiroyuki FUKUYAMA,1) Kakeru TAKAHASHI,1) Shoji SAKASHITA,1) Hidekazu KOBATAKE,1) Takao TSUKADA2) and Satoshi AWAJI3)

1) Institute of Multidisciplinary Research for Advanced Materials, Tohoku University, 2-1-1 Katahira, Aoba-ku, Sendai 980-8577 Japan. 2) Department of Chemical Engineering, Tohoku University, 6-6-07 Aramaki, Aoba-ku, Sendai 980-8579 Japan. 3) Institute for Materials Research, Tohoku University, 2-1-1 Katahira, Aoba-ku, Sendai 980-8577 Japan.

(Received on March 31, 2009; accepted on May 7, 2009)

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 Lorenz force. The specific heat capacity of the liquid SUS 304 was successfully measured at temperatures ranging from 1 750 to 1 970 K. No clear temperature dependence was observed. The mean value over the whole temperature range is 794±76 J · kg⁻¹ · 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±9 W · m⁻¹ · 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. 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 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. 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 Lorenz force in a dc magnetic field. Based on the studies described above, the present authors have newly developed a noncontact modulated laser calorimetry for metallic melts in a dc magnetic field. 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. 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. Moreover, we successfully measured the heat capacity, thermal conductivity and hemispherical total emissivity of liquid Si. 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. 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 (rad · s⁻¹) using a modulated laser...
with a form of \( p_s(1 + \cos \omega t) \) (W 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

\[
V_h C_p \frac{dT_i}{dt} = Q_s + \alpha S_h A_p \rho_s(1 + \cos \omega t) - S_h A \sigma \epsilon \sigma(T_i^4 - T_{\infty}^4) - S_h A h(T_i - T_{\infty}) - K_c(T_i - T_h) \tag{1}
\]

that at the laser-nonirradiated part is

\[
(1 - V_h)C_p \frac{dT_i}{dt} = Q_s - (1 - S_h) A \sigma \epsilon \sigma(T_i^4 - T_{\infty}^4) - (1 - S_h) A h(T_i - T_{\infty}) + K_c(T_h - T_i) \tag{2}
\]

In these 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 \( S_h, C_p \) (J K\(^{-1}\)) represents the isobaric heat capacity, \( T \) (K) is the absolute temperature, \( Q \) (W) is the power input from the rf coil, \( \alpha \) is the absorptivity, \( A \) (m\(^2\)) is the surface area of the droplet, \( h \) (W m\(^{-2}\) K\(^{-1}\)) is the forced convection heat transfer coefficient of a gas surrounding the sample droplet, \( K_c \) (W K\(^{-1}\)) is the thermal conductance for conductive heat transfer from the laser irradiated part to the nonirradiated part, \( K_c \) (W K\(^{-1}\)) is the thermal conductance for radiative heat transfer from the sample surface to the heat reservoir in vacuum, \( \epsilon \) is the hemispherical total emissivity, and \( \sigma \) (W m\(^{-2}\) 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 \( T_o \) and the average increase in temperature \( \Delta T_{dc} \) (dc component), and the modulation amplitude \( \Delta T_{ac} \cos(\omega t - \phi) \) (ac component) as

\[
T = T_o + \Delta T_{dc} + \Delta T_{ac} \cos(\omega t - \phi) \tag{3}
\]

By solving Eqs. (1) and (2) under the condition of \( K_c/K_{ch} \leq 0.01 \), where \( K_c = A(4 \pi \epsilon \sigma T_i^4 + h) \), the temperature amplitude \( \Delta T_{ac} \) and the phase difference \( \phi \) between the laser signal and temperature response are expressed as follows

\[
\Delta T_{ac} = \frac{\alpha S_h A_p \rho_s}{\omega C_p} \left\{1 + \frac{1}{\omega^2 \tau_0^2} + \omega^2 \tau_c^2\right\}^{-1/2} \tag{4}
\]

\[
\cos \phi = \frac{\tau_c}{\omega} \left[1 - \frac{1}{\omega^2 \tau_c^2} + \frac{1}{\omega^2 \tau_c^2} + \omega^2 \tau_c^2\right]^{-1/2} \tag{5}
\]

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

\[
\tau_e = \frac{C_p}{K_c} \tag{6}
\]

\[
\tau_s = \frac{C_p}{K_c} \tag{7}
\]

The term \( \alpha S_h A_p \rho_s \) 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 \pm 0.005 at 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

\[
f = \left\{1 + \frac{1}{\omega^2 \tau_0^2} + \omega^2 \tau_c^2\right\}^{-1/2} \tag{8}
\]

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 \( \omega^2 \tau_c^2 \gg 1 \Rightarrow \omega^2 \tau_c^2 \), 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 \( \tau_c \), i.e. larger value of \( K_c \). The forced convection heat transfer of a gas surrounding the droplet is attributable to the larger \( K_c \) value. The value of \( f \) is estimated by using both \( \tau_e \) and \( \tau_s \) 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 \( \phi \) and \( \omega \) 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

\[
\rho C_p \frac{\partial T}{\partial t} = \kappa \frac{1}{r^2} \frac{\partial}{\partial r} \left( r^2 \frac{\partial T}{\partial r} \right) + \frac{1}{r^2 \sin \theta} \frac{\partial}{\partial \theta} \left( \sin \theta \frac{\partial T}{\partial \theta} \right) + Q(r, \theta) \tag{9}
\]
In this equation, \( \rho \) (kg·m\(^{-3}\)) is the density, \( c_p \) (J·kg\(^{-1}\)·K\(^{-1}\)) is the isobaric specific heat capacity, \( \kappa \) (W·m\(^{-1}\)·K\(^{-1}\)) is the thermal conductivity, \( Q(r, \theta) \) (W·m\(^{-1}\)) is the heat generation rate attributable to electromagnetic induction heating, \( r \) (m) and \( \theta \) (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

\[
(i) \quad -\kappa \frac{\partial T}{\partial n} = \sigma\varepsilon(T^4 - T_s^4) + h(T - T_w) - \frac{2\alpha P}{\sigma r_s^2} \exp\left[-\frac{2R^2\sin^2 \theta}{r_s^2}\right] - n \cdot \mathbf{e}_\text{laser}
\]

\[\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cd-
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 $\Delta T_{ac}$ 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 rad · s$^{-1}$). The temperature amplitude and the phase difference were measured by changing the modulation frequency to obtain both the $\phi$–$\omega$ and the $\omega \Delta T_{ac}$–$\omega$ relation.

Figure 5 shows both the $\phi$–$\omega$ and the $\omega \Delta T_{ac}$–$\omega$ 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 $\phi$ is equal to $-90^\circ$ at the frequency, as predicted by the principle of modulation calorimetry. The relaxation times $\tau_1$ and $\tau_2$ 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 $\omega$.

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 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 absorbptivity 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 $794 \pm 76$ J · kg$^{-1}$ · 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 Cr$^{11}$ within experimental uncertainty. In the solid state, there are two data reported by Cezairliyan and...
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±9 W·m⁻¹·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,

\[
h = \frac{C_p}{4\pi R^2 \tau} - \frac{4\epsilon\sigma T_0^3}{\eta} \quad .......
\]

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 \( K/K_0 \) is defined as follows:

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

| Sample No. | \( \text{Ar}+\text{He} \) | \( T \text{r}-\text{cool} \) current | Laser power | Sample mass | \( T_\text{exp} \) | \( T_\text{ref} \) | \( r_g \) | \( s \) | \( \alpha \) | \( \eta \) | \( K \) | \( K_0 \) | \( K/K_0 \) |
|------------|-----------------|-----------------|-----------|-------------|--------------|--------------|--------|------|-------|-----|------|------|---------|
| SUS304-080040b | 2.0 | 2.5 | 641 | 31.5 | 1.475 | 1.431 | 1828 | 6.61 | 0.60 | 0.92 | 32 | 826 | 63 | 14 |
| SUS304-080040c | 2.0 | 3.0 | 641 | 31.5 | 1.521 | 1.483 | 1801 | 6.34 | 0.63 | 0.91 | 32 | 804 | 64 | 15 |
| SUS304-080040d | 2.0 | 2.5 | 622 | 31.5 | 1.515 | 1.429 | 1900 | 5.80 | 0.68 | 0.90 | 32 | 822 | 55 | 15 |
| SUS304-080050b | 2.0 | 2.0 | 680 | 31.5 | 1.538 | 1.483 | 1600 | 6.50 | 0.68 | 0.91 | 32 | 810 | 57 | 16 |
| SUS304-080050c | 2.0 | 2.5 | 680 | 31.5 | 1.442 | 1.400 | 1782 | 5.90 | 0.66 | 0.90 | 32 | 840 | 65 | 16 |
| SUS304-080060a | 2.0 | 2.0 | 660 | 31.5 | 1.555 | 1.527 | 1744 | 6.91 | 0.63 | 0.92 | 32 | 811 | 62 | 16 |
| SUS304-080050b | 2.0 | 2.0 | 680 | 31.5 | 1.504 | 1.424 | 1699 | 6.00 | 0.75 | 0.89 | 32 | 754 | 52 | 16 |

© 2009 ISIJ

1440
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. \( K_r / K_c / H_1 = 0.01 \)) 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} \quad \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cd \]
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.

Acknowledgements

The authors thank Prof. T. Hibiya (Keio University), Prof. M. Watanabe (Gakushuin University), S. Ozawa (Tokyo Metropolitan University), Dr. T. Ohji (Virtual Weld), Dr. T. Baba (AIST), Dr. H. Tanaka (AIST) and Mr. T. Wakamatsu (Daifuku Software Development Co., Ltd) for their helpful comments and discussion. This work is the result of Research and Development to Promote the Creation and Utilization of an Intellectual Infrastructure-Research and Development to Construct the Databases for Computer Aided Welding System, which is supported by the New Energy and Industry Technology Development Organization (NEDO). This development was also supported by ISIJ Research Promotion Grant and SENTAN, JST. This work was performed at the High Field Laboratory for Superconducting Materials, Institute for Materials Research, Tohoku University.

REFERENCES

1) T. Wakamatsu, S. Ozawa, H. Fukuyama, H. Kobatake, M. Watanabe, A. Mizuno and T. Hibiya: Proc. of the 29th Japan Symposium on Thermophysical Properties, Japan Society of Thermophysical Properties, Tokyo, (2008) 179.
2) H.-J. Fecht and W. L. Johnson: Rev. Sci. Instrum., 62 (1991), 1299.
3) R. K. Wunderlich and H.-J. Fecht: Appl. Phys. Lett., 62 (1993), 3111.
4) R. K. Wunderlich, D. S. Lee, W. K. Johnson and H.-J. Fecht: Phys. Rev. B, 55 (1997), 26.
5) R. K. Wunderlich and H.-J. Fecht: Meas. Sci. Technol., 16 (2005), 402.
6) H. Yasuda, I. Ohnaka, Y. Ninomiya, R. Ishii, S. Fujita and K. Kishio: J. Cryst. Growth, 260 (2004), 475.
7) H. Fukuyama, H. Kobatake, K. Takahashi, I. Minato, T. Tsukada and S. Awaji: Meas. Sci. Technol., 18 (2007), 1.
8) H. Kobatake, H. Fukuyama, I. Minato, T. Tsukada and S. Awaji: Appl. Phys. Lett., 90 (2007), 094102-1.
9) H. Kobatake, H. Fukuyama, I. Minato, T. Tsukada and S. Awaji: J. Appl. Phys., 104 (2008), 054901-1-8.
10) T. Tsukada, H. Fukuyama and H. Kobatake: Int. J. Heat Mass Trans., 50 (2007), 3054.
11) T. Makino, H. Hasegawa, Y. Narumiya, S. Matsuda and T. Kunitomo: Trans. Jpn. Soc. Mech. Eng. (B), 50 (1974), No. 459, 2655.
12) T. Matsumoto, T. Misono, H. Fujii and K. Nogi: J. Mater. Sci., 40 (2005), 2197.
13) M. W. Chase, Jr., ed., NIST-JANAF Thermochemical Tables, 4th ed., The American Chemical Society, Washington, DC and the American Institute of Physics, New York, (1998).
14) A. Cezairliyan and A. P. Muller: Int. J. Thermophys., 1 (1980), No. 1, 83.
15) T. Zacharia, S. A. David and J. M. Vitek: Metall. Trans. B, 22B (1991), 233.
16) K. C. Mills, B. J. Monaghan and B. J. Keene: Int. Mater. Rev., 41 (1996), No. 6, 209.
17) V. Y. Zinovyev, V. F. Polev, S. G. Taluts, G. P. Zinovyeva and S. A. Ilinykh: Phys. Met. Metallog., 61 (1986), No. 6, 85.
18) L. Kirkup and R. B. Frenkel: An Introduction to Uncertainty in Measurement Using the GUM (Guide to the Expression of Uncertainty in Measurement), Cambridge University Press, Cambridge, (2006).
19) T. Tsukada, K. Sugiooka, T. Totsusumo, H. Fukuyama and H. Kobatake: Int. J. Heat Mass Trans., 52 (2009), 5152.