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Abstract

Surface tension data for molten Al–Si alloys are important for modeling high-temperature melt-processing phenomena, but the surface tension values in the literature show considerable scatter, particularly with respect to their composition dependence. In this study, surface tension measurements were conducted for pure liquid Al, pure liquid Si, and molten Al–Si alloys containing 5–80 at. % Si using the oscillating drop method with electromagnetic levitation. Oxide-affected heating curves were excluded from the pyrometer calibration, and only oscillation data for which no oxide film was observed on the droplet surface were analyzed. For all examined compositions, the measured surface tension decreased linearly with increasing temperature. Near 1700 K, the surface tension decreased monotonically and nearly linearly with increasing Si concentration, and previously reported nonlinear behaviors, such as relatively high values in the Al-rich region and an increase toward the Si-rich side, were not observed. Uncertainty analysis confirmed that the nearly linear composition dependence was not due to measurement uncertainty. Butler equation calculations were performed using the pure-component surface tension values obtained in this study. The ideal-solution approximation reproduced the measured composition dependence and temperature coefficients more consistently than the subregular-solution calculation using the evaluated excess Gibbs energies. These results indicate that thermodynamic nonideality makes only a limited contribution to the surface tension behavior of molten Al–Si alloys under the present experimental conditions.

Keywords: surface tension, Al–Si alloys, electromagnetic levitation, Butler equation, ideal-solution approximation.

1. Introduction

Al–Si alloys are widely used in high-temperature melt-processing applications such as casting and brazing. In these processes, surface tension plays an important role in melt flow, capillary-driven infiltration, mold filling, joint formation, and defect formation. Reliable data on the temperature and composition dependences of surface tension are therefore essential for quantitative modeling and numerical simulation of such processes.

However, the surface tension data for molten Al–Si alloys reported in the literature are not fully consistent [1,2]. Some studies have reported a nearly monotonic decrease in surface tension with increasing Si concentration, whereas others have reported relatively high values in the Al-rich region and an increase in the surface tension toward the Si-rich side. Furthermore, even the data reported for pure liquid Al and pure liquid Si show considerable scatter [2–14]. The differences in the experimental surface tension values and trends may be related to differences in the experimental conditions, data analysis procedures, sample purity, contamination from supporting materials, and oxygen-related effects at the melt surface. In particular, because liquid Al is highly susceptible to oxidation, surface oxidation or oxide film formation may affect the droplet shape and surface conditions, thereby contributing to the scatter in the reported data. However, the relatively high surface tension values reported in the Al-rich region and the increase in the surface tension toward the Si-rich side cannot be readily explained by simple oxygen adsorption alone because surface-active oxygen is generally expected to reduce, rather than increase, the surface tension of molten metals and alloys. In addition to these experimental factors, thermodynamic nonideality may also influence the composition dependence of the surface tension through changes in the surface composition.

Therefore, a comparison between the measured surface tension and thermodynamic calculations can be used to clarify whether the reported nonlinear composition dependences of surface tension reflect the thermodynamic behavior of molten Al–Si alloys or arise from experimental factors. However, the role played by thermodynamic nonideality in the surface tension of molten Al–Si alloys has not been elucidated to date.

In this study, surface tension measurements were conducted for pure liquid Al, pure liquid Si, and molten Al–Si alloys using the oscillating drop method with electromagnetic

levitation (EML). This method enables container-free measurements and minimizes contamination from the supporting materials. To elucidate the composition dependence of the surface tension in the Al–Si system and evaluate the role of thermodynamic nonideality, the measured values were compared with Butler equation calculations using the pure-component surface tensions obtained in this study. Calculations were performed using both the evaluated excess Gibbs energies and the ideal-solution approximation to examine how thermodynamic nonideality affects the surface tension of molten Al–Si alloys.

2. Experimental Procedure

High-purity aluminum (>99.99 mass%) and silicon (electrical resistivity: $1.2 \times 10^{-2} \Omega \cdot \text{cm}$) were used as starting materials. Small pieces of Al and Si were cut and ultrasonically cleaned in a hydrofluoric-nitric acid solution ($\text{HF}:\text{HNO}_3 = 1:3$ by volume) to remove surface oxides and then rinsed with acetone. For alloy measurements, one piece each of Al and Si was placed on a quartz holder in the EML chamber.

A high-purity Ar–He gas mixture with an oxygen partial pressure, P_{O_2} , of 10^{-2} Pa was continuously supplied to the chamber at a flow rate of $2 \text{ L} \cdot \text{min}^{-1}$. First, the Al sample was electromagnetically levitated and melted by applying a high-frequency current to the coil. The Si sample was then brought into contact with the levitated Al droplet, and the two pieces were levitated together. The Si sample subsequently melted into the Al melt to form a single alloy droplet under container-free conditions. Nominal alloy compositions were calculated from the initial masses of Al and Si. The maximum mass loss during the measurements was less than 0.25% of the initial sample mass, corresponding to less than 1 mg for the 400 mg sample. Assuming that the entire mass loss originated from the evaporation of either Al or Si, the resulting change in the alloy composition was estimated to be less than 0.3 at.% for all alloy compositions examined in this study. This value is much smaller than the composition intervals of the measurements. Therefore, the effect of the mass loss on the alloy composition was considered to be negligible.

The droplet temperature was measured using a monochromatic pyrometer with a wavelength range of $\lambda = 1.45\text{--}1.6 \mu\text{m}$ and controlled by adjusting the Ar/He gas flow ratio.

For the emissivity calibration, the droplet was temporarily solidified by switching the atmosphere from the Ar–He gas mixture to He gas at an increased flow rate of $10 \text{ L} \cdot \text{min}^{-1}$, followed by reheating. During reheating, a distinct inflection point corresponding to the completion of melting was observed in the pyrometer signal. The emissivity setting of the pyrometer was adjusted such that the apparent temperature at this inflection point matched the equilibrium liquidus temperature, T_L , of each Al–Si alloy. Only the heating curves for which no oxide was observed within the pyrometer measurement spot in the high-speed video (HSV) images were used for this calibration. This is because the higher emissivity of the oxide compared to the molten alloy gives rise to an overestimation of the apparent temperature when the oxide is present within the pyrometer spot.

After the stabilization of the droplet temperature, the droplet oscillations were recorded using an HSV camera at 500 fps for 8192 frames (16.384 s). Only the HSV data for which no detectable oxide film was observed on the droplet surface were used for the frequency analysis. The frequencies of the surface oscillations ($m = 0, \pm 1$, and ± 2 for the $l = 2$ mode) and those of the translational oscillations ($m = 0$ and ± 1 for the $l = 1$ mode) were determined from the HSV time-series data using the fast Fourier transform (FFT). The analysis accounted for apparent rotations arising from the phase differences between the $m = +1$ and $m = -1$ oscillations and between the $m = +2$ and $m = -2$ oscillations, as well as actual droplet rotation [15]. The surface tension of the molten samples, σ , was calculated from the measured frequencies using the Rayleigh equation [16] with the Cummings and Blackburn correction [17]:

$$\sigma = \frac{3}{8}\pi M \left\{ \frac{1}{5} \sum_{m=-2}^2 f_{2,m}^2 - 1.905 f_t^2 + 1.200 \frac{G^2}{64\pi^4 f_t^2} \left(\frac{4\pi\rho}{3M} \right)^{\frac{2}{3}} \right\} [\text{N} \cdot \text{m}^{-1}], \quad (1)$$

$$f_t = \frac{1}{3} \sum_{m=-1}^1 f_{1,m} [\text{Hz}], \quad (2)$$

where M is the sample mass, $f_{2,m}$ are the frequencies of the $l = 2$ surface oscillation mode, f_t is the translational frequency, G is the gravitational acceleration, and ρ is the droplet density. Assuming ideal mixing of the molar volume [18,19], the droplet density

was calculated by neglecting the excess volume as described by:

$$\rho_{\text{AlSi}}(T) = \frac{x_{\text{Al}}M_{\text{Al}}^{\text{mol}} + x_{\text{Si}}M_{\text{Si}}^{\text{mol}}}{x_{\text{Al}}V_{\text{Al}}(T) + x_{\text{Si}}V_{\text{Si}}(T)} \quad [\text{kg} \cdot \text{m}^{-3}], \quad (3)$$

where x_i is the mole fraction of component i , M_i^{mol} is the molar mass, and $V_i(T)$ is the molar volume of pure liquid component i (Al or Si) at temperature T . $V_i(T)$ was calculated from the reported density $\rho_i(T)$ [20, 21] using

$$V_i(T) = \frac{M_i^{\text{mol}}}{\rho_i(T)}. \quad (4)$$

3. Results

3.1. Surface tensions of pure liquid Al and pure Si

Figures 1 and 2 show the temperature dependence of the surface tensions of pure liquid Al and pure liquid Si, respectively, measured by the oscillating drop method using EML, together with the literature values [2–14]. In this study, the measurement temperature ranges were approximately 1330–2120 K for pure Al and 1430–2180 K for pure Si. For both pure melts, the surface tension decreased linearly with increasing temperature. The temperature dependences were fitted by least-squares and are expressed as follows:

$$\sigma_{\text{Al}} = 878.7 - 0.105(T - 933) \quad [10^{-3}\text{N} \cdot \text{m}^{-1}] \quad (5)$$

$$\sigma_{\text{Si}} = 742.9 - 0.084(T - 1687) \quad [10^{-3}\text{N} \cdot \text{m}^{-1}] \quad (6)$$

where T is temperature in K. The intercepts of Eqs. (5) and (6) correspond to the surface tension values at the melting temperatures of Al and Si, respectively. The results for pure liquid Al are in good agreement with those reported by Kobatake et al. [2], Giuranno et al. [5], and Brillo et al. [6], while the results for pure liquid Si are consistent with the values reported by Rhim et al. [11] and the values obtained in our previous study [14]. Eqs. (5) and (6) were used to calculate the values of the pure-component surface tensions in the Butler equation calculations described below.

3.2. Surface tension of molten Al–Si alloys

Figure 3 shows the temperature dependence of the surface tension of the molten Al–Si alloys, together with the results for pure Al and pure Si. For all alloy compositions, the surface tension decreased linearly with increasing temperature, as observed for the pure melts. At a given temperature, the surface tension decreased with increasing Si concentration. The measured data were fitted by the linear least-squares method using the liquidus temperature, T_L , of each composition as the reference temperature. The resulting surface tensions at T_L and temperature coefficients are summarized in Table 1; the uncertainty in σ_L was evaluated based on the Guide to the Expression of Uncertainty in Measurement (GUM) [22], as described in Section 4.1, and the uncertainty in $d\sigma/dT$ represents the standard error of the slope obtained from the least-squares fit.

Figure 4 shows the composition dependence of the surface tension of molten Al–Si alloys using the data obtained in the temperature range of 1700 ± 20 K together with literature values [1,2] used for comparison. Based on the measured temperature coefficients, this temperature range corresponds to the variation in the surface tension of approximately $\pm 2 \times 10^{-3} \text{ N}\cdot\text{m}^{-1}$, which is considerably smaller than the expanded uncertainty of the surface-tension measurements. The surface tension decreased monotonically with increasing Si concentration and exhibited an approximately linear dependence on the composition. Within the uncertainty of the present measurements, neither an increase in the Si-rich region reported by Kobatake et al. [2] nor the relatively high values in the Al-rich composition range reported by Shen et al. [1] were observed. No clear deviation from the approximately linear composition dependence was observed, even near the eutectic composition.

4. Discussion

The present measurements revealed a monotonic and nearly linear decrease in the surface tension with increasing Si concentration, in contrast to some previous reports, which showed relatively high values in the Al-rich region and an increase toward the Si-rich side. To assess whether the observed composition dependence can be resolved beyond the experimental uncertainty and whether it reflects the intrinsic composition

dependence of the molten Al–Si system, the uncertainty of the present measurements was evaluated, and the measured composition dependence was analyzed using the Butler equation to examine the role of thermodynamic nonideality.

4.1. Uncertainty in surface tension measurements

The uncertainty in the surface tension measurements of the molten Al–Si alloys in this study was evaluated according to GUM [22]. The combined standard uncertainty of the surface tension, $u_c(\sigma)$, is given by

$$u_c(\sigma) = \sqrt{\sum_i \left[\left(\frac{\partial \sigma}{\partial q_i} \right) u(q_i) \right]^2}, \quad (7)$$

where q_i is the input quantity, and $u(q_i)$ is its standard uncertainty. The sample mass, M , the frequencies of the $l = 1$ and $l = 2$ oscillation modes, $f_{l,m}$, and the droplet density, ρ , were considered sources of uncertainty. $u(M)$ was evaluated based on the calibration, resolution, and weighing reproducibility of the electronic balance. $u(f_{l,m})$ was evaluated based on the time resolution of the high-speed camera and the reproducibility of the frequency analysis of the free-oscillation data recorded seven times under identical conditions. $u(\rho)$ was evaluated based on Eq. (3) by applying the law of propagation of uncertainty to the relevant input quantities, including the reported uncertainties in the densities of the pure liquid components, $\rho_i(T)$ [20,21]. The expanded uncertainty, U , was obtained by applying a coverage factor $k = 2$ to the combined standard uncertainty $u_c(\sigma)$.

Table 2 presents the uncertainty budgets for the data points with the highest uncertainty. The maximum expanded uncertainty was evaluated as $U = \pm 14.3 \times 10^{-3} \text{ N} \cdot \text{m}^{-1}$, corresponding to approximately 2% of the measured surface tension value. No systematic deviation from the nearly linear composition dependence is observed within the expanded uncertainties of the measured values. This result indicates that the monotonic and nearly linear decrease in the surface tension with increasing Si concentration is a robust feature of the present measurements rather than an apparent trend arising from measurement uncertainty.

4.2. Evaluation of surface tension behavior using the Butler model

In the present measurements, the surface tension of the molten Al–Si alloys decreased linearly with increasing temperature, and the surface tension measured near 1700 K decreased nearly linearly with increasing Si concentration. However, these experimental trends alone do not clarify how thermodynamic nonideality affects the surface composition and the resulting surface tension. Therefore, the measured data were analyzed using the Butler equation [23], which assumes chemical-potential equilibrium between the surface and bulk liquid phases. According to the Butler equation, the surface tension of the molten Al–Si alloys, σ_{AlSi} , is expressed in terms of the pure liquid components, Al and Si as

$$\begin{aligned}\sigma_{\text{AlSi}} &= \sigma_{\text{Al}} + \frac{RT}{A_{\text{Al}}} \ln \frac{x_{\text{Al}}^{\text{s}}}{x_{\text{Al}}^{\text{b}}} + \frac{G_{\text{Al}}^{\text{ex,s}}(T, x_{\text{Al}}^{\text{s}}) - G_{\text{Al}}^{\text{ex,b}}(T, x_{\text{Al}}^{\text{b}})}{A_{\text{Al}}} \\ &= \sigma_{\text{Si}} + \frac{RT}{A_{\text{Si}}} \ln \frac{x_{\text{Si}}^{\text{s}}}{x_{\text{Si}}^{\text{b}}} + \frac{G_{\text{Si}}^{\text{ex,s}}(T, x_{\text{Si}}^{\text{s}}) - G_{\text{Si}}^{\text{ex,b}}(T, x_{\text{Si}}^{\text{b}})}{A_{\text{Si}}}.\end{aligned}\quad (8)$$

Here, R is the gas constant, x_i is the mole fraction of component i , and G_i^{ex} is the partial molar excess Gibbs energy of component i . Superscripts b and s indicate the bulk and surface phases, respectively.

The molar surface area, A_i , was calculated as

$$A_i = 1.091 N_{\text{A}}^{1/3} V_i^{2/3}, \quad (9)$$

where N_{A} is Avogadro's number and V_i is the molar volume of pure liquid component i . Assuming a surface-to-bulk coordination parameter $\beta = 0.83$ [24], the excess Gibbs energy of the surface phase was approximated as

$$G_i^{\text{ex,s}}(T, x_i^{\text{s}}) = \beta G_i^{\text{ex,b}}(T, x_i^{\text{s}}). \quad (10)$$

The surface composition and surface tension were determined by numerically solving Eq. (8) using Eqs. (9) and (10) under the constraint

$$x_{\text{Al}}^{\text{s}} + x_{\text{Si}}^{\text{s}} = 1. \quad (11)$$

Two calculations were performed: the first calculation was based on a subregular-solution model using the evaluated thermodynamic parameters for the bulk phase [25], and the

second approach was based on the ideal-solution approximation in which

$$G_i^{\text{ex,b}} = G_i^{\text{ex,s}} = 0. \quad (12)$$

Figure 5 compares the surface tensions measured near 1700 K with those calculated using the Butler equation at 1700 K. The calculation temperature was selected to facilitate comparison with the literature data reported near 1700 K. The subregular-solution calculation predicted a slight positive curvature in the composition dependence, whereas no systematic deviation corresponding to this curvature was observed within the expanded uncertainties of the measured values. In contrast, the ideal-solution approximation was more consistent with the present measurements and reproduced the nearly linear dependence reasonably well.

Figure 6 compares the measured temperature dependence of the surface tension with the values calculated using the Butler equation under the ideal-solution approximation for molten Al–Si alloys with different Si concentrations. The ideal-solution approximation reproduced the composition dependence near 1700 K as well as the temperature coefficients of the surface tension for each alloy composition. These results suggest that thermodynamic nonideality makes only a limited contribution to the observed surface tension behavior of the molten Al–Si alloys under the present experimental conditions.

Consequently, the relatively high values in the Al-rich region and the increase toward the Si-rich side reported in previous work are unlikely to arise solely from the intrinsic thermodynamic composition dependence of the molten Al–Si alloys. Rather, the discrepancies among the reported data may reflect differences in experimental conditions, data analysis procedures, sample purity, oxide-related effects, or contamination from supporting materials.

5. Summary

The surface tensions of pure liquid Al, pure liquid Si, and molten Al–Si alloys containing 5–80 at. % Si were measured by the oscillating drop method using EML. For all examined compositions, the surface tension decreased linearly with increasing temperature. The surface tension measured near 1700 K decreased monotonically and nearly linearly with increasing Si concentration, and the nonlinear behavior reported in some previous studies

was not observed within the uncertainty of the present measurements.

Thermodynamic analysis based on the Butler equation showed that the ideal-solution approximation reasonably reproduced both the measured composition dependence and the temperature coefficients of the surface tension. These results indicate that, within the framework of the Butler model used in this study, thermodynamic nonideality makes only a limited contribution to the surface tension behavior of molten Al–Si alloys. The previously reported relatively high surface tension values in the Al-rich region and the increase in the surface tension toward the Si-rich side are therefore difficult to attribute solely to the intrinsic thermodynamic composition dependence of molten Al–Si alloys.

Declarations

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Competing interests

The authors declare that they have no competing interests.

Author contributions

Y.S.: conceptualization, methodology, investigation, formal analysis, visualization, and writing – original draft. S.O.: conceptualization, supervision, writing – review and editing, and project administration. H.Y.: investigation and methodology. All authors contributed to the discussion of the results and approved the final version of the manuscript.

Data availability

The data supporting the findings of this study are available from the corresponding author upon reasonable request.

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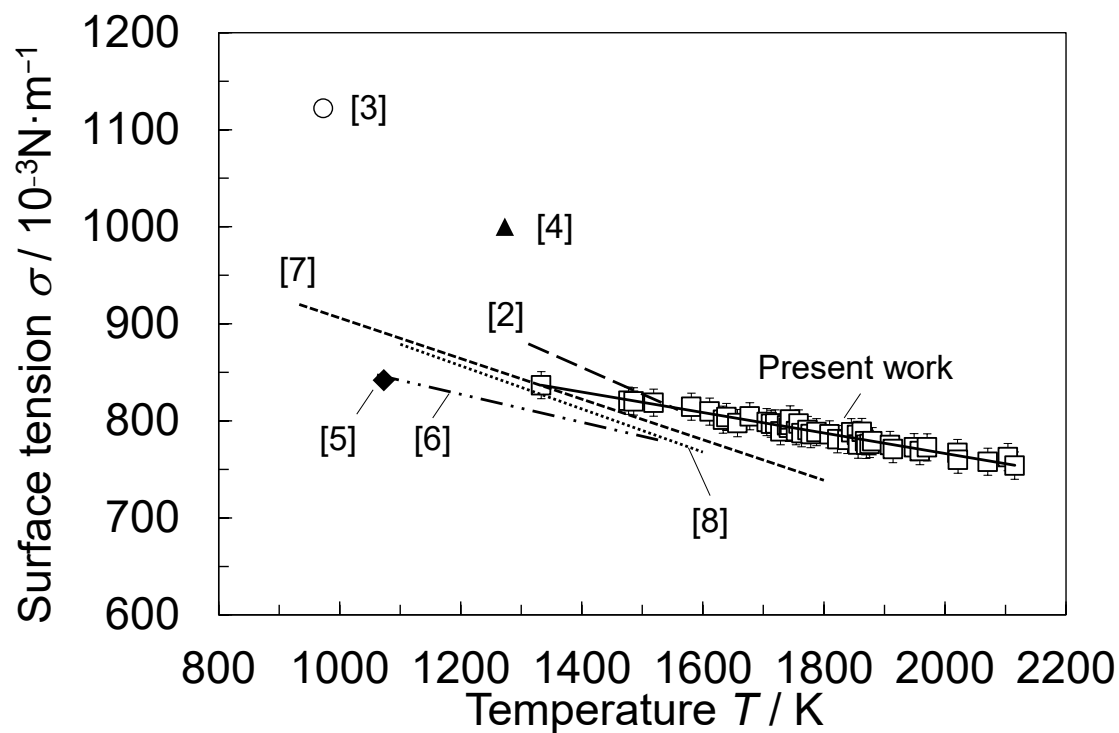
Table 1 Surface tension at the liquidus temperature and temperature coefficient for molten Al–Si alloys.

Sample	Liquidus temp. T_L , [K]	Surface tension σ_L , [$10^{-3}\text{N}\cdot\text{m}^{-1}$]	Temperature coefficient $d\sigma/dT$, [$10^{-3}\text{N}\cdot\text{m}^{-1}\text{K}^{-1}$]	Temperature range [K]
Al	933	878.7 ± 13.2	-0.105 ± 0.003	1333–2115
Al–5 at. %Si	898	878.8 ± 14.3	-0.107 ± 0.003	1475–1991
Al–10 at. %Si	863	873.7 ± 13.8	-0.103 ± 0.004	1476–1981
Al–20 at. %Si	964	855.5 ± 12.9	-0.099 ± 0.003	1421–2076
Al–40 at. %Si	1210	821.2 ± 12.6	-0.095 ± 0.003	1510–2117
Al–60 at. %Si	1412	788.7 ± 13.6	-0.091 ± 0.003	1371–2118
Al–80 at. %Si	1572	764.7 ± 12.9	-0.090 ± 0.005	1561–2135
Si	1687	742.9 ± 12.4	-0.084 ± 0.002	1426–2174

Table 2 Uncertainty budget for the surface tension measurement of molten Al–Si alloys for the largest calculated uncertainty.

Source of uncertainty	Input quantity, q_i	Standard uncertainty, $u(q_i)$	Sensitivity coefficient, c_i	Uncertainty contribution, $u_\sigma(q_i)$
Calibration of balance	M	5×10^{-9} kg	1448 s^{-2}	$7.24 \times 10^{-6} \text{ N}\cdot\text{m}^{-1}$
Resolution of balance	M	2.89×10^{-8} kg	1448 s^{-2}	$4.18 \times 10^{-5} \text{ N}\cdot\text{m}^{-1}$
Reproducibility of mass measurement	M	4.22×10^{-8} kg	1448 s^{-2}	$6.11 \times 10^{-5} \text{ N}\cdot\text{m}^{-1}$
Frequency resolution of FFT analysis	$f_{1,-1}$	1.76×10^{-2} Hz	$3.00 \times 10^{-3} \text{ kg}\cdot\text{s}^{-1}$	$5.28 \times 10^{-5} \text{ N}\cdot\text{m}^{-1}$
	$f_{1,0}$	1.76×10^{-2} Hz	$2.86 \times 10^{-3} \text{ kg}\cdot\text{s}^{-1}$	$5.04 \times 10^{-5} \text{ N}\cdot\text{m}^{-1}$
	$f_{1,+1}$	1.76×10^{-2} Hz	$4.40 \times 10^{-3} \text{ kg}\cdot\text{s}^{-1}$	$7.74 \times 10^{-5} \text{ N}\cdot\text{m}^{-1}$
	$f_{2,0}$	1.76×10^{-2} Hz	$1.00 \times 10^{-3} \text{ kg}\cdot\text{s}^{-1}$	$1.77 \times 10^{-4} \text{ N}\cdot\text{m}^{-1}$
	$f_{2,\pm 1}$	1.76×10^{-2} Hz	$3.97 \times 10^{-2} \text{ kg}\cdot\text{s}^{-1}$	$7.00 \times 10^{-4} \text{ N}\cdot\text{m}^{-1}$
	$f_{2,\pm 2}$	1.76×10^{-2} Hz	$3.87 \times 10^{-2} \text{ kg}\cdot\text{s}^{-1}$	$6.82 \times 10^{-4} \text{ N}\cdot\text{m}^{-1}$
	$f_{1,-1}$	3.90×10^{-2} Hz	$3.00 \times 10^{-3} \text{ kg}\cdot\text{s}^{-1}$	$1.17 \times 10^{-4} \text{ N}\cdot\text{m}^{-1}$
	$f_{1,0}$	2.66×10^{-2} Hz	$2.86 \times 10^{-3} \text{ kg}\cdot\text{s}^{-1}$	$7.62 \times 10^{-5} \text{ N}\cdot\text{m}^{-1}$
	$f_{1,+1}$	7.63×10^{-2} Hz	$4.40 \times 10^{-3} \text{ kg}\cdot\text{s}^{-1}$	$3.36 \times 10^{-4} \text{ N}\cdot\text{m}^{-1}$
	$f_{2,0}$	1.73×10^{-2} Hz	$1.00 \times 10^{-2} \text{ kg}\cdot\text{s}^{-1}$	$1.76 \times 10^{-4} \text{ N}\cdot\text{m}^{-1}$
Reproducibility of frequency identification	$f_{2,\pm 1}$	1.47×10^{-1} Hz	$3.97 \times 10^{-2} \text{ kg}\cdot\text{s}^{-1}$	$5.82 \times 10^{-3} \text{ N}\cdot\text{m}^{-1}$
	$f_{2,\pm 2}$	1.03×10^{-1} Hz	$3.87 \times 10^{-2} \text{ kg}\cdot\text{s}^{-1}$	$3.99 \times 10^{-3} \text{ N}\cdot\text{m}^{-1}$
Standard uncertainty of droplet density [20,21]	ρ	$13.7 \text{ kg}\cdot\text{m}^{-3}$	$5.90 \times 10^{-6} \text{ m}^3\cdot\text{s}^{-2}$	$8.07 \times 10^{-5} \text{ N}\cdot\text{m}^{-1}$
Combined standard uncertainty, $u_c(\sigma) = 7.14 \times 10^{-3} \text{ N}\cdot\text{m}^{-1}$				
Expanded uncertainty, $U = 14.3 \times 10^{-3} \text{ N}\cdot\text{m}^{-1}$ (coverage factor $k = 2$)				

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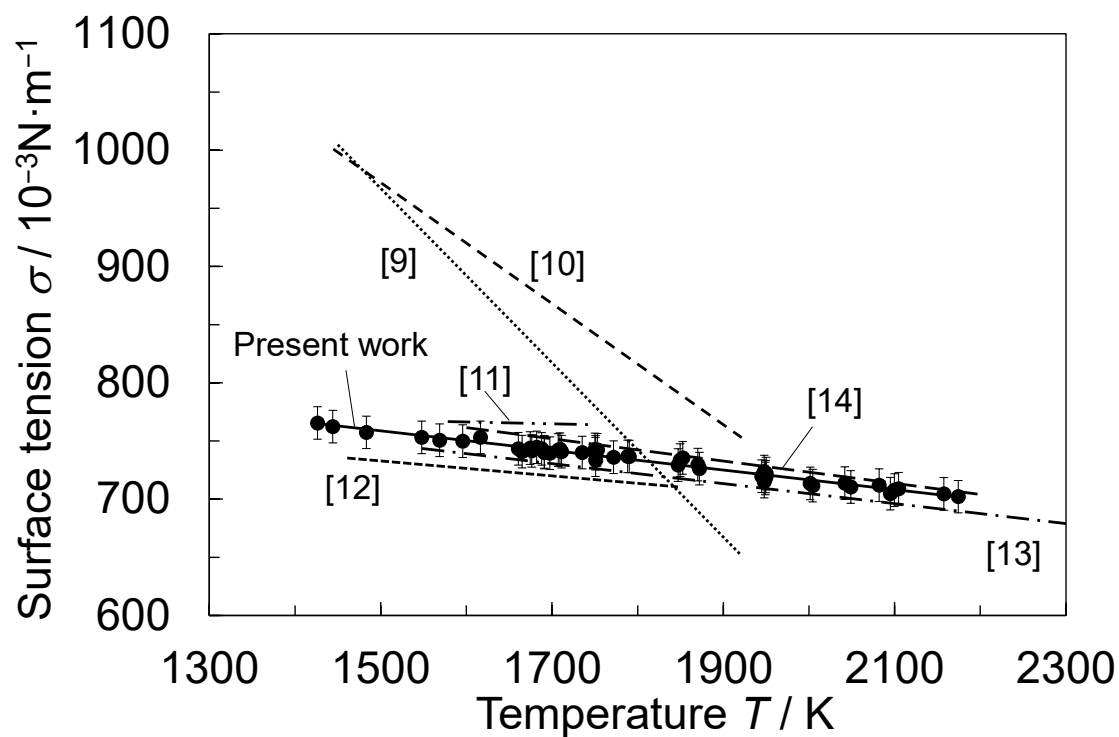


378

379 Fig. 1 Measured surface tension of molten pure aluminum plotted as a function of
 380 temperature and compared with literature values

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383

384 Fig. 2 Measured surface tension of molten pure silicon plotted as a function of
 385 temperature and compared with literature values.

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387

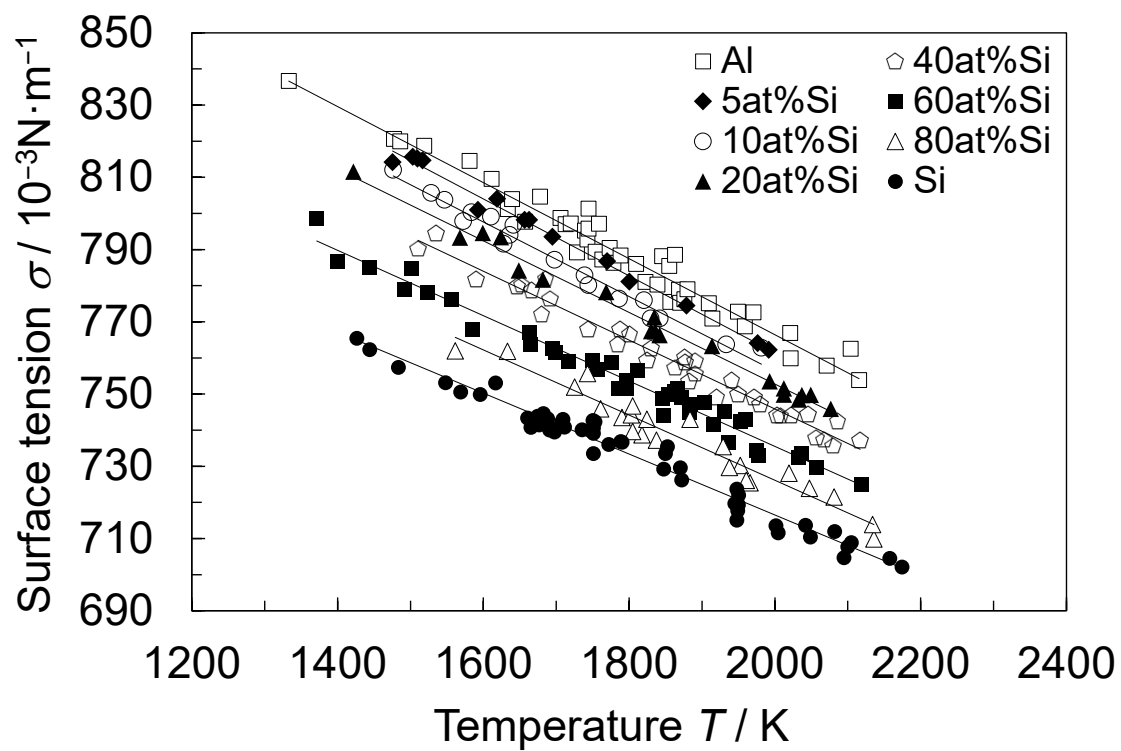


Fig. 3 Temperature dependence of the surface tension for molten Al-Si alloys.

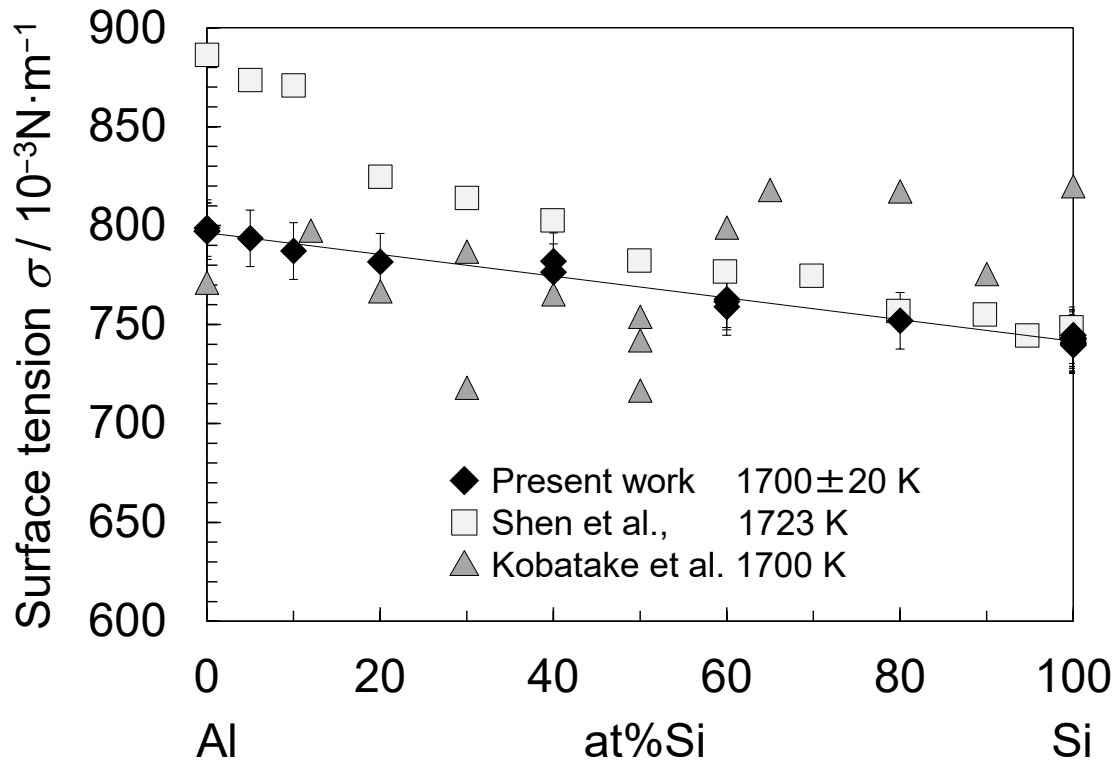


Fig. 4 Composition dependence of the surface tension measured at $1700 \pm 20 \text{ K}$ for molten Al-Si alloys compared with literature values [1,2].

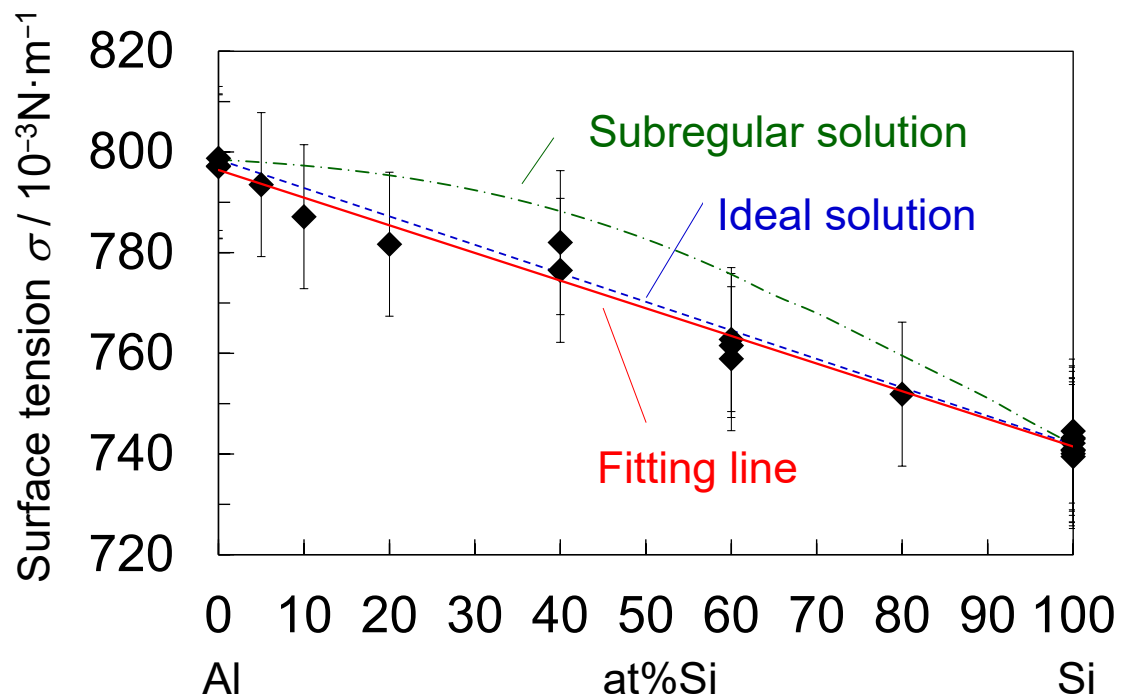
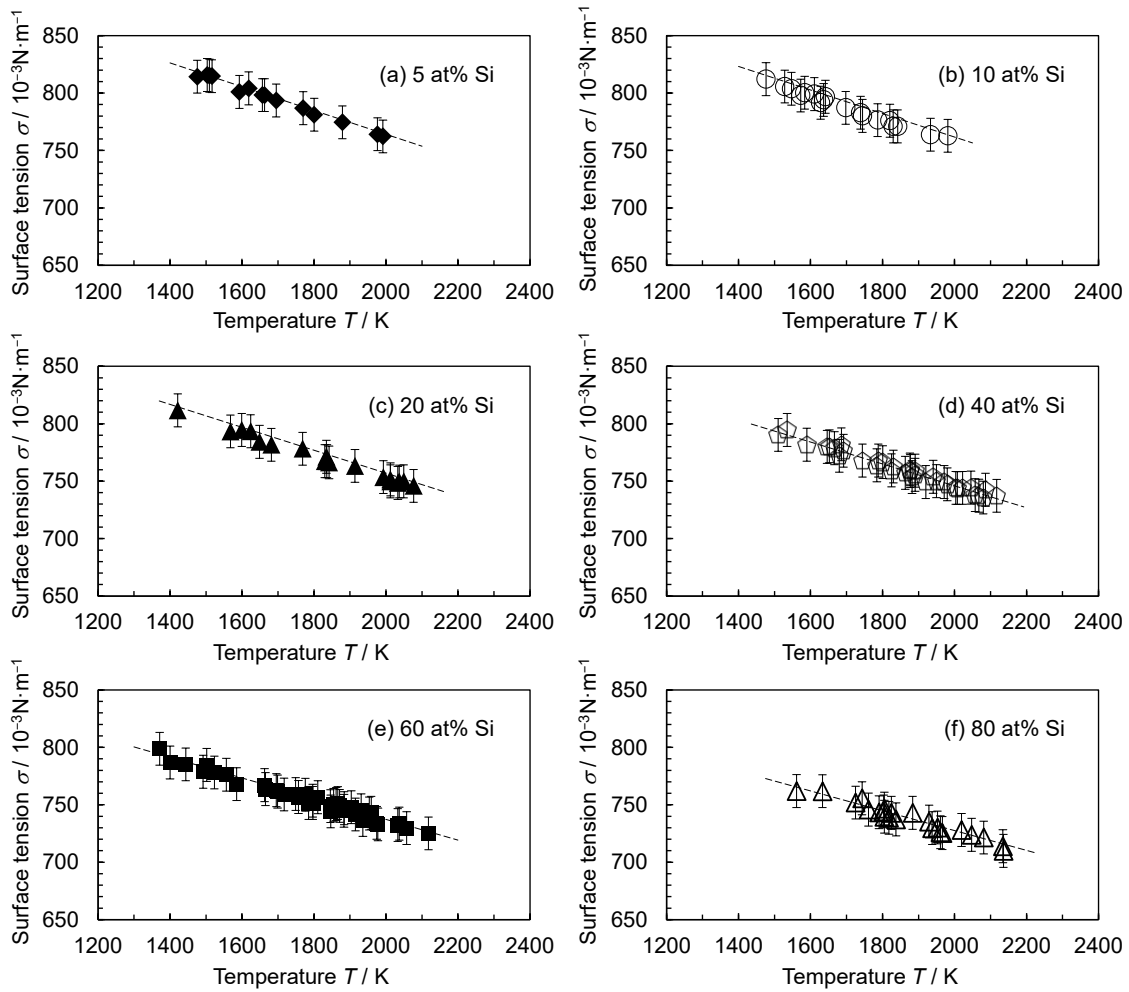


Fig. 5 Comparison of the surface tension values measured at 1700 ± 20 K for molten Al–Si alloys with the values calculated using the Butler equation at 1700 K. The solid line represents the linear fit to the measured data.



404

405 Fig. 6 Comparison of the measured temperature dependences of the surface tension of
 406 molten Al-Si alloys with those calculated using the ideal-solution approximation. The
 407 symbols and dashed lines represent the measured and calculated values, respectively.

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