

Electromagnetic Levitation Part I: Theoretical and Experimental Considerations

Sayavur I. Bakhtiyarov[1] **and Dennis A. Siginer**[2]

Abstract: Levitation of liquid bodies against gravity is a contactless confinement process appropriate for manufacturing very pure materials. A variety of levitation techniques have been developed over the last few decades, such as aerodynamic, acoustic, electrostatic, microwave, and electromagnetic levitations. More recently, a new generation of novel techniques, essentially combinations of the established primary techniques, has been successfully introduced. Examples are acoustic-electric, aerodynamic-acoustic and acoustic-electromagnetic. The purpose of this series of papers in three parts, Bakhtiyarov and Siginer (2007a,b), is to review the advances in electromagnetic levitation (EML) since its introduction as a containerless melting technique, and a tool for the determination of the thermophysical properties of molten metals under both terrestrial and microgravity conditions.

Keyword: electromagnetic levitation; thermophysical properties; microgravity; undercooling; droplet stability; metallic melt

1 Introduction

Faraday's law of induction dictates that eddy currents are induced in a conductor placed in an alternating magnetic field. Lorentz forces are generated as a result of interactions between these eddy currents and the external magnetic field. These eddy currents cause induction heating of the sample due to ohmic resistive losses. High frequency EML melting was first proposed by Muck (1923). Lovell (1946, 1951) considered EML of solid droplets without melting. The first experimental results were obtained by Okress et al. (1952) in Westinghouse laboratories. The most reactive metals of high melting point, such as titanium, zirconium, vanadium, tantalum, and molybdenum were melted in a containerless process. In late 1950s and early 1960s the technique was considered a challenge to the existing metal casting methods. NRC Equipment Corporation (Newton, MA) and Vacuum Industries, Inc. (Somerville, MA) designed and built commercial versions of the levitation-melting furnace. The applications of the technique includes alloy preparation, metal purification, vapor plating, sintering, and determination of thermophysical properties of liquid metals such as density and emissivity, physicochemical studies of gas-metal reactions, metal supercooling, vaporization phenomena and alloy thermodynamics, Rony (1964).

The history of levitation melting is replete with ups and downs, the periods it was in the running as a new metal casting technique to be used on a commercial scale, and the periods when researchers and manufacturers were disappointed and decided to terminate their activities. From studies of Etay and Garnier (1982) and Mestel (1982a) it can be concluded that EML melting will never be utilized on a commercial scale. But, evidence abounds that the technique is very promising as revealed by theoretical and experimental investigations and its potential should be further explored. For example, Garnier (1988) showed that the promise of the EML melting could be improved by the use of a cold crucible, which transforms a discrete distribution of the inducting currents into a continuous distribution of induced currents. The magnetic field concentration induced by the cold crucible allows increasing typically the mass of the levitated liquid metal

[1] Department of Mechanical Engineering, New Mexico Institute of Mining and Technology, Socorro, NM 87801-4796 USA
[2] Department of Mechanical Engineering, Wichita State University, Wichita, KS 67230-0133, USA

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2 Theory of Electromagnetic Levitation

The study of EML can be divided into three major groups, Hahn et al. (1998):

1. Analysis of the electromagnetic field to predict the lifting force and the power absorption in the liquid droplet;
2. Analysis of the temperature and flow fields in the liquid sample due to the electromagnetic force;
3. Analysis of the deformation of the drop shape caused by the electromagnetic force.

The fundamental equations for the levitation force **F** and the absorbed power P for the conductive sphere are given by Rony (1964),

$$\begin{aligned} \mathbf{F} &= -\frac{3mg\alpha}{2\rho\mu_0}(\mathbf{B}\cdot\nabla)\mathbf{B}, \\ P &= \frac{3\pi R\beta}{\sigma\mu_0^2}(\mathbf{B}\cdot\mathbf{B}) \end{aligned} \tag{1}$$

where m, ρ, σ and μ_0 denote, respectively, the mass, density, electrical conductivity and magnetic permeability of a sphere with radius R. **B** is the magnetic flux density vector, and α and β are "skin depth" functions. "Skin depth" represents the surface thickness of a conductive sample whose DC resistance is equivalent to the total AC resistance. It is defined as the depth below the surface of a sample where the current density or magnetic field strength has decreased to e^{-1} (37% of its value at the surface) Rony (1964). An estimate of the "skin depth" is given by,

$$\delta = \sqrt{\frac{2}{\omega\mu_0\sigma}}, \tag{2}$$

where ω is the frequency of the alternating magnetic field. Thus the ratio of the sample radius to "skin depth" is proportional to the square root of the frequency, Rony (1964). Electromagnetic levitation force is proportional to the product of the field and field gradient as it is evident from equation $(1)_1$. Therefore, the levitation force is greater for two fixed coils with horizontal axis than for those with vertical axis. Also as heating power P is proportional to the square of the field intensity the heating rate will be higher for coils with horizontal axis as well.

The levitation force on a homogeneous metal sphere was derived by assuming that the magnetic field generated by eddy currents in the sphere is equivalent to that produced by either an equatorial current or an alternating magnetic dipole, Okress et al. (1952). The equivalent equatorial current was evaluated from the magnetic field of the primary loops at the center of the sphere. The electromagnetic force exerted by one circuit on another is expressed as

$$F = \frac{I_1^2}{2}\frac{dL_1}{dz} + I_1 I_2\frac{dM_{12}}{dz} + \frac{I_2^2}{2}\frac{dL_2}{dz}. \tag{3}$$

In this L denotes the self-inductance, M the coefficient of mutual inductance, and I the current. Indices "1" and "2" refer to fixed primary and equivalent secondary current circles, respectively. Using this approach the expression for the levitation force in the case of two and three coaxial current loops was derived. Both the levitation force and the induction heating power vary as the square of the circulating current in the coil system. However, in this study sample size and shape were not taken into consideration. The electromagnetic levitation of a conducting solid sphere has been analyzed numerically by Brisley and Thornton (1963) in terms of the necessary currents, stability and reaction to small perturbation when the axially symmetric field is produced by a system of circular single and three current loops. Smith (1965) showed that the eddy-current force exerted on the sphere sample might be expressed in terms of the dependence of the effective inductance of the coil system on the position of the sphere:

$$F_x = \frac{I_0^2}{2}\frac{\partial L}{\partial x}. \tag{4}$$

F_x, x, I_0, and L are the average levitation force, the separation of the coil and sphere, the rms current in the coil and the effective inductance, respectively. Fromm and Jehn (1965) calculated approximately the electromagnetic force F_z exerted on the spherical droplet and its power absorption N in levitation melting under the assumption of axial symmetry by the following expressions:

$$F_z = \frac{3}{2}\pi\mu I_1^2 a^3 G(x) \cdot \sum \frac{b_n^2}{\left[b_n^2+(z-z_n)^2\right]^{\frac{3}{2}}} \sum \frac{b_n^2(z-z_n)}{\left[b_n^2+(z-z_n)^2\right]^{\frac{5}{2}}}, \quad (5)$$

$$N = 3a^2H^2\sqrt{\frac{\pi^3\mu f}{\sigma}}, \quad (6)$$

where I_1 is the current in the coil, a and b are the radii of the sphere and the loop, respectively, μ is the permeability, $G(x)$ is a dimensionless function, H is the intensity of the external magnetic field, f is the frequency, and σ is the electrical conductivity. The dependence of the force on different electrical and geometrical parameters is discussed. Experiments were conducted to validate the calculations for Al, Cu, Zr, V, Mo, and Nb specimens. The results confirmed the validity of the simulations for the applied force and the absorbed power.

Piggott and Nix (1966) consider a long conducting non-magnetic circular cylinder supported by the magnetic field produced by an alternating current carried in two horizontal wires parallel to the axis of the cylinder. The boundaries of the region of stable levitation have been determined for an aluminum bar of 2 cm in diameter. The wires are 2, 4 and 6 cm apart. The frequency of the supply was 50, 400 and 2000 c/s. It is shown that both the width of the region of stable levitation and the loss in the bar increase as the distance between the wires increases and the frequency is raised. As the frequency is raised and the wires are brought closer, the current required to levitate the bar decreases. Experimental measurements of the lifting force performed with an aluminum cylinder of 2cm in diameter showed good agreement with theoretical predictions. Miyoshi et al. (1987) proposed a combined finite element boundary integral method to solve the unbounded magneto-quasi-static problem with cylindrical symmetry. The method has been applied to predict load characteristics of a practical induction heating system which is important in the design of inverter circuits. The accuracy of the proposed method was verified for a single coil.

The power absorbed by a solid, non-ferromagnetic conducting sphere exposed to an external, time-varying magnetic field was analytically calculated by Lohöfer (1989) who solved the quasi-static Maxwell equations by expanding the solution in spherical harmonics and Bessel functions,

$$P = \frac{\pi}{2R\sigma}\sum_n \sum_{l=1}^{\infty} H_l\left(\frac{R}{\delta}\right) \cdot \left(I_{n,l}^2 + 2\sum \overline{\delta}_{\omega_n,\omega_{n'}} \cdot \cos\left(\alpha_n - \alpha_{n'}\right) I_{n,l} I_{n',l}\right), \quad (7)$$

$$H_l\left(\frac{R}{\delta}\right) = \sum \frac{8\left(\frac{R}{\delta}\right)^4}{4\left(\frac{R}{\delta}\right)^4 + x_{l+1/2,\kappa}^4},$$

$$I_{n,l} = \sqrt{\frac{2l+1}{l(l+1)}} I_n \left(\frac{R}{R_c}\right)^l \sin\theta_n P_l^1(\cos\theta_n).$$

I_n is the current in the n^{th} coil and the zeros of spherical Bessel function are denoted by x. P, R_c, θ_n, (n,n'), δ, α, (l,k) represent the Legendre polynomial, the coil radius, the angle of coil position from the rotational axis, the coil indices, the Kronecker delta, the phase, and the (l,k) summation indices, respectively. The analytical results obtained by Lohöfer (1989) do not provide information on the induced force field or heat generation, and equation (7) is valid only for spherical specimens.

Within the skin depth the interaction between induced currents and magnetic field results in a pressure effect related to magnetic field distribution along the free surface. If the levitated specimen is in the liquid state, the total pressure exerted on the specimen is defined as

$$\begin{aligned} P &= P_G + P_S + P_M + P_H, \\ P_G &= gh(\rho-\rho_0), \\ P_S &= \frac{2\gamma}{R}, \\ P_M &= \frac{B_1^2 - B_2^2}{2\mu_0}. \end{aligned} \quad (8)$$

P_G, P_S , P_M and P_H represent the gravitational, surface tension, magnetic and hydrodynamic pressures, respectively. ρ_0 is the density of the surrounding medium, γ is the surface tension of the liquid specimen, B_1 and B_2 are magnetic flux densities at the bottom and at the top of the sample. When the specimen is in a dynamically stable position the gravitational, surface tension, magnetic pressures and hydrodynamic forces are balanced. This force balance determines the shape of the free surface. Hence, from the balance equation it is possible to estimate the radius of the sample that can be levitated.

The stability of the droplet inside the excitation coil during EML experiments is a frequently encountered difficulty. A model circuit for a levitation system which leads to the prediction of the vertical motion of specimens by a linearized equation was developed by Bocian and Young (1971) to study the stability of levitated droplets. They consider both the growth of vertical oscillations which lead to the ejection of the droplet through the supporting coil and the rupture of the suspended droplets. Instabilities resulting from vertical motions of a metal droplet should be attributed to the presence of impedance-matching capacitors in the coil circuit, or to capacitance in the output circuit of the power supply rather than to the resistive and inductive circuit elements contributed to the coil arrangement and sample. The system becomes unstable when a capacitance is included in the circuit of the levitation coil. The damping coefficient in the linearized equation for the vertical motion of the droplet becomes negative and an unstable motion occurs when the capacitance is too small. Holmes (1978) theoretically studied the stability of magnetically levitated spherical droplets whose radius is much smaller than the coil size and expressed the levitation forces on metal spheres in an axially symmetric magnetic field. Neglecting dynamic stability within the sample, surface tension, electromagnetic heating of the sample and the heat exchange with the surroundings, the stability criteria is derived and is verified through practical numerical examples. An expression is obtained for the axial component of the magnetic field on the axis of a spiral coil wound on the surface of a cone. It is concluded that the magnetic field strength must decrease linearly with distance along the coil axis to achieve stable levitation. Even for very thin skin depth a stirring effect occurs in the liquid due to the interaction between induced currents and magnetic field. Electromagnetic forces have a rotational part related to the magnetic pressure variations along the boundary. This generates turbulent recirculating flows within the skin depth, Gagnoud and Leclercq (1988).

Sneyd (1982) provides a magneto-static analysis of the local equilibrium in a mender coil, which consists of parallel conductors with periodic reversals of current direction. A layer of liquid metal levitated by a row of equal and parallel high-frequency line currents is considered. The problem is solved by the method of images for surface tension tending to infinity corresponding to a plane solid slab conducting layer. Ignoring internal fluid motion, the problem is formulated in terms of a variational principle and solved numerically via conformal transformation. The calculations reveal positive lower limits for current strength, layer thickness and surface tension.

Most theoretical studies of EML avoid addressing the interaction between the magnetic field, the free surface and the internal flow. Sneyd and Moffat (1982) investigate the fluid dynamical aspects of the problem. In this study two equal parallel currents levitate a circular cylinder in phase. The equilibrium and stability of the solid specimen, the dynamics of the surface film in the beginning of melting, the equilibrium shape of the completely melted specimen and the dynamics of the interior turbulent flow were analyzed in this order. Simulations show that EML levitation is possible with zero surface tension, and there is no limit to the mass of liquid specimen that can be levitated. However, longitudinal instabilities due to surface tension may appear which can divide the specimen into drops. The assumption is made that these instabilities can be eliminated by a strong longitudinal magnetic field. The results are limited to negligible dynamic pressure effects and uniform eddy viscosity. Garnier and Moreau (1982) discuss the influence of an AC magnetic field on flow stability in liquid metals. Two kinds of instabilities are identified:

- Instabilities with a length scale of the same order as the size of the inductor or the gap between the inductor and the molten metal.
- Instabilities with a small length scale for which the external magnetic field may be considered as uniform.

An AC magnetic field has a stabilizing effect on small-scale deformations of the free surface, and may also stabilize the free surface against gravity if the surface is flat. A constricted jet shape evolves for the free surface with a steep slope. Although at small scale an AC magnetic field stabilizes the surface deformations, it can also generate internal liquid circulation under the free surface. The conditions leading to large scale Rayleigh-Taylor instability are conjectured when the free surface of liquid metal is shaped by an AC magnetic field.

Understanding the relation between the external coil arrangement, the surface shape and the internal fluid flow is pivotal. To this end Mestel (1982a, 1982b) conducted an analytical and numerical analysis of electromagnetic levitation; assuming an equilibrium temperature and neglecting all thermal effects the equations for the mean-velocity field and free surface shape are derived for the axisymmetric, single-frequency case. Buoyancy forces are negligible compared with the Lorentz force, and laminar flow regime (effective eddy viscosity replaces the molecular viscosity) is assumed. The solution for high magnetic Reynolds numbers is discussed together with the case of high surface tension. The Navier-Stokes equations are solved in the sphere using finite-difference techniques to calculate the surface perturbations; numerical experiments reveal the asymptotic behavior of the vorticity. El-Kaddah and Szekely (1983) developed a mathematical model for the electromagnetic force field, the flow field, the temperature field, and transport controlled kinetics in a levitated metal droplet. Mutual inductances are used to calculate the current density distribution in the droplet leading to the prediction of the lifting and stirring forces within the sphere and the heat generation pattern. The turbulent Navier-Stokes (N-S) equations were coupled with the thermal energy balance equation which includes convection, eddy conduction, and heat generation. To represent the carburization of an iron specimen due to the CO decomposition at the sample surface, a differential component balance is developed. The governing equations were solved numerically, using the $\kappa - \varepsilon$ model for the turbulent viscosity assuming that the specimen is a sphere and surface tension driven flows are negligible. Theoretically predicted lifting force and bulk temperature of the levitated specimen were in good agreement with experimental measurements reported previously. The flow in the core of the sphere is turbulent (v=0.1-0.3 m/s), but a laminar flow region attributed to surface tension forces exists in the vicinity of the free surface. The laminarization of the flow field had a significant effect on transport phenomena (temperature field) and transport controlled kinetics (carburization rate).

The effect of rotation on the frequency of oscillations of a liquid droplet imbedded in a fluid of the same or different density is investigated by Busse (1984). Rotation affects the oscillations through the Coriolis and centrifugal forces assuming a constant surface tension at the interface. For non-axisymmetric oscillations Coriolis force splits the frequency in two modes differing in their sign of circular polarization with respect to the axis of rotation. In axisymmetric oscillations the centrifugal and Coriolis forces combine to increase the frequency if the density of the droplet exceeds the density of the surrounding fluid.

Two methods to simulate the free surface problem in liquid metals are formulated by Gagnoud et al. (1986). In the first method normal stresses on the free surface are considered constant, and in the second a minimum energy approach is used to describe the free surface. In a later effort Gagnoud and Leclercq (1988) solved a free boundary problem to predict the equilibrium shape of molten droplets given the electrical and geometrical parameters of the system. A boundary integral method is used to calculate the magnetic field distribution, and the free surface is obtained through minimizing the total energy. The solution takes into account the effects of gravity, surface tension and electromagnetic stresses at small electromagnetic skin depth, and predicts the flow and temperature fields. Gagnoud et al. (1988) presented two methods to optimize the classical electromagnetic levitation device and to predict the magnetic field distribution required to increase the mass of the liquid droplet. The solution of the coupled problem of fluid mechanics and electromagnetism led to a new technology called *cold crucible levitation*. This levitation technique reduces the stagnation region, which occurs at the bottom of the liquid load where only surface tension can balance hydrostatic pressure.

Moffat (1991) reviews the principles of high-frequency inductive stirring inside a sphere. He shows that the driven flow is not a Stokes flow, and that inertia forces modify the flow pattern, and in practice the flows generated are turbulent. Li (1994) presents the results of an analytical study of magnetically driven flow in electromagnetic levitation processes. The local electromagnetic force distribution is integrated to obtain the total lifting force for earthbound levitation. The problem is linearized in a way similar to Stokes flow and solved analytically. Turbulence is modeled via the constant eddy viscosity concept. The flow phenomena in a levitated droplet is studied for both earthbound and microgravity conditions. The flow pattern predicted by the analytical solution compares well with that obtained earlier by numerical computations, El-Kaddah and J. Szekely (1983).

Zong et al. (1992a) developed another computational technique for the simulation of the electromagnetic force field, the power absorption and the deformation of an electromagnetically levitated metal specimen. This technique is based on the volume integral method and a coordinate transformation, which allows considering a broad class of rotationally symmetrical specimens. The results of the simulations are compared with the analytical solution obtained by Lohöfer (1989) and with the results of previous computations for spherical samples, El-Kaddah and Szekely (1983), and an excellent agreement is found. Numerical simulations are extended to predict the behavior and the shape of non-spherical specimens in the presence of a strong magnetic field. It is shown that the deformation of the specimen significantly alters the thermal energy input. For example, if the surface area of the deformed droplet is increased by $\sim 4.5\%$, the actual heating rate decreases by $\sim 31.4\%$ because the distance between the coil and the sample surface is considerably increased as a result of the deformation.

Okress et al. (1952) and Krishnan et al. (1989) suggest a combination of electromagnetic and acoustic methods for high-temperature thermophysical property measurements. Bayazitoglu and Suryanarayana (1989) present a comparative analysis of the requirements of acoustic and electromagnetic systems and assess the feasibility and the acoustic forces necessary to drive electromagnetically levitated and melted materials. The analysis is conducted for both terrestrial and microgravity conditions. In microgravity the equilibrium shapes are more nearly spherical due to minimal forces required. Also, radiation is the dominant mode of heat transfer in microgravity.

Expressions for the magnetic field and field gradients due to the current flowing in a helix wound on the surface of a cone of circular cross section are derived and the results for the right circular helix are compared with those for an equivalent stack of coaxial loops, Bayazitoglu and Sathuvalli (1993). For small coils with a small number of turns, the fields obtained by the stack model are considerably different from the fields resulting from the helix model. Sathuvalli and Bayazitoglu (1993) also calculated the field and its gradient due to current flowing in a conical helix. The influence of the pitch and the semi angle of the cone on the behavior of the field are investigated together with the effect of the Lorentz force acting on a metallic sample and a comparison is made with the stack model of winding. The helix model predicts more realistic values of the field and of the influence of the Lorentz force whereas the stack model overestimates the Lorentz force near the bottom of the coil. Analytical simulations of the power absorption as a function of the geometry of the coil that produces the applied magnetic field were done by Bayazitoglu and Sathuvalli (1994). For a spherical specimen placed in a magnetic field of a circular loop absorbed power strongly depends on the relative size of the sphere and its position with respect to the coil. The non-homogeneous model for the power absorbed by the sphere gives more realistic results than the homogeneous model. Bayazitoglu (1996) also solved an induction problem for the electromagnetic levitation of both spherical and aspherical specimens, and compared the predictions of the diffusion solution for the homogeneous and non-homogeneous models. The homogeneous model underestimates the power generation in the sphere for large spheres. For relatively small spheres both models yield identical results, but the predictions of the homogeneous model are better when the number of turns per unit length is large.

Ciocirlan et al. (2001) consider the vertical motion of a spherical metal droplet levitated by two parallel loops carrying electric currents in opposed directions. The mathematical model of the motion is developed and simulations performed for aluminum and copper specimens for various parameter sets of the levitation system. The equation of motion is linearized around the equilibrium position and the damping factor is estimated. The computed natural frequency is favorably compared with that reported by Holmes (1978). In a previous paper Ciocirlan et al. (1998) had studied the control in both horizontal and vertical directions of a non-linear magnetic spherical droplet suspended in an electromagnetic field. A pair of horizontal electromagnets was added to the typical magnetic levitation system to handle the horizontal displacement of the particle. A fuzzy logic controller was designed to bring the droplet to the operating location situated on the symmetry axis. Simulations with different initial positions of the droplet were run to show that the controller has a good behavior for almost any set of initial conditions.

A comparative numerical modeling of the electrodynamic and hydrodynamic phenomena in magnetically and electrostatically levitated droplets in microgravity was developed by Li (1999) based on the solution of the Maxwell equations using the boundary element technique and the Navier-Stokes and energy/mass balance equations by the finite element method. Physical insight is gained into important issues in space applications, such as viscous surface oscillations and heat transfer, turbulent flow behavior in droplets, internal fluid flow and heat transfer, and stability of levitated droplets through the comparative study of magnetically and electrostatically levitated droplets.

A computational study of the effects of buoyancy-driven convection on constrained melting of phase change materials within spheres was conducted by Khodadadi and Zhang (2001). The computations are based on a finite-volume formulation using time-dependent continuity, momentum and energy equations. The effect of phase change on convection is framed in terms of a porous medium abiding by Darcy's law. In early stages of the melting process conduction heat transfer is dominant giving rise to concentric temperature contours. As buoyancy-driven convection increases in magnitude driven by the growing melt zone, melting in the top region of the sphere is much faster than in the bottom region due to enhanced convection heat transfer. Three time-dependent recirculating vortices are predicted when buoyancy effects are significant. It is concluded that buoyancy-driven convection accelerates the melting process markedly when compared to the diffusion-controlled melting. The magnitude of the Prandtl number plays an important role in shaping flow and melting patterns. The numerical simulations were verified experimentally using a high-Prandtl number wax. A non-linear dynamical analysis of the time evolution of electromagnetically levitated flexible droplets was done by Dupac et al. (2002). The droplet is modeled as a system of lumped masses, elastic springs, and rigid links. The behavior of the levitated droplet is studied by quantitative characterization of time series data such as attractor dimension or largest Lyapunov exponent, and chaotic behavior of pure aluminum and copper droplets were analyzed.

3 Experimental Considerations

A typical EML device consists of a hollow metallic tubing coil with few turns. Between the reverse wound turn at the top called "capping coil" and the levitation coils cooled by water there is a zone of low magnetic induction called "potential well". High frequency alternating current flows through the coil to generate an alternating magnetic field. This magnetic field induces eddy currents in the specimen which dissipate energy and produce Lorentz forces.

Several types of coil systems to improve the stability and the effectiveness of the levitation process for the molten sample were investigated by Okress et al. (1952). The electromagnetic force acting to maintain the specimen was found to be inadequate in the initial experiments with a single coil. It was discovered that an adequate radial restoring force could be realized by using two coaxial coils, in which the alternating currents are in series opposition. The currents in these fixed coils generate eddy currents in the interposed conductive sample. Interaction of the induced eddy currents with the inducing magnetic field gives rise to supporting and lateral restoring forces. Levitation force is greater (for example, 3.5 times for 2.5 cm diameter bronze ball) for double coils with horizontal axis when compared to coils with vertical axis. The alternating magnetic field made possible the levitation of up to 550 g of solid samples of brass, Sn, Al, and Ti. The input power, primary circuit design, frequency, heat losses and thermophysical properties of the specimen are factors affecting the heating and melting capability of the system. Stable levitation was achieved for 21.5g of Al. In a vacuum it was possible to levitate approximately 10 g of liquid Al for about 1 min. It is estimated that commercially viable amounts of samples (i.e., few kilograms) may be stably levitated with a power source of 50 kW and 60 kHz frequency.

It is important to measure the magnitude of the generated magnetic field strength and gradient for optimum design of the electromagnetic levitator. In most experimental works the magnetic field strength varies between 0.025 to 0.05 T. In the studies of Okress et al. (1952) the magnetic field strength was up to 0.07 T. Typical magnetic field gradients are of the order of $0.5 \sim 5$ T m^{-1} depending on the diameter and number of turns, magnitude of current, coil material and design. Bunshah and Juntz (1964) describe a technique for levitation melting of 70-120 gram of aluminum in air, and 60-80 gram of beryllium in a vacuum of 5×10^{-5} torr. The samples were kept molten for 2 minutes and cast into 2.54 and 3.81 cm diameter rods. The experiments were not continued further because the induction coil was covered rapidly with a deposit of beryllium and shorted out after a relatively brief period of time. An analysis of the experimental and practical aspects of EML such as levitation coils and chambers, temperature control and measurement, stability of the melt, and magnetic field and levitation is given by Peifer (1965). A new type of electromagnetic levitator developed by Sagardia and Segsworth (1977) makes the processing of large metallic loads without reliance on surface tension effects a distinct possibility. Several magnetic fields of different frequencies are shaped and oriented to produce adequate pressure distributions and necessary surface and bulk stability. Sets of levitation coils made of copper tubing cooled by circulating water were used together with a refractory lining to protect the levitation coils against the effects of radiation from the load and against contact with molten metal. The levitation melting of 1 kg aluminum spheres has been achieved with 16.29 kW total input power.

The problem of the long-term dynamic instability of electromagnetically levitated liquid specimens was considered by Essmann and Kiessig (1979). The focus of the study is on decarburizing and degassing of a monocrystalline niobium sphere of 7 mm diameter in ultra high vacuum for about 16 hours to show that the modulations of the levitating RF signal have to be eliminated to achieve dynamic stability of the center of gravity of a levitated specimen. The kinetics of decarburization and carburization of levitated 1 g liquid iron-carbon alloy droplets at 1650^{o}C temperature and 40 atm pressure in CO-CO_2 gas mixtures were studied by El-Kaddah and Robertson (1978).

The effective diffusivity of carbon in the liquid was close to atomic diffusivity, and as a consequence the levitated drops behave as static spherical particles. A transport model is developed to explain the experimental results. The study concludes that reaction rates are controlled by transport in the gas phase (decarburization) and by mixed transport control (carburization). Etay and Garnier (1982) experimentally studied the equilibrium of liquid metals in high frequency alternating magnetic fields and compared the results to theoretical predictions available in the literature. Their analysis is based on the electromagnetic skin effect phenomena. An imposed magnetic field changes the shape of the liquid metal jet from circular vein to either a cruciform or a thin ribbon cross section. The goal of the experimental study of Krishnan et al. (1988) is the electromagnetic levitation and melting of small (0.5-1.0 g) samples of Cu, Ni, and Ni-based alloys in inert atmospheres. The evolution of the droplet motion was recorded by high-speed photography. The study clarifies aspects of the dynamics of the droplets including axisymmetric oscillation, rotation, and oscillation mode changes. The mode changes are attributed to possible thermal instabilities. The related problem of damped oscillations of a viscous spherical droplet immersed in a viscous medium was studied by Bayazitoglu and Suryanarayana (1992). Oscillation frequency and damping rate results are presented for the fundamental mode and for liquid-gas and liquid-liquid systems. The properties of the host medium influence the damping rate and the frequency of oscillations of liquid droplets. Increasing the viscosity of the host medium delays the onset of oscillations. Host medium effect is negligible in liquid-gas systems, but is significant in liquid-liquid systems. Predicted frequencies are in good agreement with experimental data. However, the predicted damping rate is much lower than that observed in experiments contributing to surface contamination.

Platzek et al. (1994) conducted undercooling experiments on the alloy $Co_{80}Pd_{20}$ below the Curie temperature using the EML technique. Large undercooling is obtained due to the absence of the container-wall induced heterogeneous nucleation. An attractive force between the sample and an external permanent magnet is observed when the temperature of the undercooled liquid decreases below the Curie temperature. Thus a metallic liquid demonstrates magnetic ordering properties. Reske et al. (1995) report the results of quantitative measurements of the magnetization as a function of temperature in the undercooled melt regime of Co-Pd alloys of various compositions by using EML. A modified Faraday balance was applied to measure the magnetization of the undercooled liquid sample as a function of temperature. The experiments reveal a very pronounced Curie-Weiss behavior of the undercooled melt with transition temperatures from the paramagnetic to the ferromagnetic state slightly below the Curie temperature. The Curie temperature is determined for the transition from the paramagnetic to the ferromagnetic state of the metallic liquid with long-range magnetic order.

Bayazitoglu and Shampine (1996, 1997) demonstrated a new type of levitator suitable for use on earth as well as in microgravity called "longitudinal electromagnetic levitator" which consists of a set of n parallel conductors referred to as n pole coil. These conductors are connected to each other with end turns forming a continuous path for current to flow. The expressions for the forces and power generated by a longitudinal levitator are derived which agree well with experimental results. It is shown that for an eight-pole coil the optimum ratio of specimen size to coil size is $\sim$ 0.35. To find the length of coil for the particular generator and specimen an expression to simulate the impedance of a longitudinal levitation coil is proposed. Copper, aluminum and brass samples up to 662 g have been levitated during test experiments. The longitudinal electromagnetic levitator has many advantages:

- Ability to support samples of spherical and non-spherical shapes
- Good visual access to the sample
- Precise control of the sample position in the levitator

- The sample is very stable and does not rotate or vibrate
- Heating rates are small
- Massive samples can be supported (up to 662 g)
- Multiple specimens can be simultaneously levitated and controlled.

The theoretical model for electromagnetic heating of a sphere proposed by Bayazitoglu and Sathuvalli (1994) and Bayazitoglu et al. (1996) was verified experimentally by Shampine et al. (1996). A good agreement was found between theoretical predictions and experimental data for radius to skin depth ratios (δ/R) between 0.3 and 3.7, which cover the critical transition range where the electromagnetic field just penetrates to the center of the sphere. For δ/R<1 experimental data confirms the theoretical prediction that power dissipated is proportional to $(\delta/R)^4$. For small δ/R values experimental data becomes less reliable due to very low heating rates, but for δ/R>1 experimental results are reliable supporting the theoretical prediction that power absorbed is proportional to δ/R.

4 Undercooling of Metallic Melts by Electromagnetic Levitation

Electromagnetic levitation (EML) techniques have been widely used to undercool metallic melts. Large undercooling of sample droplets can be achieved due to the absence of crucible. The technique allows the simultaneous experimental determination of sample undercooling and the observation of the solidification process. The main problem in investigating undercooling phenomena in liquid metals is to avoid heterogeneous nucleation. Turnbull and Cech (1950) accomplish this by partitioning a relatively large mass of liquid metal into a number of small droplets (~50 μm in diameter) which don't induce heterogeneous nucleation. A spectrum of freezing temperatures was obtained from observations on a large number of droplets. Droplets, which freeze after a maximum degree of undercooling, are considered as homogeneously nucleated. Extensive supercooling of 1-2 g nickel samples was achieved by Shiraishi and Ward (1964) who used a levitation melting technique. Gomersall et al. (1965) obtained ~ 400^{o}C undercooling during levitation melting of nickel and iron samples in a hydrogen environment. They used up to 100^{o}C/sec cooling rates, and the largest supercooling was found at 25^{o}C/sec. Willnecker et al. (1986) report the results of undercooling experiments on bulk $Fe_{1-x}Ni_x$ samples of about 700 mg in mass by the EML technique. A series of 16 samples of different concentration was levitated in UHV environment. The temperature of the specimens was measured using a two-color pyrometer with absolute accuracy ± 10 K. It is shown that EML yields extended degrees of undercooling of Fe-Ni alloys, not accessible by any other technique. The solidification of the undercooled melt is dominated by surface induced heterogeneous nucleation due to Fe and Ni oxides rather than by volume heterogeneous or homogeneous nucleation.

Flemings and Matson (1998) studied the effect of microgravity on metastable solidification of ternary steel alloys (Fe-12wt%Cr-16wt%Ni and Fe-16wt%Cr-12wt%Ni). The TEMPUS (Tiegelfreies Elektro-Magnetisches Prozessieren Unter Schwerelosigkeit) EML facility aboard the shuttle Columbia was used for containerless processing of molten ternary steel alloys. Comparing the growth rate under ground-based and microgravity conditions a significant difference in the delay between primary and secondary recalescence was found. Clearly a difference exists between the high convective environment of ground-based EML and that attainable in microgravity.

According to Eckler et al. (1997) and Volkmann et al. (1997), NdFeB alloy droplets are not so easy to undercool by comparison to Fe-based alloy melts. Hermann and Löser (1998) demonstrated that in levitated NdFeB alloy droplets only poor bulk undercooling could be realized. They observed primary γ-Fe phase over a wide range of alloy composition. The undercooling of levitated NdFeB alloy samples is limited primarily by Nd_2O_3 inside the droplet. Volkmann et al. (2002) developed a method to reduce the amount of the Nd-oxides. Levitated droplets are highly overheated under low protective gas pressure. Due to thermodynamic instability at elevated temperatures, solid Nd_2O_3 oxide reacts with liquid Nd element and transforms into volatile NdO oxide which evaporates into the surrounding atmosphere. Thus, the amount of Nd_2O_3 in the droplet is reduced, and a large undercooling is achieved during the cooling phase. The same technique has been used by Gao et al. (2002) to study the metastable solidification behavior of bulk $Nd_{14}Fe_{79}B_7$ alloy droplets at significant melt undercooling. The test samples were processed using the EML facility described by Herlach et al. (1984). The results show that γ-Fe solid solution, $Nd_2Fe_{14}B$ compound and the metastable $Nd_2Fe_{17}B_x$ compound were solidified as primary phase in sequence of increasing bulk undercooling level. Cao et al. (2001) determined the metastable miscibility gap in the undercooled state of the Cu-Co system directly by differential thermal analysis (DTA) and indirectly by concentration analysis on the solidified samples processed by electromagnetic levitation technique (EML). They show that the DTA-processed samples have a more pronounced macro-segregation than the EML-processed samples. It is assumed that the phenomenon is related to the electromagnetic stirring effect and to the faster cooling of the levitated specimens. The nucleation temperature of the Co-rich liquid significantly influences the spatial distribution of the minority phase and microstructure of the Co-rich phase. A lower nucleation temperature develops coagulation of the minority phase and causes a smaller particle population. The α-Co phase formed from the separated Co-rich phase shows a significant grain refinement in the case of deeper undercooling.

5 Conclusions

Most theoretical studies of electromagnetic levitation consider the interaction between the magnetic field, the free surface, and the internal flow. The external coil arrangement and the fluid dynamical aspects of the problem are very important in predicting temperature distributions inside the levitated sample. Instabilities are another important factor in EML. For example, longitudinal instabilities due to surface tension can divide the specimen into drops. In most theoretical studies buoyancy forces are taken to be of negligible magnitude as compared with the Lorentz force, and laminar flow regime is assumed. Only a few studies involving turbulent flow are available in the archival literature. Turbulence modeling is based on the constant eddy viscosity concept.

The size and arrangement of coil systems are targeted in experimental studies to improve the stability and the effectiveness of the levitation process. Longitudinal levitation coil arrangement is found to be the most advantageous in supporting large and non-spherical samples. Alternating magnetic fields make the levitation of large solid metal samples possible, up to 550 g. However long-term dynamic instability of electromagnetically levitated liquid specimens is still an unsolved problem. The EML is also shown to be an effective tool in avoiding heterogeneous nucleation, which is a pivotal problem in liquid metals processing. It is assumed that the phenomenon is related to the electromagnetic stirring effect and to the faster cooling of the levitated specimens.

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