NASA/CR-95- 207126 N/S NAG8-1078

Electromagnetic Levitation—A Useful Tool in Microgravity Research

IN-29-CR
067180

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Electromagnetic levitation is one area of the electromagnetic processing of materials that has uses for both fundamental research and practical applications. This technique was successfully used on the Space Shuttle Columbia during the Spacelab IML-2 mission in July 1994 as a platform for accurately measuring the surface tensions of liquid metals and alloys. In this article, we discuss the key transport phenomena associated with electromagnetic levitation, the fundamental relationships associated with thermophysical property measurement that can be made using this technique, reasons for working in microgravity, and some of the results obtained from the microgravity experiments.

INTRODUCTION

Electromagnetic levitation, the positioning of conducting materials by electromagnetic forces, has been practiced by metallurgists and materials scientists for several decades.[1] During the past 10–15 years, major advances have been made in our quantitative understanding of the underlying phenomena and, partly as a result, many important practical applications of the electromagnetic levitation principle have evolved. The most important of these are the melting of titanium in induction furnaces and the control of the metal-mold contact in the CREM (name derived from cast-refine-electromagnetic) continuous casting process.[2,3] These are quite well documented in the general literature and in the specific symposia dedicated to the electromagnetic processing of materials.[4,5]

This article presents a brief review of a rather specific application of the electromagnetic levitation (EML) principle—microgravity research. There are several motivations for such an undertaking, including the fact that the July 1994 Spacelab IML-2 (the Second International Microgravity Laboratory) mission, which had an electromagnetic levitation facility on board, has yielded very interesting new results. Furthermore, microgravity experiments require precise planning, because of the great expense and the very long lead times involved. Thus, EML studies necessarily require sophisticated mathematical modeling efforts during the planning and evaluation of the experiments.

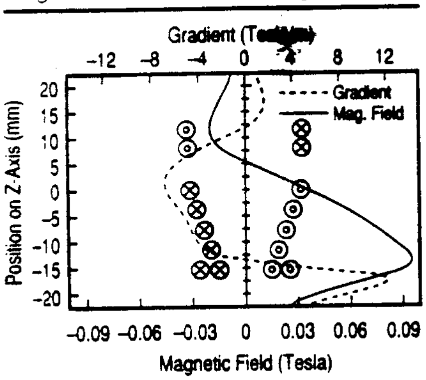

Figure 1. Schematic sketch of conical coil arrangement with field strength and gradient along symmetry axis for peak applied current of 405 A. Figure provided by I. Egry et al.

THE PRINCIPLE OF ELECTROMAGNETIC LEVITATION

The principle of electromagnetic levitation is illustrated in Figure 1, which shows the coil arrangement in an earthbound facility. A high-frequency (typically 100–800 kHz) current is passed through conically wound coils, generating an electromagnetic field (also sketched in the figure). If a metallic specimen is placed between these coils, eddy currents will be induced in the specimen with the following results:

- A lifting force will be exerted on the specimen due to the coupling between the induced current and the applied electromagnetic field. If this force is sufficiently strong, it can levitate the specimen.
- The electromagnetic forces within the specimen induce fluid flow in a molten specimen, which is turbulent under earthbound conditions.
- The induced current provides Joule heating through Ohmic losses, which may melt, or even superheat, the specimen.

As a practical matter under earthbound conditions, the ability to levitate is confined to metallic specimens of moderate size (about 10–15 mm in diameter) for conventional coil designs and moderate to high melting temperatures (above 1,000°C). More sophisticated coil designs have allowed the levitation of rather larger specimens. Garnier has reported levitating copper samples 50 mm in diameter and Japanese researchers have reported the levitation of 20 kg titanium specimens.

The electromagnetic phenomena are governed by the well-known Maxwell's equations, which are given by[6]

$$\vec{\nabla}\cdot\vec{E}=0 \quad (1)$$

$$\vec{\nabla}\times\vec{E}+\frac{\partial\vec{B}}{\partial t}=0 \quad (2)$$

$$\vec{\nabla}\cdot\vec{B}=0 \quad (3)$$

$$\vec{\nabla}\times\vec{H}=\vec{J} \quad (4)$$

where $\vec{E}$, $\vec{B}$, $\vec{H}$, and $\vec{J}$ are the vector fields for electric field intensity, magnetic flux density, magnetic field intensity, and current density, respectively.

The time-averaged electromagnetic force and power absorbed per unit volume in the sample are calculated according to the formulae[7]

$$\vec{F}=\frac{1}{\tau}\int_0^{\tau}\vec{J}\times\vec{B}dt \quad (5)$$

$$Q=\frac{1}{\tau}\int_0^{\tau}\frac{\vec{J}\cdot\vec{J}}{\sigma_{el}}dt \quad (6)$$

where τ is the period of the applied alternating current and σ_{el} is the electrical conductivity of the specimen.

The governing equations for the electromagnetically driven fluid flow inside the molten specimen are the Navier-Stokes equations, which express the conservation of momentum in the fluid. Using an effective viscosity μ_{eff} that is uniform throughout the fluid, the Navier-Stokes equations, expressed as a single vector equation, are given by[8]

$$\rho\left(\frac{\partial\vec{u}}{\partial t}+\vec{u}\cdot\vec{\nabla}\vec{u}\right)= -\vec{\nabla}p+\mu_{eff}\nabla^2\vec{u}+\rho\vec{g}+\vec{F} \quad (7)$$

where $\vec{u}$ is the velocity vector field, which represents the internal fluid flow in the specimen, p is the pressure scalar field, $\vec{g}$ is the gravitational acceleration vector, and ρ is the density of the fluid. The effective viscosity is equal to the sum of the laminar (molecular) viscosity μ and a turbulent viscosity μ_t.

The equation of continuity, the statement of mass conservation, is given for the incompressible fluid by[8]

$$\vec{\nabla}\cdot\vec{u}=0 \quad (8)$$

For axisymmetric geometries such as the specimens processed in levitation facilities, the free surface shape at any time is defined by the boundary condition, which is a balance of components of stress normal to the free surface[9]

$$p - p_a = \gamma\left(\frac{1}{R_1} + \frac{1}{R_2}\right) - 2\mu_{eff}\frac{\partial u_n}{\partial n} \quad (9)$$

where p_a is the atmospheric pressure, R_1 and R_2 are the principal radii of curvature, and u_n is the component of velocity in the direction normal to the free surface.

The temperature distribution in the specimen is governed by the thermal energy balance equation, given by[9]

$$\rho C_p\left(\frac{\partial T}{\partial t} + \bar{u}\cdot\bar{\nabla}T\right) = k\nabla^2 T + Q \quad (10)$$

where T is the temperature, and C_p and k are the heat capacity and the thermal conductivity of the specimen.

The boundary condition at the free surface of the specimen, which expresses heat losses by conduction to the cooling gas, if used, and by radiation, is given by[10]

$$-k\frac{\partial T}{\partial n} = (h_{cond} + h_{rad})(T - T_c) \quad (11)$$

where h_{cond} is the coefficient of heat transfer by conduction to the stagnant inert gas, h_{rad} is the radiation heat transfer coefficient, and T_c is the temperature of the water-cooled coils, which serve as the heat sink.

In order to rationally plan the microgravity experiments, we used numerical techniques to calculate

- Electromagnetic lifting and squeezing forces
- Induced power
- Melt circulation
- Free surface deformation
- Heat transfer

The calculations were verified experimentally in earthbound levitation facilities wherever possible. The calculated melt circulation and free surface shape in a pure nickel specimen levitated in an earthbound facility and the actual shape are illustrated in Figure 2. The capability to calculate free surface shapes was used to select the value of the applied coil current used to deform the molten specimens in the microgravity experiments.

Over the years, notable contributions to the mathematical modeling of electromagnetic levitation have been made by researchers at MADYLAM in Grenoble, France;[11,12] Cambridge University in England;[13,14] DLR in Cologne, Germany;[15,16] the University of Alabama;[17,18] Rice University;[19,20] and at the Massachusetts Institute of Technology,[21,22] among others.

Because of the need to operate in an efficient manner, mathematical models are being increasingly used to predict behavior and intelligently control industrial materials processing operations. The accuracy of the results produced by such models is limited by the accuracy of thermophysical property data such as surface tension, heat capacity, and viscosity. The property database for liquid metals in the superheated and undercooled states is incomplete, and the conventional measurement techniques are not entirely satisfactory, providing motivation for the development and execution of the microgravity experiments.[23]

BRIEF HISTORY

In order to improve upon the accuracy of existing property data and work with high-temperature, corrosive metals, researchers have developed methods to measure properties in a containerless mode. A brief, and by no means complete, historical background of thermophysical property measurements using electromagnetic levitation is presented below.

In 1971, Fraser et al.[24] developed a method to measure the surface tension of liquid metals in a containerless fashion, the oscillating drop technique using electromagnetic levitation. Further developments were made by Soda et al.,[25] Keene et al.,[26] and Egry et al.[27] In this technique, the oscillations of a levitated droplet about its equilibrium shape are observed. The restoring force for surface oscillations of the spherical sample of mass m is the surface tension γ, which can be related to the frequency of the oscillations ν by Rayleigh's formula[28]

$$\gamma = \frac{3}{8}\pi m \nu^2 \quad (12)$$

The method has the advantage of eliminating persistent sources of contamination that arise through the use of substrates and/or capillary tubes associated with conventional methods such as the sessile drop, the capillary rise, and the maximum bubble pressure methods.[29] It avoids any contact with a crucible and thus reduces not only systematic errors due to surface contamination but also allows deep undercooling of the liquid metal.[30]

Fecht and Johnson[31] developed a noncontact method for measuring heat capacity based on the temperature response of a specimen exposed to a sinusoidally modulated heat source. In an electromagnetic levitation facility, the heat capacity C_p can be determined from the modulation frequency ω_m, the amplitude of the temperature modulation (ΔT_m), the increase in the average sample

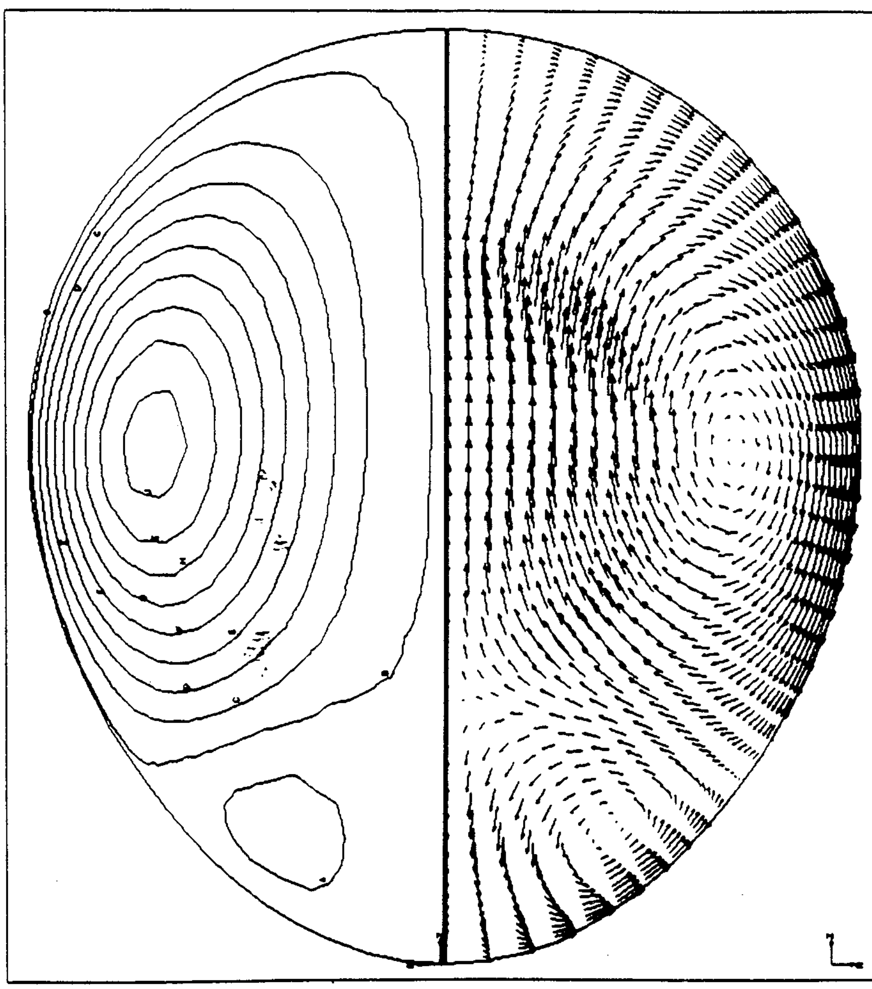

Figure 2. Calculated streamline pattern (left side), velocity vector field (right side), and equilibrium free surface shape of a nickel droplet levitated in earthbound electromagnetic levitation facility with conical coil arrangement.

temperature (ΔT_{iv}), and the sample bias temperature (T_o) by the relationship[32]

$$C_p = 4\sqrt{2}A\varepsilon\sigma T_o^4 \frac{1}{\omega_m \Delta T_m}\sqrt{\frac{\Delta T_{iv}}{T_o}} \quad (13)$$

where A and ε are the surface area and the emissivity of the specimen, respectively, and σ is the Stefan-Boltzmann constant.

Lamb[33] suggested that the viscosity μ of a spherical droplet of radius R and density ρ could be related to the oscillation damping constant Γ by the formula

$$\mu = \frac{1}{5}R^2\rho\Gamma \quad (14)$$

It has not been possible to use the oscillating drop technique using electromagnetic levitation to measure viscosity in earthbound experiments because of the turbulent fluid flow driven by the strong electromagnetic forces.

ISSUES IN MICROGRAVITY

Electromagnetic levitation provides the means for processing metallic specimens in a containerless mode, which offers the great benefit of avoiding contamination. Work with very reactive or corrosive liquid metals is thereby possible without concern for falsification of results by chemical reaction with the crucible material. Electromagnetic levitation offers the further advantage of eliminating heterogeneous nucleation on container walls, making it possible to work in the metastable regime of undercooled melts.[34]

Electromagnetic levitation in a microgravity environment is particularly suitable for measurements of thermophysical properties such as the surface tension, heat capacity, and possibly viscosity, because much weaker electromagnetic fields are necessary to position the metallic specimens than are required in earthbound experiments. This offers a direct benefit to surface tension measurements because the apparent increase in the surface tension value due to the magnetic field in earthbound experiments is thereby eliminated.

The noncontact calorimetry method used to measure heat capacity requires that the only method of specimen heat loss is radiation, but in earthbound levitation experiments cooling gas is required to reach specimen temperatures below about 1,100°C. The reduction in the necessary magnetic field strength in microgravity makes it possible to process under a vacuum and perform containerless heat capacity measurements on deep eutectic alloys with low melting points.

Microgravity makes it possible to perform viscosity measurements using electromagnetic levitation by greatly reducing the magnitude of the electromagnetic lifting forces needed to overcome gravity. The turbulent fluid flow present in earthbound experiments makes the measurement of viscosity impossible because momentum transfer and the decay of the oscillations are governed by the turbulent eddies rather than by the molecular viscosity.[35]

Electromagnetic levitation in a microgravity environment is also attractive for studies relating to undercooling, nucleation, and recalescence. Comparison of the results of earthbound experiments with those of microgravity experiments could provide insight into the effects of fluid flow on nucleation and growth. Microgravity makes it theoretically possible to study the metastable states of materials obtained through deep undercooling.

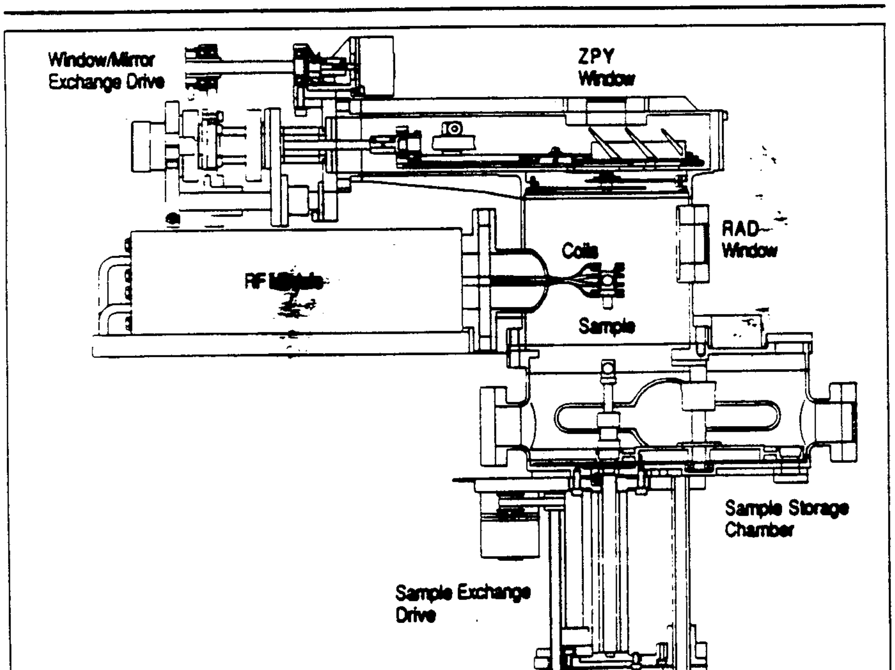

Figure 3. Sketch of the TEMPUS experimental arrangement illustrating the main subsystems, including the cylindrical geometry of the induction coils.

EXPERIENCE AND RESULTS FROM IML-2

The experiments were conducted using TEMPUS (Tiegelfreies Elektromagnetisches Prozessieren Unter Schwerelosigkeit), an electromagnetic containerless processing facility. TEMPUS uses electromagnetic levitation for containerless positioning and heating of metal samples and can be used under microgravity conditions. A schematic sketch of the experimental arrangement of TEMPUS is shown in Figure 3. TEMPUS was designed to process 8 mm and 10 mm diameter spherical metal samples within two sets of induction coils. The outer (positioning) coils, which operate at a frequency of about 140 kHz and create a quadrupole magnetic field, position the sample. The inner (heating) coils, which operate at a frequency of about 400 kHz and create a dipole magnetic field, provide most of the thermal energy to the sample through induction (Joule) heating.[6]

TEMPUS was built by Dornier GmbH under contract from DARA, the German space agency. A significant part of the work for the participating experiment teams was the determination of the set of parameters used to configure the generic main process flow for the performance of each particular experiment. The parameter set included such variables as the emissivity for temperature measurement, inert gas pressure, heating and positioning coil voltages, heating times, maximum and minimum allowable sample temperatures, and heating coil voltage and duration. This preparation consisted primarily of a substantial mathematical modeling effort and experimentation with the development model at the Microgravity User Support Center (MUSC) in Cologne, Germany.

The microgravity experiments took place July 8–July 23, 1994, aboard the Space Shuttle Columbia as part of the Spacelab IML-2 (Second International Microgravity Laboratory) mission. During that time, we monitored our experiments from the Payload Operations Command Center (POCC) at NASA's Marshall Space Flight Center in Huntsville, Alabama. From there, we telecommanded our experiments and coordinated experimental runs with the other TEMPUS scientists.

All of our microgravity experiments were performed jointly with Ivan Egry and his group from the German Aerospace Research Establishment (DLR) in Cologne, Germany. Prior to the mission, experiments on the noble metals gold and copper, the congruent-melting alloy

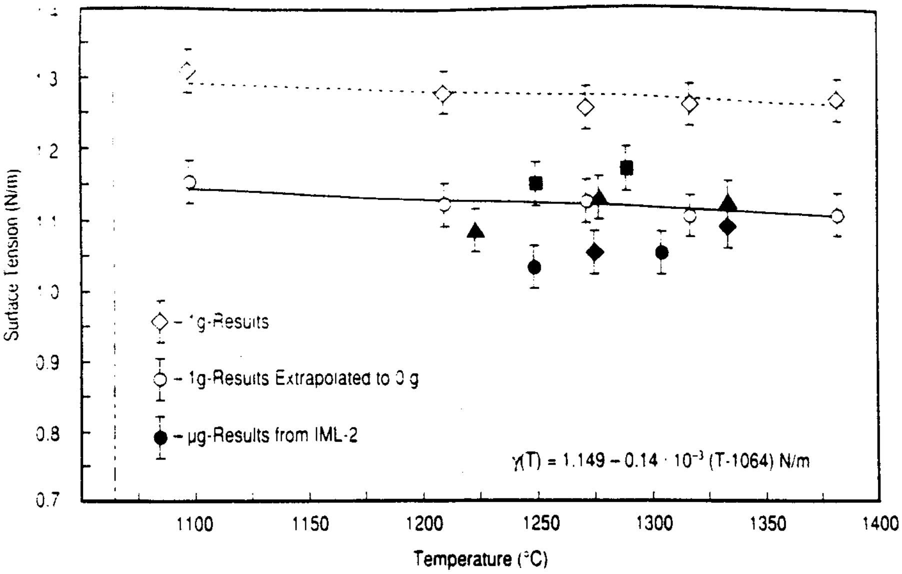

Figure 4. Surface tension data for liquid Au obtained from Spacelab IML-2 microgravity experiments, with linear fit of the data points. For the purpose of comparison, the "1 g-results" are uncorrected data obtained by Sauerland et al.[24] in earthbound levitation experiments. The "1 g-results extrapolated to 0 g" are surface tension values obtained using the Cummings and Blackburn correction formula, which accounts for the apparent increase in the surface tension value caused by the magnetic field.

AuCu, and nickel had been planned. The experiments on gold and AuCu were performed successfully based on the preparation before the mission, and a successful experiment was also conducted on a sample of eutectic ZrNi previously used for heat capacity measurements. The experiment was planned during the mission based on the experience and teamwork of the groups.

Using electromagnetic levitation in microgravity, we measured the surface tensions of a pure metal (Au), a congruent-melting alloy (AuCu), and a eutectic alloy (ZrNi). The surface tension measurements for gold, which were in the temperature range of 1,225–1,330°C, are shown in Figure 4. The filled points on the plot are data points obtained from the microgravity experiments. The different symbols represent different experiment cycles. The "1 g-results" indicate uncorrected surface tension values obtained from the earthbound levitation experiments of Sauerland et al.,[36] and the "1 g-results extrapolated to 0 g" indicate the surface tension values obtained using the correction formula of Cummings and Blackburn.[37] It can be seen in Figure 4 that the data points from the microgravity experiments and the "1 g-results extrapolated to 0 g" fall very close to a single regression line, illustrating the accuracy of the results from the microgravity experiments. We confirmed our hypothesis that microgravity experimentation would eliminate the need for the Cummings-Blackburn formula, which is used to account for the effect of magnetic field on the surface tension value in earthbound levitation experiments. The microgravity surface tension measurements and the results of the TEMPUS team will be presented in forthcoming papers.

ACKNOWLEDGEMENTS

The authors acknowledge the financial support provided by NASA under contract numbers NAG8-815, NAG8-970, and NAG8-1078.

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