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Electromagnetic Levitation Part III: Thermophysical Property Measurements in Microgravity

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Abstract: Strong inhomogeneous magnetic fields are necessary to generate a finite levitation force in ground based electromagnetic levitation techniques. External forces such as magnetic and gravitational forces influence the oscillation spectrum and counteract the surface movement resulting in a frequency shift, and making the use of electromagnetic levitation techniques in microgravity an attractive alternative to measure thermophysical properties of liquid metals. Under microgravity conditions the magnetic field strength around a liquid droplet is significantly lower than that required to position the same specimen against earth gravity. Hence, a low magnetic field strength results in a low amount of heat energy absorbed by the specimen making the deep undercooling of molten metals in UHV environment possible. There is no need to cool samples convectively using a high-purity inert gas. The low strength and uniformly distributed magnetic force fields do not change the spherical shape of the droplet, and the theories which assume spherical droplet shape can be applied to determine thermophysical properties, such as viscosity, surface tension and electrical conductivity. A low magnetic field strength slows down the stirring of the molten specimen and reduces the turbulence of fluid motion.

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

1 Introduction

The combination of containerless processing and microgravity offers the exclusive possibility to measure thermophysical properties of molten metals both above and below their melting points in a wide temperature range and with high accuracy, Egry and Szekely (1991). Feuerbacher et al. (1986) consider the containerless processing of melts in microgravity environment as the most effective technique to

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obtain extended degrees of undercooling. Levitation against earth gravity involves a lower bound to the power absorption. Therefore, the EML technique under terrestrial conditions is applicable only to metals of high melting point. As heat transfer takes place by radiation only, the sample temperature cannot be decreased beyond a minimum ($\sim$1300 °K). Positioning forces under microgravity conditions are at least three orders of magnitude lower than those required in 1g. This reduces the heat energy input, and the specimens can be levitated at much lower temperatures. The low positioning forces also prevent undesirable violent agitation of the liquid, convection and sedimentation. Space experiments will advance our understanding of heterogeneous and homogeneous nucleation processes over a wide range of temperatures. It will allow developing new alloys with novel microstructural properties in stable and metastable phases. But we should be mindful that any use of space facilities must evolve from a comprehensive and competent ground based research program in materials processing. In this context material processing in reduced gravity environment of space is discussed in the review of Carruthers and Testardi (1983).

2 Thermophysical Property Measurements

The theoretical predictions of the electromagnetic force field, the velocity field and the temperature field in a levitated liquid droplet reported by El-Kaddah and Szekely (1983) were extended by the same authors to zero gravity conditions, El-Kaddah and Szekely (1984). The formulation and the computational procedure utilized are the same in both papers. The computational results were used for the interpretation of experimental measurements made during *SPAR 1* flight program. They found a substantial difference in the velocity fields and turbulence levels in the levitated droplet under earthbound and zero gravity conditions. In zero gravity simulations show a symmetrical circulation pattern and four recirculating loops as opposed to an asymmetric circulation pattern and two circulation loops obtained under 1 g conditions, and the spatial variation of turbulent kinetic energy is significantly reduced when compared to that under earthbound conditions. The experiments of Herlach et al. (1984) on undercooling Ni within a Al_2O_3 crucible in containerless state show the effect of heterogeneous nucleation due to container walls. Any containerless processing using EML eliminates heterogeneous nucleation and enables a significant increase of undercooling by a factor of about four. But, high power absorption necessary to levitate metal samples limits the application of the EML to high melting point metals. However, operating in the reduced gravity environment can eliminate this limitation. In microgravity required positioning forces are much smaller, and the power absorption of the samples is reduced.

Lundgren and Mansour (1988) applied a boundary-integral method to study numerically nonlinear oscillations and other motions of large axially symmetric liquid drops in zero gravity. Keeping first order viscous terms in the normal stress boundary condition allows accounting for the effects of small viscosity in the computations. In earthbound flows of contained liquids with free surfaces the main source of viscous effects comes from boundary layers at the walls with smaller inputs from the free surface. In containerless zero gravity processing the free surface is the only damping source. The effect of viscosity is smaller in the fourth-mode computations, and it increases for higher modes.

In microgravity, electromagnetic levitation and undercooling are possible under vacuum conditions, Egry et al. (1993). Hence, heat losses are entirely due to radiation,

$$P_{out} = P_{rad} \sim 4\pi R^2 \varepsilon T^4. \tag{1}$$

P_{out} is the heat output and ε is the total emissivity. The power input to the specimen can be calibrated with respect to the only directly measurable quantity the power input to the heating coil if temperature and emissivity are known.

Operating in microgravity environment has many advantages. For instance levitating magnetic fields unavoidably introduce disturbances into a liquid specimen. Microgravity can minimize these disturbances. The aspherical shape of liquid metal specimens limits the applicability of the electromagnetic levitation technique under terrestrial conditions to measure electrical conductivity. But variation of the total impedance with the sample electrical conductivity is known for simple geometrical shapes such as sphere making the technique more suitable for the microgravity environment, where the electrical conductivity of liquid metals can be determined for a wide temperature range, Egry et al. (1993). Most theories for prediction of the surface tension of liquid metals are valid for spherical samples only. Under terrestrial conditions, the levitated specimens are always deformed. On the oscillation spectrum instead of a single peak for each value of n, as in the case of spherical samples, there are 3-5 peaks. EML in microgravity simplifies the quantitative evaluation of the oscillation spectra. Convection modifies effective thermal conductivity under 1-g conditions. Experimenting in microgravity conditions allows eliminating convective effects. The electromagnetically induced flow in the liquid metal may be turbulent on Earth affecting apparent viscosity measurements. Microgravity allows conducting experiments with small magnetic fields which helps reduce turbulence inside the sample. The phenomenon which occurs when the density of the liquid phase is higher than that of the solid phase is called *density catastrophe*. Measurements in microgravity can shed light on the relationship between this phenomenon and the *entropy catastrophe*, Herlach et al. (1993). Microgravity experimentation can shed light on the interesting conjecture that if the density measurements in the undercooled liquid regime are extrapolated by a straight line, there is a hypothetical temperature at which the densities of liquid and solid phases would become equal.

The theoretical model developed by Zong et al. (1992b) to simulate the behavior of electromagnetically levitated metal droplets in microgravity is capable of predicting the actual shape of the specimen deformed by the electromagnetic field generated by a "squeezing coil". Knowledge of the force field and the droplet shape leads to the calculation of the velocity field via *FIDAP* computational package, on the assumption that the velocity field does not affect the droplet shape. The simulations show that for the operating conditions in the *TEMPUS* facilities, positioning coils introduce a circulation with very small velocities (10^{-2} m s^{-1}) whereas heating coils initiate a turbulent flow with high velocities (0.3 m s^{-1}). In the turbulent range velocity depends linearly on the applied current. Maximum liquid velocity is independent of the sample size and the sample conductivity, but inversely proportional to the square root of the density. In the proposed microgravity experiments at *TEMPUS* facilities metallic specimens are electromagnetically positioned and heated to the temperature above their melting point. The current through the heating coils is then switched off and the sample is allowed to cool. The main objective of the experiments is to allow the specimens to undercool and study the structures obtained by the recalescence and solidification, Willnecker et al. (1986). It is important to know Zong et al., (1993a),

- the time scale of the velocity decay,
- the time scale of the heat transfer,
- whether the recalescence and solidification takes place in a stagnant or in an agitated liquid,
- whether significant temperature gradients are sustained in the sample.

Zong et al. (1993a) present computational results for the transient behavior of levitation-melted and electromagnetically positioned liquid metal droplet while the current through the positioning coils is sustained at its original level when the supply of the current to the heating coils has been turned off. The numerical solution of the transient Navier-Stokes and the thermal energy balance equations trace out the decay of both the velocity and the temperature fields. The decay of the former is related to the driving force for recirculation produced by the heating coils, which is larger than that of the positioning coils. The radiative heat exchange with the surroundings generates the temperature decay in the specimen, Zong et al. (1993a). The results predict that the overall rate of thermal energy losses is limited by thermal radiation at the surface. Hence, the droplet may be considered as isothermal and convection within the droplet does not affect the heat transfer. The velocity field decays more rapidly than the temperature field. When the velocity field approaches the "positioning asymptote", the heat loss from the droplet is quite small. Cooling and undercooling of the droplets takes place in a stagnant liquid or in a liquid very gently agitated by the positioning coils. The theoretical predictions of the lifting forces and the power absorption are compared with those determined experimentally on *TEMPUS* facilities, Zong et al. (1993b). The simulations and the experiments were conducted for a range of conditions, such as coil configuration, sample position, sample conductivity and current levels. An excellent agreement was found between the theoretical predictions and the measurements.

Egry and Sauerland (1994) discuss the advantages of microgravity environment for surface tension and viscosity measurements by EML, and Herlach et al. (1993) review the most frequently used containerless techniques, such as free fall facilities and levitation facilities including potential applications in microgravity with an emphasis on thermophysical property measurements, nucleation experiments, crystal growth, and solidification of non-equilibrium states of undercooled melts. Highlights of the advantages of the microgravity environment are,

- No deformation of the sample; the spherical shape is maintained.
- No turbulent flow in the liquid specimen.
- No gas stream is required for cooling the sample, undercooling is possible in UHV.
- Wider temperature range becomes accessible and temperature control is facilitated.
- Processing and undercooling of low melting point metals is possible.

The analytical solutions obtained with Stokes flow assumption, Li (1994), show that for earthbound conditions the levitation coil must be carefully arranged to ensure the global stability of the levitation process, and the levitation coil needs to be displaced from the equator plane to counter-balance the gravity effect. The coil placed at the equatorial plane in microgravity gives rise to a flow structure characterized by two counter rotating vortices of equal size. Flow behavior is correlated to the distribution of the curls of the electromagnetic force field. The characteristic velocity is linearly proportional to the input current and inversely proportional to the molecular viscosity when the flow is in the Stokes flow regime. In turbulent regime, the characteristic velocity is linearly proportional to the input current and inversely proportional to the square root of the density of the droplet material. Sadhal et al. (1997) theoretically examined an unsteady localized spot heating of a liquid droplet under microgravity conditions. The analysis is focused on the thermal and the flow effects during spot heating of the liquid droplet. Convective heat transport is neglected as the Marangoni convection is considered to be weak, and isotherms as well as streamfunction plots are presented.

2.1 Drop Tube Experiments

Drop tube, drop shaft and drop tower apparatus complement orbital space experiments to study containerless processes in high-temperature metals and alloys. A drop tube is an enclosed space where molten droplets are allowed to cool and solidify while falling freely down a tube within which there is a controlled atmosphere. In a drop tower or drop shaft a whole experimental setup (furnace, sensor electronics, instrumentation, and specimen) is dropped within an enclosure. The technique has some advantages over space experiments, since its simple construction and operation allows testing samples with a low cost, and changing parameters during the experiment. For example the cooling rate in a falling droplet can be increased significantly by back filling the drop tube with an inert gas at a certain pressure. The existing drop tower facilities give a residual gravitational level of 10^{-5}-10^{-6} g and free fall time up to 10-12 s. In microgravity in drop tubes pure metals solidify as single crystals at high undercooling. Beyond a critical undercooling the grain refinement effect was not observed in most pure metals and alloys.

Cech and Turnbull (1956) first used the drop tube technique to study phase formation in Fe-Ni alloys. Lacy et al. (1981) constructed a high vacuum 32 m drop tube apparatus to conduct various containerless low-gravity solidification experiments. Niobium droplets with 2-5 mm diameter have been undercooled by 525^{o}K. A relatively high (320 m s^{-1}) dendritic solidification speed was obtained for test specimens. Solidification at large undercooling resulted in single crystalline spheres with the formation of interdendritic shrinkage channels on the sample surface rather than internal shrinkage voids. It is suggested that this behavior may be related to the purity of the sample, its crystallographic structure or the containerless microgravity environment. A containerless low-gravity environment eliminates container induced kinematic forces, which result in cavitation and grain refinement in 1 g. Naumann and Elleman (1986) described two free-fall facilities, Marshall Space Flight Center's (MSFC) drop tube and Jet Propulsion Laboratory's (JPL) aerodynamic drop facility. The free-fall techniques eliminate difficulties, such as shape distortions and electromagnetic field's impact on the heating and cooling of the sample. However, the limited free-fall distance restricts the sample to a size that can be solidified in the time available. Fujii et al. (2000) conducted surface tension studies via the EML technique in microgravity using high-speed video camera in the drop-shaft at the Japan Microgravity Center. Pure silicon was used to eliminate eddy currents in the liquid sample. The droplet shape was controlled by changing the current ratio in coils. It is shown that surface oscillations of the sample are simpler in microgravity (10^{-5} g) than under terrestrial conditions. They also observed the established relationship between number of peaks and sphericity of the droplet.

2.2 Sounding-Rocket Flight Experiments

A mixture of *Be* and *BeO* was melted and re-solidified on the SPAR 3 sounding-rocket in a low gravity experiment, Wouch et al. (1978). A sample of 9.22 mm in diameter was levitated in the NASA electromagnetic containerless processing payload (ECPP) during 230 s. It is shown that under microgravity conditions a more uniform dispersion can be achieved than at 1 g conditions. Piller et al. (1987) pointed out that the microgravity interval during a sounding-rocket flight is sufficient for one cycle of a complete melting-solidification test. The *Space Processing Applications Rocket* (SPAR) 1 flight experiments were conducted in microgravity ($\sim 10^{-5}$ g) conditions for short ($\sim$ 5-7 min) free-fall time periods, El-Kaddah and Szekely (1984). Berillium spheres of 9 mm in diameter were levitated using spherical coil made of 2.5 mm copper tubing consisting of two turns wound on a 16 mm diameter sphere. The azimuthal angles formed by the two coil turns were 46^o and 74^o. A radio frequency generator (1.2 kW and 107 kHz) was used as a power supply. To achieve 1400^o C sample temperature, 46 W power absorption rate at 300 A current was needed.

To understand the containerless processing of molten materials in space, Jacobi et al. (1981) used a 2.5 cm diameter water drop levitated in a triaxial acoustic resonance chamber during a 240 s low gravity SPAR flight. Oscillation and rotation of the droplet were induced by modulating and phase shifting the signals to the speakers. The film records were digitized and analyzed. The normalized equatorial area of the rotating drop plotted as a function of a rotational parameter was in excellent agreement with values derived from the theory of equilibrium shapes of rotating liquid drops.

2.3 Space Flight Experiments

The microgravity environment in an orbiting vehicle extends the free-fall time indefinitely and allows much larger samples to be processed as well as close observation and manipulation of the sample during processing, Naumann and Elleman (1986). However, the small residual accelerations in an orbiting vehicle require the use of some form of non-contacting positioning force to hold the sample in the confines of its processing chamber for extended periods of time. Rodot and Bisch (1985) describe an EML facility in the Fluid Physics module during the Spacelab 1 mission. A facility for containerless processing of liquid metals using electromagnetic positioning and inductive heating constructed under the TEMPUS program the primary objective of which is the study of high undercooling in the lower temperature region not accessible in 1g is described, and the concept of dividing a desired composite field into a superposition of a dipole field for heating and a quadrupole field for positioning is discussed in detail by Piller et al. (1987).

TEMPUS (Tiegelfreies Elektro-Magnetisches Prozessieren Unter Schwerelosigkeit) is a multi-user and multipurpose Spacelab facility designed for containerless processing of metallic samples. It offers an opportunity to investigate the characteristics of undercooled metallic melts and their solidification behavior under microgravity conditions. TEMPUS was built by Dornier GmbH for DARA, the German space agency. TEMPUS experiments have been conducted on three Spacelab missions: on IML-2 in 1994, and on MSL-1, and MSL-1R in 1997. A technical description and technical data of the facility are presented by Piller et al. (1999). Up to 24 different metallic samples of 6-10 mm diameter can be made to melt without container constraints, undercooled, and stimulated in an inert purified gas (Ar or He) atmosphere or UHV environment at a pressure of 10^{-9} mbar. The facility was designed to provide independent control of heating and positioning using two independent coils. Switching off the heating coil reduces both the input power into the sample, allowing cooling of the sample without a cooling gas, and the forces on the droplet's surface. An additional heating coil between the positioning coils has been provided in this facility to generate a magnetic dipole field of high strength around the sample. This allows controlling independently the heating power and positioning forces under microgravity. A two-color radiation pyrometer was used for the contactless temperature measurements in the range 300-2400^{o}C with high measuring frequency ($\sim$1 MHz). A charge coupled device (CCD) camera (50 Hz monochrome) is used to observe the process along the symmetry axis of the coil system.

Electromagnetic levitation (EML) technique requires contactless temperature measurement by pyrometry. At high temperatures and high-vacuum conditions the specimen is subject to evaporation losses. The evaporated material condenses on the cold parts of the experimental apparatus including the front lenses of the pyrometer leading to reduced radiation intensity reaching the pyrometer and giving the mistaken impression that the temperature has dropped. There are several methods to protect the pyrometer against contamination and avoid the measurement errors:

- The contaminated window is replaced by a clean shield when measurement errors become unbearable. The technique can be improved if a rotor with high rotational speed is inserted in the optical path between the sample and the pyrometer. Then the system becomes quite complex, particularly in UHV environment.

- The diffraction grating technique is an alternative to the shielding mechanism without moving parts. A transmission diffraction grating is placed into the optical path normal to the incident radiation to the sample. It will deflect the light beam, but not metal atoms. However, it is difficult to eliminate radiation losses and there may still be some due to the light not deflected.

- A gas jet in front of the pyrometer is another method to protect the pyrometer against contamination. However this method cannot be used in UHV environment.

- In a periscopic mirror system, contamination can be avoided by the mirror, which blocks the straight line between the sample and the pyrometer. The emissivity and reflectivity of the mirror depend on the type of the material, its surface structure and appearance. Under certain vapor pressure and vacuum conditions the evaporated sample material does not significantly deteriorate the optical quality of the mirror surface consisting of the same material. The absorptivity and reflectivity of the metallic mirror surface remains unchanged during the condensation of sample material, Neuhaus et al. (1992).

- In the double mirror system, two mirrors are placed between the sample and the pyrometer, and the straight line between sample and pyrometer is blocked. Evaporated particles condense on the mirror facing the sample and do not reach the pyrometer. It is assumed that the contamination of the mirror does not severely influence the optical system quality as the condensate metal vapor has the same reflectivity as the mirror itself.

To protect the pyrometer against contamination by condensation of vapor emanating from the sample onto the exposed optical components of the TEMPUS facility, different protection mechanisms: replaceable shielding windows, single mirrors, and double mirror system were tested, Neuhaus et al. (1992). The TEMPUS laboratory module was equipped with a two-color pyrometer with a sampling rate of 1 MHz operating in the infrared region from 300 to 2400^{o}C. The temperature ratio is calculated from the first and the second temperature signals with wavelength range 1-2.5 μm and 3-4 μm, respectively. The temperature-time profile obtained for aluminum sample using CaF_2 shielding windows indicate that this technique could not solve the problem of reproducible and correct temperature data. Metal mirrors of nickel and aluminum on glassy substrates were prepared in specially designed equipment. A nickel mirror and another of aluminum face the specimen and the pyrometer, respectively. The nickel-aluminum combination is chosen because the sample is of nickel. Hence evaporated nickel particles condense onto the nickel mirror surface. The aluminum mirror has higher reflectivity and will not be coated with sample vapor. A high-speed video camera with frame-repetition frequencies up to 500 Hz has been used to observe the droplet from the side in TEMPUS facility. The signals were digitized to obtain sharp contours of the droplet for further image analysis in a computer. The experiments conducted with nickel and aluminum samples for 15 minutes at 1570 and 1100ºC, respectively, showed that the optical quality of the double mirror does not change significantly during the evaporation process.

Lohöfer et al. (1991) discuss the methods and advantages of TEMPUS facility in the measurement of thermophysical properties of liquid metals. They show in particular that the temperature uncertainty in measuring thermal expansion of liquid metals by the method proposed by Shiraishi and Ward (1964) is $\sim$10-45 $^\circ$K. The optical method proposed by Ruffino (1989) for thermal expansion measurements with one CCD camera only is considered preferable to use in TEMPUS facility. Precise measurements of the generator input power as well as of the frequency leads to the determination of the electrical conductivity of molten metals. During the measurements the voltage drop over the condenser can be controlled and kept constant. Another method to determine electrical conductivity from the resonant frequency, which changes with the inductance of the coil generated by a change of the sample conductivity, is also proposed.

Egry et al. (1990, 1999) summarize a proposal for EML experiments in microgravity to measure viscosity and surface tension of undercooled liquid metals as a function of temperature. The applicability of the Arrhenius, the Vogel-Fulcher and the power-law models for the temperature dependence of the viscosity is analyzed. It is assumed that in alloys, intermolecular forces may lead to short range order and association of clusters thereby significantly affecting the viscosity of the sample and leading to the concentration dependence of the viscosity. This effect becomes more pronounced when the freezing temperature is approached from above. Surface tension and viscosity can be determined by exciting the oscillations of a freely floating droplet. The frequency of the oscillations is related to surface tension, while viscosity is determined from the damping. Egry et al. (1990, 1999) single out the following advantages of the microgravity environment as important:

- The sample maintains its spherical shape permitting direct application of the theory.
- There is no turbulent flow in the droplet, and the centrifugal forces on the surface are significantly reduced.
- The processing in UHV and at lower temperatures becomes possible due to the small amount of heat absorbed by the specimen.

- The absence of additional damping due to the magnetic field of the oscillations.

TEMPUS user support tasks are surveyed by Diefenbach et al. (1995). TEMPUS provides high resolution, fast three-color pyrometer and a high-speed video system for diagnostic measurements at the metastable state of a melt below its melting point.

Surface tension of pure gold (T=1225°C, m=5.1 g), gold-copper ($Au_{56}Cu_{44}$, T=970-1080°C, m=4.21 g) and zirconium-nickel ($Zr_{64}Ni_{36}$, T=980-1150°C, m=1.94 g) alloys have been measured in microgravity via the oscillating drop technique by Egry et al. (1996). The experiments were conducted during the Spacelab IML-2 mission in 1994 using the electromagnetic containerless processing facility *TEMPUS*. It is shown that in microgravity the magnetic pressure of the levitation field on the droplet is negligible while in 1g some corrections are necessary, for example see Cummings and Blackburn (1991). The data are in good agreement with those measured by conventional methods. The correction formula accurately accounts for the magnetic field and the gravitational effects.

During MSL-1 mission the surface tension of Zr, $Co_{80}Pd_{20}$, $Pd_{82}Si_{18}$, $Pd_{78}Cu_6Si_{16}$, $Zr_{11}Ti_{34}Cu_{47}NI_8$, and Fe-Ni-Cr alloys was measured using TEMPUS facilities, Damaschke et al. (1999), Lohöfer and Egry (1999). Some surface tension and viscosity measurements of undercooled melts ($Pd_{82}Si_{18}$) recorded during MSL-1 (April 1997), and STS-83 and STS-94 (July 1997) missions are reported by Hyers et al. (1998, 1999). They use contactless modulation calorimetry to measure the specific heat of a number of glass-forming alloys both in the equilibrium melt and in the undercooled region. The viscosity data on $Co_{80}Pd_{20}$, $Pd_{82}Si_{18}$, $Pd_{78}Cu_6Si_{16}$, and $Zr_{11}Ti_{34}Cu_{47}NI_8$ are parametrized according to the Arrhenius law. The surface oscillations are related to the viscosity by Lamb's equation, Eq. (29) and to the surface tension by Rayleigh's equation Eq. (19) in Part II of this series of papers, Bakhtiyarov and Siginer (2008). Specific heat measurements in the stable and undercooled melt of the bulk metallic glass forming alloys by contactless electromagnetic AC-calorimetry in reduced gravity are reported by Wunderlich et al. (1999). A high-resolution radial video camera equipped with telecentric optics was used to measure density and thermal expansion of glass-forming alloys ($Zr_{65}Cu_{17.5}Al_{7.5}Ni_{10}$, $Zr_{60}Al_{10}Cu_{18}Ni_9Co_3$, $Zr_{11}Ti_{34}Cu_{47}Ni_8$, Zr_{57}, $Cu_{15.4}Ni_{12.6}Nb_5Al_{10}$, $Pd_{78}Cu_6Si_{16}$, and $Pd_{82}Si_{18}$) in the undercooled regime. Thermal transport properties such as the total hemispherical emissivity and thermal conductivity of test samples are also investigated.

Although TEMPUS was not specifically designed to measure the electrical resistivity of the samples, Lohöfer and Egry (1999) proposed that the generator voltage, current, and frequency, recorded by the facility could be used to determine the electrical resistivity. The calibration and evaluation processes used in deriving the temperature dependent values of the electrical resistivity of $Co_{80}Pd_{20}$ alloy at solid, liquid, and liquid undercooled states are described in detail. It is shown that the electrical resistivity of $Co_{80}Pd_{20}$varies with temperature linearly in solid and liquid states as

$$\begin{aligned} \rho_s(T) &= 51.9 + 0.044T, \\ \rho_l(T) &= 69.8 + 0.058T. \end{aligned} \tag{2}$$

Rösner-Kuhn et al. (1999) applied two different methods to detect surface oscillations on liquid droplets and to obtain the corresponding frequencies, analysis of the temperature-time signals of pyrometers with fast Fourier transformation and sample imaging with a CCD-camera with subsequent Fourier transformation of the integrated pixel intensity. The experiments were performed using two different electromagnetic levitation facilities on earth and the TEMPUS levitation facility during Spacelab Missions MSL-1 and MSL-1R in April and July 1997. Rösner-Kuhn et al. (1999) determined that the differences in the resulting surface tension values are due to the different levitation conditions.

The thermal expansion coefficient of liquid samples of glass forming metallic alloys in microgravity was measured by Damaschke et al. (1999) in the electromagnetic levitation facility TEMPUS on board the space orbiter Columbia (mission MSL-1). The measured values for the thermal expansion coefficient are between 1.8×10^{-5} K^{-1} and 32×10^{-5} K^{-1} in good agreement with experiments done earlier at lower temperatures.

The TEMPUS facility on Spacelab mission MSL-1R is used by Hofmeister et al. (1999) to conduct statistical nucleation experiments on pure zirconium. Maximum fluid velocities of 5 cm s^{-1}, 27 cm s^{-1}, and 43 cm s^{-1} were imposed on the melt with 50 and 9 undercooling and nucleation cycles. Standard statistical methods are then applied to determine the influence of the flow conditions on nucleation behavior to show that the latter is not altered by increasing the flow velocity in the melt from 5cm s^{-1} to 43cm s^{-1}. Nucleation is affected at velocities above 50cm s^{-1}. Hofmeister et al. (1999) speculate that in the higher flow regime dynamic pressure exceeds static pressure thereby providing the driving mechanism for cavitation. Barth et al. (1999) proposed dendrite growth models by measurements of the growth velocities in pure Ni and dilute Ni-0.6 wt % C alloy melts. The experiments were performed during the MSL-1R mission in July 1997 using the TEMPUS facility. Molten samples of ternary steel alloys also were processed in the TEMPUS facility during the MSL-1R mission aboard the Shuttle Columbia, Matson et al. (1999). Transformation from the metastable ferritic phase to the stable austenitic phase was observed following both triggered and spontaneous nucleation for undercooled samples with a nominal composition of Fe-12wt%Cr-16wt%Ni and Fe-16wt%Cr-12wt%Ni. Predictions based on simultaneous growth of the competing metastable and stable phases show that a significant difference in delay time is observed for ground-based and space processed samples of identical composition, especially at low undercooling, explained by the suppression of melt convection in microgravity.

The experimental results obtained during MSL-1 mission, and the capabilities of *Advanced EML Facility* (former TEMPUS) for thermophysical property measurements of liquid metals on the *International Space Station* (ISS) are discussed by Piller et al. (1999) and Egry et al. (2000). Due to the permanent nature of the ISS, a modular design is proposed to exchange the consumables without replacing the entire facility. Non-contact diagnostic tools, such as pyrometry, videography, inductive measurements are used to measure specific heat, surface tension, viscosity, thermal expansion and electrical conductivity of liquid metals and alloys.

The experiments on board two Spacelab missions STS 83 and STS 94 in 1997 in *TEMPUS* facility conducted on an electromagnetically positioned $Co_{80}Pd_{20}$ sample of 8 mm diameter inductively heated, melted, and overheated are described by Lohöfer et al. (2000). During cooling cycle an excitation pulse was applied every 50 °K until the sample solidified. From image analysis the radius of the sample was determined as a function of time. The damping constant and the frequency are obtained from the time signal and the Fourier transform of the signal, respectively, and are used to estimate the surface tension and viscosity of the liquid sample as functions of temperature. The surface tension changes linearly with temperature,

$$\gamma_{Co_{80}Pd_{20}}(T) = 1.69 - 15 \cdot 10^{-5} \cdot (T - 1613) \tag{3}$$

where T is the temperature in °K. The viscosity can be expressed by an Arrhenius type expression:

$$\eta_{Co_{80}Pd_{20}}(T) = 0.15 \cdot \exp\left(\frac{6790}{T}\right). \tag{4}$$

Linear temperature dependency characterizes the electrical resistivity of $Co_{80}Pd_{20}$ in solid and liquid states:

$$\begin{aligned} \rho_s(T) &= 122 + 0.042\,(T - 1563)\,, \\ \rho_l(T) &= 146 + 0.050\,(T - 1613)\,. \end{aligned} \tag{5}$$

2.4 Parabolic Flight Experiments

TEMPUS is unable to levitate samples in 1g, Lohöfer et al. (1991). The positioning capability of *TEMPUS* has been tested during parabolic flights on a KC-135 airplane, which provides ∼10 s of microgravity (10^{-2} g) at each parabola, Egry et al. (1992). The microgravity time was enough to position and melt a 10 mm diameter 75%Fe-25%Ni specimen with a mass of 4.2 g in a helium atmosphere, and to excite its surface oscillations. In the first 2 s of the experiment, the sample was in solid state without any oscillation. Then the sample was heated up to ∼1580^{o}C (above melting point) and oscillations were excited at about 3 s. At t $\approx$ 6 s when gravity sets in again and the sample hits the sample holder, the oscillations stop. The Fourier analysis reveals only one sharp peak at ν=17.8 Hz in the frequency spectrum, which corresponds to the spherical shape of the specimen in microgravity. Visual inspection of the video recordings identified this peak as (l=2, m=0) mode. Hence, the sample remains essentially spherical in microgravity conditions. Equation (21) in Bakhtiyarov and Siginer (2008) is used to determine the surface tension of the sample near the melting point to obtain a value γ=1.6 N m^{-1} in good agreement with those reported by Keene (1988), but ∼10% lower than the value obtained in the same research in 1g. It is to be noted that time available in microgravity during parabolic flights is too short to estimate the viscosity of the liquid droplet from the frequency spectrum.

From high-speed digital images of the double recalescence behavior of Fe-Cr-Ni alloys in ground-based testing and in reduced gravity aboard the NASA KC-135 parabolic aircraft, Flemings et al. (2002) have shown that phase selection can be predicted based on a growth competition model. An important parameter in this model is the delay time between primary nucleation and subsequent nucleation of the stable solid within the liquid/ metastable solid array. This delay time is a strong function of composition and a weak function of the undercooling of the melt below the metastable liquidus (Figure 1). From the results obtained during the MSL-1 mission and in ground based electrostatic levitation testing at NASA Marshall Space Flight Center (MSFC), they also knew that convection may significantly influence the delay time, especially at low undercooling. For ternary alloys with a similar thermal driving force, the nucleation delay is comparable; this contrasts with the observation that for a single alloy, different nucleation delays are seen under different convective conditions. The authors admit that it is unclear what mechanism controls the formation of a heterogeneous site that allows nucleation of the austenitic phase on the pre-existing ferritic skeleton. By examining the behavior of the delay time under different convective conditions attainable in microgravity, they speculate that it is possible to differentiate among several of these mechanisms to gain an understanding of how to control microstructural evolution.

Egry et al. (2003) reported the results of the surface tension and viscosity measurements on commercial Ti alloys including Ti6Al4V and of the Ni-base super alloy CMSX-4 obtained by the sessile drop, the pendent drop and the oscillating

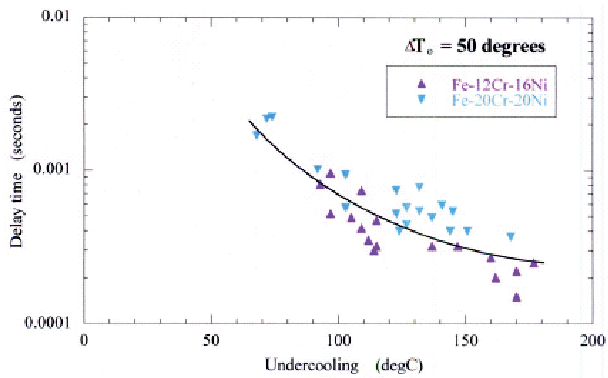

Figure 1: Delay time as a function of undercooling.

drop techniques in an EML device in a ground-based laboratory and during the reduced gravity phase of a parabolic flight. For both classes of alloys, the value of the surface tension is smaller than a weighted average of the individual components, indicating that surface tension is determined by the presence of surface-active elements such as Al rather than by the refractories. This conclusion is supported by the predictions of a model of surface segregation in the Ni-Al system taken as a first step to the CMSX-4 Ni-base super alloy. Overfelt et al. (2000) reported containerless surface tension measurements utilizing an electromagnetic levitator (Figures 2 and 3) in microgravity on NASA's KC-135 aircraft. The device was powered by a commercial 1 kW *Ameritherm* power supply. A vacuum level of 5×10^{-6} torr was maintained during measurements by an *Alcatel* turbopump. Partial pressures of background gases were measured with a *Leybold Transpector* residual gas analyzer. Up to eight samples can be processed without breaking vacuum. The temperature of the samples was measured by a two-color pyrometer calibrated for a nickel sample with an internal B-type thermocouple. Rayleigh's equation is used in calculations of nickel droplet oscillation frequency assuming γ = 1.78 N m^{-1}. Good agreement was found between the predicted and experimentally observed oscillation frequencies for nickel samples with masses less than 0.2 g. However, Rayleigh's theory underpredicts the oscillation frequencies for droplets larger than about 0.2 g.

3 Conclusions

A review of the progress made in EML melting technique since its introduction as a containerless processing technique provides ample evidence on its potential to manufacture certain metallurgical melts with desirable properties which cannot

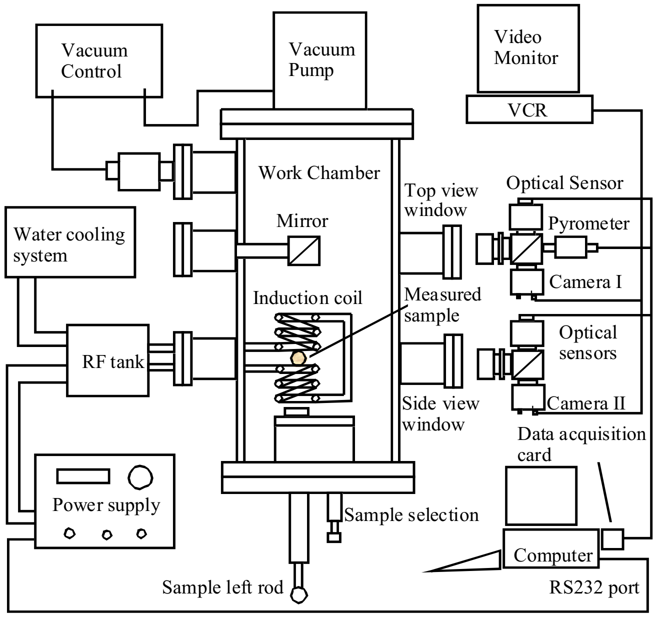

Figure 2: Schematic of electromagnetic levitator designed at Auburn University.

Figure 3: Electromagnetic levitator designed at Auburn University.

be produced by conventional melting methods. Since numerical values of most thermophysical properties are very much influenced by impurities, the EML melting technique as a containerless processing tool is the favored method for their measurements the accuracy of which would be significantly improved if the experiments are conducted in microgravity. Reliable theories are developed to predict the lifting force, the power absorption, the deformation of the droplet, the temperature and the flow field under both terrestrial conditions and in microgravity.

In microgravity the magnetic field strength around a liquid droplet is significantly lower than that required to position the same specimen against earth gravity, a low magnetic field strength results in a low amount of heat absorbed by the specimen, a deep undercooling of molten metals in UHV environment is available, there is no need to cool samples convectively using a high-purity inert gas, the low-strength and uniformly distributed magnetic force fields keep the shape of the droplet spherical, the theories that assume spherical droplet shape can be applied to determine thermophysical properties, and a low magnetic field strength slows down the stirring of the molten specimen and reduces the turbulence of fluid motion. The combination of containerless processing and microgravity offers the possibility to measure thermophysical properties of molten metals both above and below their melting points in a wide temperature range and with high accuracy.

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