Available online at www.sciencedirect.com

ScienceDirect

Procedia CIRP 124 (2024) 590–593

www.elsevier.com/locate/procedia

13th CIRP Conference on Photonic Technologies [LANE 2024], 15-19 September 2024, Fürth, Germany

Surface tension of falling droplets at high temperature

Joerg Volpp[1,2]*

[1]Department of Mechanical Engineering, University West, 46132 Trollhättan, Sweden
[2]Department of Engineering Sciences and Mathematics, Luleå University of Technology, 97187 Luleå, Sweden

* Corresponding author. Tel.: +46 701811639; *E-mail address:* jorg.volpp@hv.se

---

Abstract

Surface tension is an essential parameter that defines many aspects of materials processing. In particular, at high temperatures, surface tension data of metals is missing. Due to the challenges during high temperature measurements, mainly extrapolated or theoretical data are available. Therefore, an adaption of the falling oscillating droplet method is suggested to derive surface tension values of liquid steel surfaces. A spherical droplet was pre-positioned on plastic foil to be melted by a laser beam. During falling, high-speed imaging could record the oscillations and related frequency spectra were derived. Based on extracted characteristic frequencies, surface tension values were obtained comparing different theoretical models and adaptions to impacts of gravity, asphericity and viscosity of the material. The method was shown to give reasonable values of surface tension when accounting for gravity impacts.

Keywords: Laser; heating; oscillating drop; surface tension; melting

---

1. Introduction

Surface tension is an important thermophysical property of materials. It contributes to many effects during laser materials processing, e.g. wetting during laser beam brazing, Marangoni flow during laser beam welding or vapor capillary stability during deep penetration welding. Since those processes require high temperatures, material properties are relevant to know also at temperatures above melting temperature of the metals. Although theoretical models can predict several aspects of temperature dependent surface tension effects, predictions can show high uncertainties. Therefore, often approximations or linear extrapolations from theoretical or experimental data are used to estimate the surface tension [1]. The main reason for the lack of surface tension data are the difficulties related to the measurement equipment that is exposed to high temperatures. Both temperature measurement and surface tension measurement methods are challenging for liquid metals.

However, some methods can be also used for high temperature surface tension measurements, e.g. the maximum bubble pressure method, surface wave analysis [2,3], levitated [4,5] or falling drop oscillations [6]. Regarding the falling drop method, the fundamental oscillation mode and frequency need to be identified to relate the frequency to a surface tension value (e.g. [7]). The measuring method has been improved to consider the influences of e.g. viscosity, gravity or rotation of the droplets.

This paper aims to clarify which oscillation frequencies of falling liquid metal drops at high temperatures need to be identified to calculate the surface tension by comparing different calculation methods considering different effects.

2. Methodology

The fundamental frequency (oscillation mode l=2) of a levitated droplet is the Rayleigh frequency ω_R calculated to

10.1016/j.procir.2024.08.180

$$\omega_R^2 = \frac{32\pi}{3}\frac{\gamma}{M} \tag{1}$$

with the surface tension γ, sample mass $M = \rho \cdot V$ and the frequency $f = \omega/(2\pi)$. Since on earth, the droplet is not free from external forces, the Rayleigh frequency splits up into three unequally spaced peaks (m=-2;-1;0;1;2) [8]. Shih & Stroud [9] suggest an adaptation to the rotation of the droplet by adding the term $m/l \cdot f_{rot}$ to each of the five frequencies. The rotational frequency f_{rot} can be derived from the recording of the droplet. In addition, the effect of viscosity need to be considered and can be corrected using [7]

$$f_{visc} = \sqrt{f^2 + \left(\frac{2\pi}{\tau}\right)^{-2}} \tag{2}$$

with the frequency f and the damping coefficient τ.

Cummings and Blackburn [10] suggested a sum formula to derive the adapted Rayleigh frequency to

$$\omega_R^2 = \frac{1}{5}\sum_m \omega_{2,m}^2 - 1.9 \cdot f_{tr}^2 - 0.3 \cdot \frac{1}{f_{tr}^2} \cdot \left(\frac{g}{R_0}\right)^2 \tag{3}$$

with the translational frequency $f_{tr} = f_{main}/2$, the gravitational constant g and the average radius R_0. In addition, they [10] derived a formula to consider the translational oscillations of the whole sample and its asphericity by

$$f_{asph}^2 = \frac{1}{10}\left(3f_{max}^2 + 3f_{min}^2 + 4f_{middle}^2\right) - 2f_{trans}^2 \pm \frac{1}{10}\left(f_{max}^2 - f_{min}^2\right) \tag{4}$$

Based on the calculated frequency, the surface tension can be calculated to [7]

$$\gamma = \frac{3\pi\rho \cdot V \cdot f^2}{l \cdot (l-1) \cdot (l+2)} \tag{5}$$

with the droplet volume $V = 4/3 \cdot \pi \cdot R^3$ assuming a spherical droplet.

The Ohnesorge number is calculated with the dynamic viscosity of the material $\eta = \tau \cdot \rho \cdot R^2$, its density ρ and the actual radius R to

$$Oh = \frac{\eta}{\sqrt{\rho \cdot \gamma \cdot R}} \tag{6}$$

Table 1. Parameters for the calculation and experiments

Param.	Density ρ	Gravity const g	Laser power	Pulse length	Defocus
Value	7030 [11]	9.81	300	2	20
Unit	kg/m^3	m/s^2	W	s	mm

A falling drop experiment was installed. A drop of 44MnSiV6 steel material was pre-placed on a thin plastic foil and illuminated by the laser beam (Table 1). An IPG fiber laser (IPG YLR-15000) at a wavelength of 1070 nm was used. The defocusing resulted in a spot diameter of ~2.7 mm. The experiment was performed in a box filled with Argon to avoid oxidation. A high-speed camera was used to observe the falling droplet from the side (0°) at 10,000 fps and a shutter time of 10 µs (Fig. 1). The droplet was melted and oscillated during its flight. The horizontal and vertical diameter oscillations were extracted in the black/white images (threshold 0.7). In addition, the area of the droplet was measured in each frame by counting the white pixels.

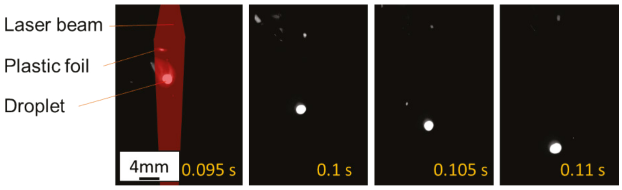

Fig. 1. High-speed imaging sequence of a falling droplet

The time series of the diameter and area oscillations were used to perform a Fourier transform and derive the frequency spectra. Those frequencies were used to calculate the surface tension using several methods.

3. Results

The evaluation of the horizontal, vertical and area oscillations show that the fundamental mode (l=2) is active (Fig. 2). The horizontal diameter and the area are the main axes that oscillate synchronized. The damping coefficient τ was derived from the normalized area oscillation as the factor in the exponent of the exponential fit of the amplitude decreases (Fig. 2).

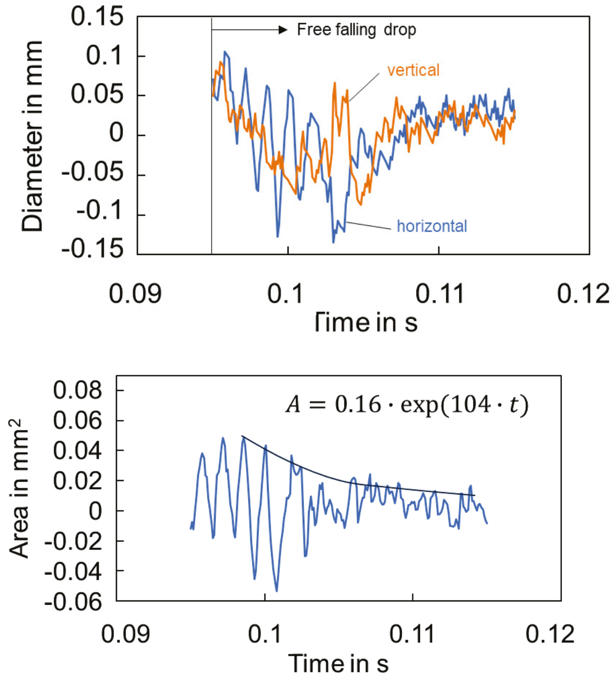

Fig. 2. Time series of the diameter (top) and area oscillations (bottom) around the median value including damping curve

From the frequency spectrum of the area oscillations, the characteristic frequencies relevant for the surface tension calculations were extracted (Fig. 3). The main frequency at 725 Hz is assumed to be split up in three peaks.

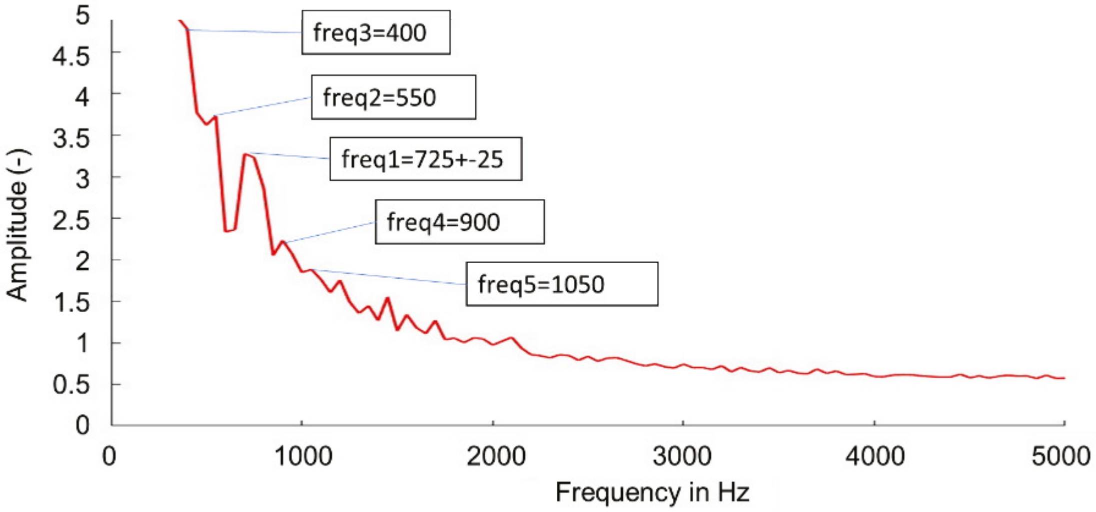

Fig. 3. Frequency spectrum of the area oscillations including characteristic frequencies

In the high-speed videos, no rotation of the droplet could be identified due to missing marks on the droplet surface that could indicate rotation. Therefore, for the surface tension calculations, the rotational frequency was assumed to be zero.

Surface tension values were calculated using different assumptions (spherical, gravity/rotation, viscosity corrected, aspherical) (Fig. 4). All Ohnesorge numbers Oh were <0.1, which justifies the use of the surface tension calculation formula [7].

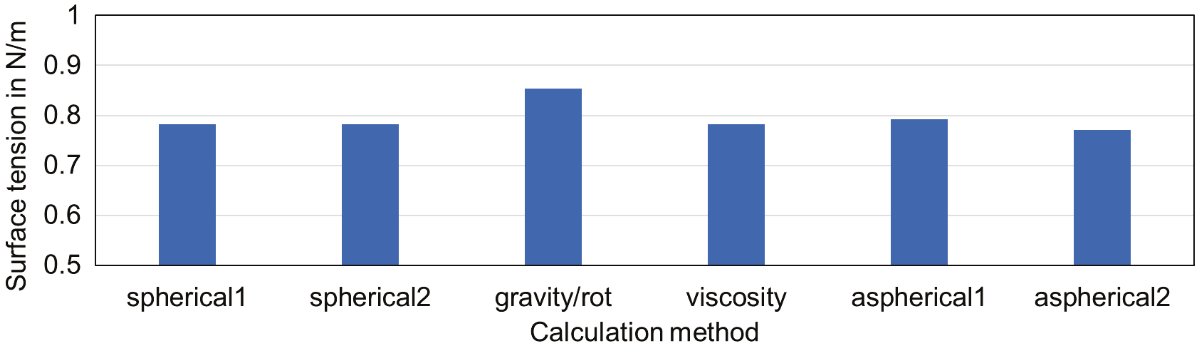

Fig. 4. Surface tension calculations (spherical1 from eq. 1 with freq1; spherical2 from eq. 5 with freq1; gravity/rotation including the rotational term and the viscosity adaption in eq. 2 to use eq. 3; aspherical1 using the positive and aspherical2 the negative part of eq. 4 to use eq. 5)

4. Discussion

Surface tension values were obtained from an oscillating falling metal droplet. The obtained values are comparable to previous surface wave measurements (Fig. 10 in [3]) for temperatures just below boiling (~2600 K). However, the derived value of 0.78 N/m is low compared to theoretical expectations. Morohoshi et al. [12] predicts a value of 1.56 N/m with a linear extrapolation. It can be assumed that the linear extrapolation from low temperature data is not sufficient to predict high temperature effects.

The different calculation methods lead to similar surface tension values of the falling droplets (Fig. 4). The assumption of having a spherical oscillating droplet seems to lead to a surface tension value comparable to after correcting the impact of viscosity or asphericity. Only the gravity impact (rotational frequency was not possible to detect from the videos) has a visible impact increasing the surface tension value by 0.07 N/m. For the small dimensions of the droplets, the gravity apparently significantly impacts the droplet shape, which requires corrections for its calculation.

5. Conclusions

The falling drop method including laser beam heating to derive surface tension values can be also used for high temperature steel droplets. Derived surface tension values are lower than linear extrapolations predict but are comparable to high temperature measurements in other works. It can be concluded that surface tension values closer to boiling temperature are lower than expected.

Acknowledgements

The author kindly acknowledges the funding of SMART—Surface tension of Metals Above vapoRization Temperature (Vetenskapsrådet—The Swedish Research Council, 2020-04250).

References

[1] Keene, B. J. (1993). Review of data for the surface tension of pure metals. International Materials Reviews, 38(4), 157-192.

[2] Kolevzon V (1998) Temperature dependence of surface tension and capillary waves at liquid metal surfaces. J Exp Theor Phys 87:1105–1109

[3] Volpp, J. (2023). Surface tension of steel at high temperatures. SN Applied Sciences, 5(9), 237.

[4] Trinh EH, Marston PL, Robey JL (1988) Acoustic measurement of the surface tension of levitated drops. J Coll. Interface Sci 124(1):95–103

[5] Egry, I., Lohöfer, G., Neuhaus, P., & Sauerland, S. (1992). Surface tension measurements of liquid metals using levitation, microgravity, and image processing. International journal of thermophysics, 13, 65-74.

[6] Matsumoto T, Fujii H, Ueda T, Kamai M, Nogi K (2005) Measurement of surface tension of molten copper using the free-fall oscillating drop method. Meas Sci Technol 16(2):432

[7] Kremer, J., Kilzer, A., & Petermann, M. (2018). Simultaneous measurement of surface tension and viscosity using freely decaying oscillations of acoustically levitated droplets. Review of Scientific Instruments, 89(1).

[8] Egry, I., Ricci, E., Novakovic, R., & Ozawa, S. (2010). Surface tension of liquid metals and alloys—Recent developments. Advances in colloid and interface science, 159(2), 198-212.

[9] Shih, W. H., & Stroud, D. (1985). Theory of the surface tension of liquid metal alloys. Physical Review B, 32(2), 804.

[10] Cummings, L, & Blackburn, DA (1991). Oscillations of magnetically levitated aspherical droplets. Journal of Fluid Mechanics, 224, 395-416.

[11] Tesfaye, F, Taskinen, P (2010). Densities of molten and solid alloys of (fe, cu, ni, co)-s at elevated temperatures-literature review and analysis.

[12] Morohoshi K, Uchikoshi M, Isshiki M, Fukuyama H (2011) Surface tension of liquid iron as functions of oxygen activity and temperature. ISIJ Int 51(10):1580–1586