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Lorentz force sigmometry: a novel technique for measuring the electrical conductivity of solid and liquid metals

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Abstract
In this paper, a novel method to measure the electrical conductivity of solid and molten metals is described. We term the method 'Lorentz force sigmometry', where the term 'sigmometry' refers to the letter sigma σ, often used to denote the electrical conductivity. The Lorentz force sigmometry method is based on the phenomenon of eddy currents generation in a moving conductor exposed to a magnetic field. Based on Ampere's law, the eddy currents in turn generate a secondary magnetic field; as a result, the Lorentz force acts to brake the conductor. Owing to Newton's third law, a measurable force, which is equal to the Lorentz force and is directly proportional to the electrical conductivity of the conductive fluid or solid, acts on the magnet. We present the results of the measurements performed on solids along with the initial measurements on fluids with a eutectic alloy composition of $Ga^{67}In^{20.5}Sn^{12.5}$; detailed measurements on molten metals are still in progress and will be published in the future. We conducted a series of experiments and measured the properties of known electrical conductive metals, including aluminum and copper, to compute the calibration factor of the device, and then used the same calibration factor to estimate the unknown electrical conductivity of a brass bar. The predicted electrical conductivity of the brass bar was compared with the conductivity measured with a commercial device called 'SigmaTest'; the observed error was less than 0.5%.

Keywords: electrical conductivity, inductive method, magnetohydrodynamics, solid metals, molten metals

(Some figures may appear in colour only in the online journal)

1. Introduction

In the industry, the knowledge of physical properties of molten metals (such as electrical conductivity, density, viscosity, and surface tension) is required for a proper optimization and control of the metallurgical processes. Until now, these properties are measured in metallurgy with an uncertainty of 10% or higher [1, 2]. Among all these properties, electrical conductivity is of particular interest because it helps determine the local skin depth of metal melts, which affects the energy efficiency of the electromagnetic processing of materials, including electromagnetic stirring [3]. Electromagnetic flow measurement techniques are base on the assumption that the electrical conductivity of the object is known [4, 5]. Sometimes, the electrical conductivity can be indirectly considered when measuring the velocity of a molten metal by the Lorentz force method [6]. Furthermore, the knowledge of the electrical conductivity of a molten metal helps draw inferences about the electronic transport properties and the structural heterogeneity of the metal [7]. Previous methods adopted to measure the electrical conductivity of both solid and molten metals can be divided in three groups:

- contact measurements
- containerless and contactless measurements
- contactless inductive measurements.

In the first group, the sensor, made of two or four probes, is in direct contact with the sample [8–10]. These probes are usually made of platinum, molybdenum, etc, and they measure the potential drops of the constant current that has been applied on the molten metal sample. As certain hot and aggressive molten metals may undergo dissolution and chemical reaction, there is no proper material for the probes to measure. This problem can be solved by using a measurement method from the second or third group.

In the second group, electromagnetic levitation is used to measure the physical properties of the sample. In this method, the sample is levitated in air by a physical force (Lorentz force) against gravity; thus, it is a containerless method. Then, an inductive method from the third group is used to measure the electrical conductivity of the sample. The sample is placed in an alternating magnetic field inside a radiofrequency current carried on the primary coil. The induced voltage in the secondary coil depends on the electrical conductivity of the sample. Marangoni convection [11] will occur if there is a temperature or concentration gradient on the surface. In addition, the levitation field also induces a fluid flow in the sample. Therefore, the levitation method is only applicable to those cases where the absence of convection is not mandatory [12–15].

Braunbek [16] was the first physicist to adopt the inductive method of measurement. This method is based on applying a rotating magnetic field to the sample, which will induce the formation of circulating eddy currents. Consequently, the eddy currents will generate a damping torque directly proportional to the electrical conductivity [17–19]. A selection of molten metals having high viscosity and specific dimensions is necessary to obtain a linear relation between the electrical conductivity and the measured torque. Lorentz force sigmometry belongs to the second group, as no direct contact between the sensor and the sample exists. Hence, it prevents the problems faced by the first group. Uhlig *et al* [20] were the first researchers to use the Lorentz force sigmometry principle to measure the electrical conductivity of solid bars; they were also able to measure the electrical conductivity of copper and aluminum bars with errors of ~3.7% and ~5.8%, respectively. We emphasize that we do not measure the Lorentz force that breaks the flow, but a different force, which has the same magnitude as the Lorentz force in the fluid and solid, but with opposite direction, and acts by virtue of Newton's third law upon the permanent magnet. This phenomenon has been exploited in contactless velocity measurement in the form of Lorentz force velocimetry [5, 6, 21] and for detecting defects in a solid bar in the form of Lorentz force eddy current testing [22].

2. Experimental setup

The Lorentz force sigmometry setup comprises mainly three parts (see figures 1–3): (i) a filling funnel through which the solid metal moves or the molten metal is poured; (ii) a collecting vessel placed on a scale connected to a computer for measuring the mass of the molten metal M with an accuracy of 0.01 g for fluid measurements; (iii) the Lorentz force sigmometry (LOFOS) apparatus (see figure 4).

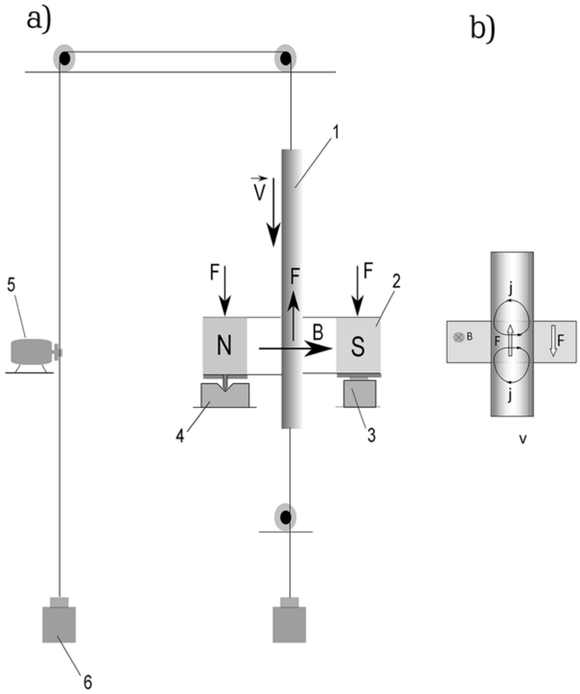

Figure 1. (a) 2D schematic of Lorentz force sigmometry setup for electrical conductivity measurements of solid metals. 1: sample of a solid metal; 2: Halbach magnet; 3: force sensor; 4: magnet support; 5: Mädler motor; 6: weight. (b) A breaking force acts on the conducting bar and is matched by an accelerating force on the magnet.

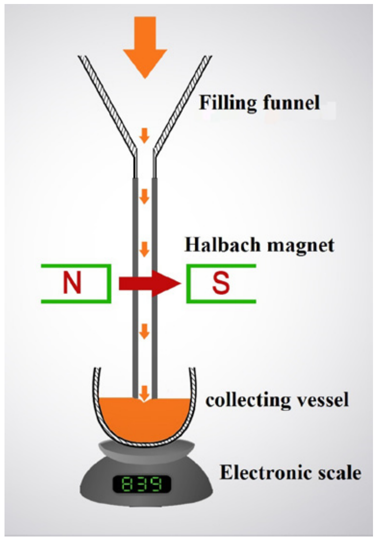

Figure 2. 2D schematic of Lorentz force sigmometry setup for electrical conductivity measurements of molten metals.

The LOFOS apparatus consists of several parts. Block-1 is a circular Halbach magnet, which is a special arrangement of small permanent magnets (12 small magnets in our case); this enhances the magnetic field on one side of the array (magnetic

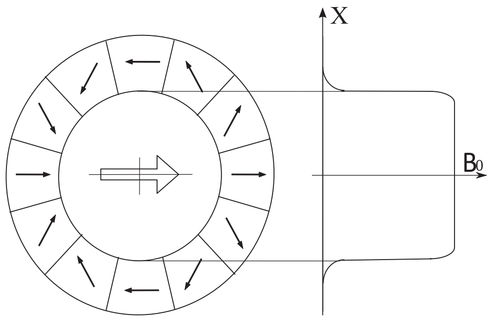

Figure 3. Magnetic field distribution in the inner space of the Halbach magnet; the arrows show the magnetization direction of the magnet elements.

field induction $B_0 = 250$ (mT)), while cancelling the magnetic field on the other side (see figure 3). A TML strain gauge sensor ($L = 1$ (mm)) is placed under the magnet to measure the force—equal to the Lorentz force—acting on it; a thermocouple sensor is located near the magnet to measure the temperature in this area.

Block-2 is an electronic box that performs many functions, such as supplying power to the force sensor and converting the voltage into electric current within the range of 4–20 (mA), which is very important in industrial environments to avoid the electromagnetic noise from surroundings, as this may affect the quality of the Lorentz force signal. Furthermore, it has two amplifying channels that amplify the signals of both sensors. Block-3 has two indicators that display the temperature and Lorentz force value. It converts the electric current back into voltage, so that it can be read by a voltmeter, and transforms the digital signal into an analog signal. Block-4 is a Keithley voltmeter model 2700 with a wide voltage measurement range (from 100 nV to 750 V), which reads the force signal with high accuracy and sends it to the computer; here, a special LabVIEW code reads and displays the analog signal of the Lorentz force.

The working principle of the Lorentz force sigmometry setup is the same for solid and fluid measurements, but with some minor changes due to technical issues, as shown in figures 1 and 2: A Mädler small geared motor type GE/I with an AC capacitor is connected to the solid bar ($L = 300$ (mm), $\varnothing = 10$ (mm)) by a rope passing through two plastic rollers. We used two stop elements to stop the rotation of the motor in both directions automatically. The rotation speed of the motor is controlled by a voltage controller, by increasing or decreasing the voltage input, or by changing the motor cylinder size (to a smaller size corresponds a slower rotation, and vice versa). The linear speed of the bar equals 10 cm/section The mass M of the bars is measured separately using an accurate scale before the experiment; we hung two weights at both ends of the rope to have an equal weight in both directions. If the weight on the side of the motor is $W1$, the weight of the bar is $W2$; then, a weight $W3 = W1 - W2$ is necessary on the side of the bar to achieve a perfect balance. Two voltmeters are connected to the LOFOS apparatus to read the measurements from both sensors, i.e. the force signal and the temperature near the force sensor.

3. Fundamentals

The Lorentz force per unit volume is approximately $F \sim \sigma v B_0^2$, where σ is the electrical conductivity of the conductor, v is the velocity of the conductor, and B_0 is the magnitude of the magnetic field. To obtain the total Lorentz force, we multiply by the volume r^2 L, where r (radius of cross section) and L (height) are the dimensions of the area where the fluid flow interacts with the magnetic field:

$$F \sim \sigma v B_0^2 r^2 L \sim \sigma L B_0^2 Q \tag{1}$$

where Q is the volumetric flow rate and is equal to $Q = \pi r^2 v$.

The mass flow rate is given by:

$$\dot{m} = \frac{Q}{\rho} \tag{2}$$

where ρ is the density of the conductor. Here, we introduce the calibration factor K:

$$K = \frac{1}{cLB_0^2} \tag{3}$$

where c is the dimensionless form coefficient accounting for the distribution of the magnetic field in LOFOS. By incorporating equations (2) and (3) into equation (1), the basic equation linking the mass flow rate $\dot{m}$ with the Lorentz force F generated by the magnetic field in the fluid can be obtained:

$$\dot{m}(t) = \frac{\rho K}{\sigma} F(t) \tag{4}$$

From equation (4), the cumulative mass during the operating time is determined as follows:

$$M = \int_{t_1}^{t_2} \dot{m}(t)\mathrm{d}t = \frac{\rho K}{\sigma}\tilde{F} \tag{5}$$

where $\tilde{F}$ is the integral of the Lorentz force over the process time. From equation (5), the final equation to calculate the electrical conductivity σ for molten metals can be derived:

$$\sigma = \rho K \frac{\tilde{F}}{M} \tag{6}$$

This equation can be also used for solid metals by considering that the cumulative mass M for solids can be immediately measured by weighing the bars with an accurate scale. The calibration factor K obtained from the preliminary test can be used for future experiments to measure the electrical conductivity of solid bars with the given design of the LOFOS apparatus.

4. Procedure of measurements

When the motor is switched on, the 30 (cm) rod (figure 1(a), pos. 1) moves through the magnetic field of the Halbach magnet with a linear speed of 10 (cm s^{-1}). The bar needs 3 s to pass through the magnetic field, as its length is 30 (cm). On the opposite side from the sensor position (figure 1(a), pos. 3), two supporting sharp needles (figure 1(a), pos. 4), which enable a frictionless turn of the magnet, are located. In the

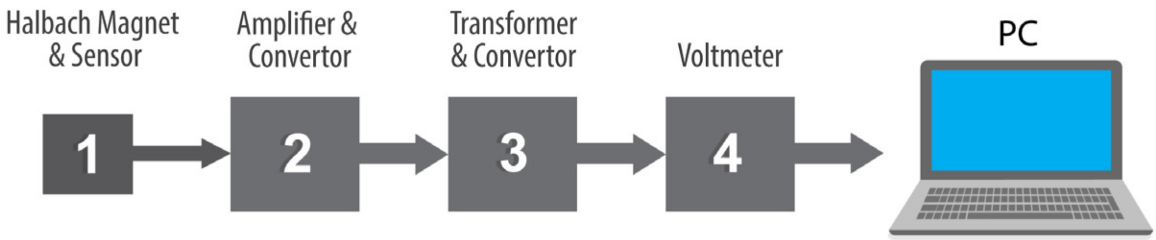

Figure 4. LOFOS apparatus diagram. 1: Circular Halbach magnet and force sensor; 2: amplifier and converter; 3: converter and transformer; 4: voltmeter; 5: computer.

diagram, they are placed one behind the other. By increasing the Lorentz force, the magnet turns around the needles and acts on the sensor. When the bar comes out of the magnetic field, the stop element automatically turns the motor off. During the experiment, the Lorentz force and temperature near the force sensor are continuously measured. During the 3 s exposure of the solid bar to the magnetic field, eddy currents are generated inside the metal (figure 1(b)). By Ampere's law, the eddy currents give in turn rise to a secondary magnetic field. As a result, the Lorentz force acts to brake the movement of the solid bar and, owing to Newton's third law, a measurable force equal to the Lorentz force acts on the magnet. This force is directly proportional to the electrical conductivity of the solid bar. The force acting on the magnet presses the strain gauge sensor located beneath the magnet system. The signal from the sensor, after being processed by the second and third device (see figure 4), is fed to a voltmeter and then to the computer defining the Lorentz force F and force integral $\widetilde{\mathrm{F}}$ within the operating time. The density ρ is measured by calculating the volume V and the mass M of the bar, and it is equal to: $\rho = \frac{M}{V}$. We conducted two series of measurements. The first measurements aimed to determine the calibration factor of the given LOFOS geometry with copper and aluminum cylindrical bars; the electrical conductivity of the bars had been previously measured with the help of a commercial device using the eddy current testing method SigmaTest 2.069. This commercial device has a wide measuring range, from 0.5 to 65 (MS m^{-1}), with an absolute accuracy of $\pm 0.5\%$ of the measured value as well as five selectable operating frequencies; we used an operating frequency of 60 KHz, for which the resolution is equal to ± 0.1 of the measured value. The second measurements were conducted with a brass bar to determine its electrical conductivity using the calibration factor obtained in the first experiment. To calculate the error of the electrical conductivity using the Lorentz force sigmometry method, we measured the electrical conductivity of the brass bar using the SigmaTest device and compared it with that measured by LOFOS.

5. Results and discussion of solid metal electrical conductivity measurements

5.1. Determination of calibration factor K

In this section, we discuss the conductivity measurements of the copper and aluminum bars. The goal of these experiments was to determine the calibration factor K, which can be calculated after transformation of equation (6) as follows:

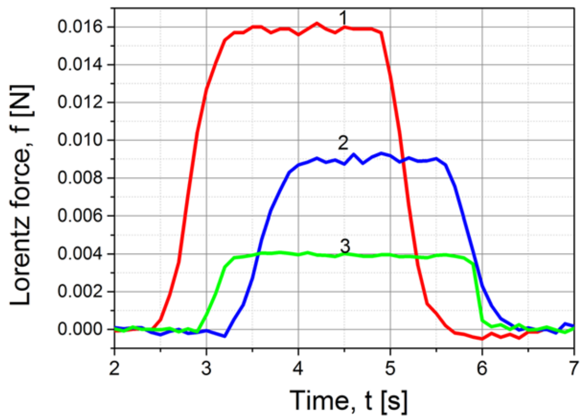

Figure 5. Lorentz force signal for copper (1, red), aluminum (2, blue), and brass (3, green) bars.

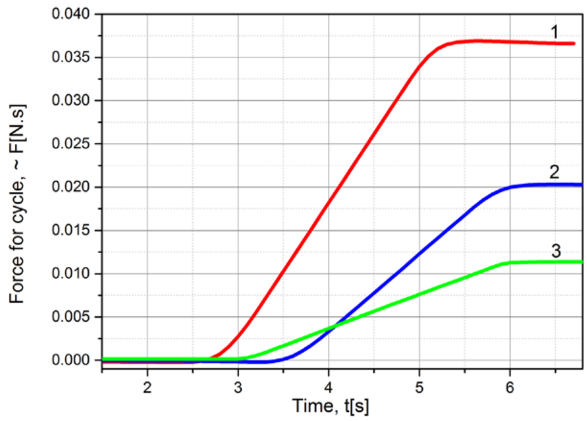

Figure 6. Integral of Lorentz force for copper (1, red), aluminum (2, blue), and brass (3, green) bars.

$$K = \frac{\sigma M}{\rho \tilde{F}} \tag{7}$$

Both bars (copper and aluminum) have a length of 300 (mm) and a diameter of 10 (mm). Their masses had been measured separately with an accurate scale, as we mentioned above, and were equal to 195.04 ± 0.01 (g) and 95.20 (g) ± 0.01, respectively. Their electrical conductivities σ were measured by a commercial device, 'SigmaTest', based on the eddy current testing method. We connected its probe to the surface of the bars and recorded the values; these experiments were repeated ten times at room temperature. Subsequently, the mean values of the measurements were calculated as $\sigma_{\mathrm{cu}} = 58.106 \pm 0.29$ (MS m^{-1}) and $\sigma_{\mathrm{al}} = 21.698 \pm 0.11$ (MS m^{-1}). Their

Table 1. Calculation of the calibration factor from copper and aluminum measurements.

Material	Conductivity (MS m^{-1})	Mass (g)	Integral force (N.s)	$K \frac{m^2}{\Omega \cdot N \cdot s}$
Copper	58.106 ±0.29	195.04 ±0.01	0.0367	34559 ±0.181
Aluminum	21.698 ±0.11	95.20 ±0.01	0.0203	36514 ±0.496

densities had been measured by the simple formula $\rho = \frac{M}{V}$ and were equal to $\rho_{cu} = 8935.3620 \pm 9.5 \times 10^{-3}$ and $\rho_{al} = 2786,7599 \pm 2.4 \times 10^{-2}$ (Kg m^{-3}). The force signal and its integral are shown in figures 5 and 6 for copper (red) and aluminum (blue) bars.

Figure 5 shows that, when the bar is outside the magnetic field area, the Lorentz force is equal to zero; then, when the bar passes through the magnetic field, the force rises and maintains a stable value for a few seconds depending on the linear speed of the motor and the length of the solid bar. When the whole bar has passed through the magnetic field, the force becomes zero again. The magnitude of the force equals ≈0.016 N for copper and 0.09 N for aluminum; the integral is equal to 0.0367 (N.s) for copper and 0.0203 (N.s) for aluminum. This experiment was repeated many times a day for several weeks to ensure the repeatability and accuracy of the measurements; here, only one signal is presented as a typical example, as the measurement results were remarkably consistent. Notably, these are raw signals obtained directly from the source and no filter has been applied to them. Equation (7) was used to calculate the calibration factor of the device (see table 1).

A small difference of ~5% can be observed between the calibration factors obtained from copper and aluminum. This difference can be attributed to the fact that, between these two series (more than 40 records for each of them), a disparity of 0.1 s in the measurement duration is enough to generate this error. We decided to use the mean value of the calibration factor from copper and aluminum measurements to determine the electrical conductivity of brass, as the calibration factor does not depend on the type of material. The mean value of the calibration factor is equal to $35546 \frac{m^2}{\Omega \cdot N \cdot s}$.

5.2. Measurement of electrical conductivity of brass bar

To prove that the Lorentz force sigmometry device is able to measure the electrical conductivity of solid metals, we prepared a brass bar with the same geometry as that of the copper and aluminum bars, and repeated the same measurement procedure. Furthermore, the experiment was repeated many times a day for several weeks to check the accuracy of the results; a characteristic signal was selected for this article. To calculate the electrical conductivity, we used equation (6) and adopted the mean value of the calibration factor obtained from the first series of measurements.

As reported in table 2, the electrical conductivity for brass was equal to 13.963 (MS m^{-1}), as measured by the Lorentz force sigmometry method. To check the accuracy of our result, we measured the electrical conductivity of the brass bar ten times using the commercial device SigmaTest at room temperature, and then calculated the mean value of the ten

Table 2. Calculation of the electrical conductivity of a brass bar.

K_mean value $\frac{m^2}{\Omega \cdot N \cdot s}$	Mass (g)	Integral force (N.s)	Conductivity (Ms m^{-1})
35546	187.47 ±0.01	0.00878	13.963

measurements. This value was equal to 14.03 (MS m^{-1}). The difference between the values obtained with the two methods is very small and the possibility of error was 0.47%; this result ensures that the Lorentz force sigmometry method is able to measure the electrical conductivity of solid metals with high accuracy. Figure 5 shows the Lorentz force signals for the three metal bars. High electrical conductivity metals, such as copper, have a strong effect on the magnetic system, and vice versa; low electrical conductivity metals, like brass, affect the magnets with a low force. After finishing the experiments with solid metals, we investigated the fluids.

6. Results and discussion of fluid electrical conductivity measurements

The schematic of the LOFOS setup for experiments on fluids is shown in figure 7. A vessel with the volume $V = 600$ [ml] is filled with an alloy having the composition of $Ga^{67}In^{20.5}Sn^{12.5}$. This is a eutectic alloy at room temperature and its melting temperature is $T_m = 10.5$ °C. Before beginning the experiment, an empty vessel with the volume of 1 l is placed on the scale platform under the LOFOS nozzle, as shown in figure 7. For fluid measurements, we fabricated a special quartz conical vessel able to sustain temperatures ranging from room temperature up to 1000 °C. The nozzle has a diameter of 8 mm and allows the flow of molten metal across the magnet system during a $\Delta t \approx 5.5$ (s), which is reasonable to measure the Lorentz force with good accuracy. The dependence of physical properties such as density and electrical conductivity on the temperature is determined by: $\rho = 6492.12–0.44$ T [kg m^{-3}] and $\sigma = 1/(R_0$ T [$0.9632 + 2.9 \times 10^{-3}$] where $R_0 = 30.32 \times 10^{-8}$[Ω.m][3].

As the nozzle geometry of the filling funnel for fluid measurements is smaller than that of the funnel used for solid measurements, a new calibration factor was necessary for an accurate fluid measurement. The experimental procedure is as follows: first, we measure the temperature of the eutectic alloy before each experiment, and then pour the alloy into the filling funnel (figure 7, pos.1) placed above the LOFOS device. The liquid metal under gravitation force penetrates in the LOFOS device (figure 7, pos.2) passing through the nozzle in the presence of a magnetic field. The interaction of the metal flow with the

[3] The physical and chemical properties of the alloy GaInSn used in the experiment are listed in a datasheet from Giredmet: the Federal State Research and Design Institute of the Rare Metal Industry, Moscow.

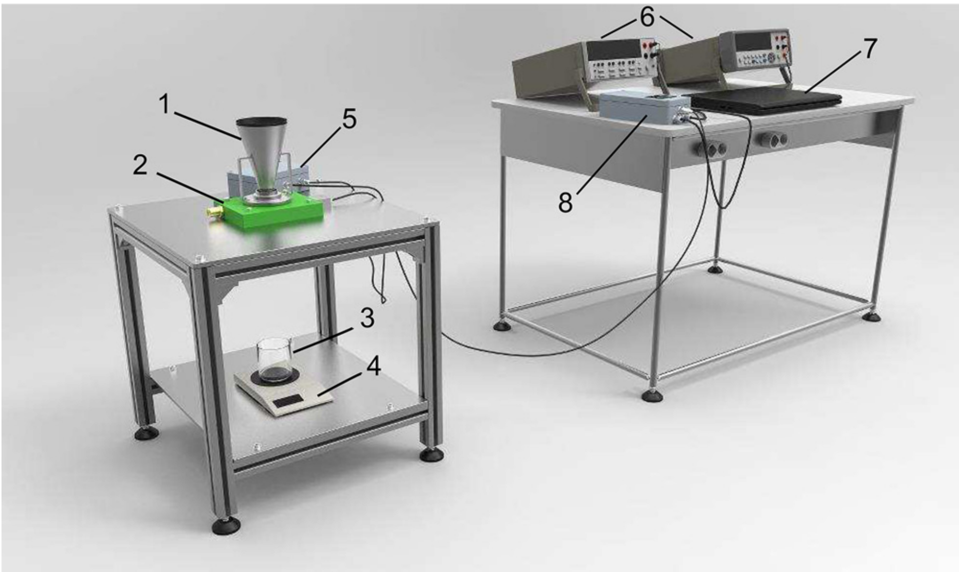

Figure 7. 3D schematic of the Lorentz force sigmometry setup for fluid measurements.1: filling funnel; 2: Halbach magnet and force sensor; 3: collecting vessel; 4: electronic scale; 5: amplifier and converter; 6: voltmeters; 7: computer; 8: transformer and converter.

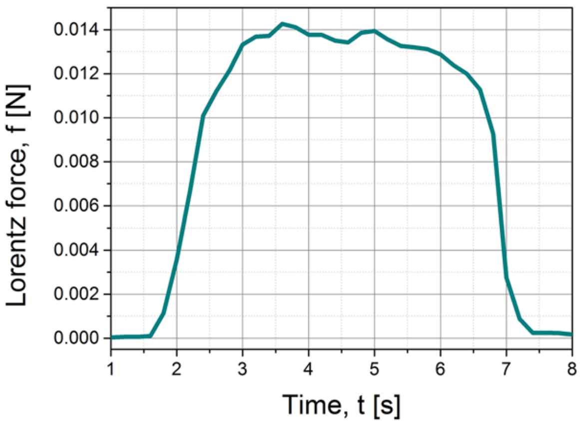

Figure 8. Lorentz force signal for the eutectic alloy.

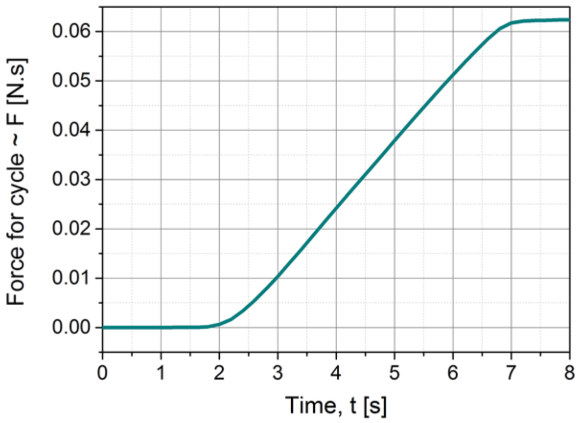

Figure 9. Integral of the Lorentz force for the eutectic alloy.

magnetic field generates the Lorentz force in the molten metal in a direction opposite to that of the flow, and induces a force acting on the magnet system directed along the flow, which is exactly equal to Lorentz force in the liquid metal. The molten metal passing through the LOFOS setup is accumulated in the collecting vessel (figure 7, pos.3) placed on the platform of the electronic scale (figure 7, pos.4) for the direct determination of the cumulative mass M with an accuracy of $\triangle M = 10^{-2}$ (g). The scale is connected to a computer(figure 7, pos.7), and special software is used for the mass measurement during the process. The force acting on the magnet presses the sensor located underneath the magnet system. The signal from the sensor is fed to a commercial voltmeter (figure 7, pos.6), and then to a computer determining the Lorentz force F and its integral $\widetilde{F}$ within the operating time $\triangle t = t_2 - t_1$. The electrical conductivity is calculated using equation (6).

Table 3. Calculation of the calibration factor from eutectic alloy measurements.

Density (kg m^{-3})	Conductivity (MS m^{-1})	Mass (g)	Integral force (N.s)	$K \frac{m^2}{\Omega \cdot N \cdot s}$
6361	3.2716	3650.9	0.06001	31290
6360.8	3.2678	3617.3	0.05999	30977
6360.7	3.2660	3617.06	0.06144	30228
6360.6	3.2631	3603.2	0.06004	30788
6360.5	3.2613	3542.8	0.05979	30382
6360.5	3.2613	3712.7	0.05882	32365
6360.4	3.2594	3706	0.05972	32030
6360.3	3.2557	3688.5	0.05946	31727
6360	3.2519	3676.2	0.06252	30064
6360	3.2510	3671.2	0.06018	31183

The force signal and its integral are shown in figures 8 and 9 for the alloy. We repeated these measurements many times for several days and calculated the calibration factor for the new LOFOS geometry. Table 3 shows ten random results as an example:

The mean value for the calibration factor calculated from the measurements (∼80 measurements in total) is equal to $30925 \frac{m^2}{\Omega \cdot N \cdot s}$. After finding the new calibration factor for fluid measurements, a molten metal with unknown electrical conductivity can be investigated. We chose to start with molten tin, as it has a low melting temperature $T_m = 232$ °C. These experiments and measurements are still in progress, and the findings will be published in the near future.

7. Conclusions

Lorentz force sigmometry is able to measure the electrical conductivity of solid metals with an accuracy of up to 6%. The method has the following advantages: (i) as there is no direct contact between the sensor and the sample, it can be implemented in the production process of any non-magnetic material (e.g. copper or aluminum); (ii) it is based on simple theory and involves a simple setup; (iii) the LOFOS setup is portable and easy to move; (iv) a relatively short period is required for the measurement (3–5 s are sufficient). The circular shape of the Halbach magnet does not limit the penetration depth, which is usually limited to a few micrometers in conventional eddy current methods. The described contactless method is applicable to the measurement of the electrical conductivity of all the common high temperature non-ferromagnetic molten metals including refractory metals. The applicability of this technique to liquid metals has been successfully tested in an experiment with a eutectic alloy with GaInSn composition. To prevent unwanted heating, the magnet has to be cooled, as the change in the magnetic field induction depends on the temperature of the magnet: $B(T) = B_0[1 - \alpha(T - T_0)]$, where α is the coefficient of the variation of the magnetic field with the temperature and leads to a change in the calibration factor K (see equation (3)). Initial experiments on the electrical conductivity of molten tin performed with the described device showed encouraging results and they will be published in the future.

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