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Electromagnetic Levitation of Metal Melts

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Abstract

The main advantage that attracted the attention of researchers was the lack of contact of liquid metal with refractory lining, which ensured the elimination of one of the main sources of metal contamination by such a harmful impurity, such as oxygen. This is especially important for melting refractory and highly reactive metals and semiconductors. Compared to other melting methods, which also ensured the absence of contact of liquid metal with the crucible (vacuum arc, electron beam floating zone, cold crucible, plasma, etc.), EML of metal melts has a number of significant advantages. Among all types of noncontact technologies, only EML has the functions of levitation and heating.

Keywords: electromagnetic levitation, magnetohydrodynamics, free-surface, cold crucible, liquid metal, numerical simulation, surface tension, oscillations, semi-levitation, inductor, coil

1. Introduction

The creation of new inorganic materials, in particular metallic, requires the improvement of existing and the development of new methods for their preparation. The latest melting methods (vacuum arc, induction and electron beam, electroslag, zone, plasma, laser, etc.) of metal melts contribute to further development of modern materials science, while possessing well-known limitations. There is no universal method of melting that would completely satisfy the most diverse requirements of scientists and engineers engaged in this problem. Therefore, it is necessary to use combinations of known melting methods. In this regard, it is of considerable interest to use new methods of melting, for example, electromagnetic levitation (EML) or induction melting furnaces with a cold crucible. It should be noted that, despite a number of obvious advantages, induction melting with a cold crucible cannot yet be widely applied due to imperfect energy conditions for heating the charge and significant heat losses, although quite a certain progress is observed in the designs of furnaces using the principle of cold crucible.

Otto Muck proposed electromagnetic levitation of a metal melt, which is also called melting in an electromagnetic crucible or noncontact, in 1923. He gave the first and simple theoretical explanation of this phenomenon-the implementation of suspension or metal levitation by an electromagnetic field. However, only 30 years later, the first works on the theory and use of this type of melting appeared. Later, studies appeared aimed at expanding the applied and scientific functions of the levitation of metals and alloys both on a laboratory and semi-industrial scale. It

is also interesting that the theoretical justification of the method has always been accompanied by the development of EML [1–11].

- Adjustable residence time of a drop of metal in a liquid state.
- Controlled gas atmosphere and slag phase.
- Controlled metal temperature (from melting temperatures to boiling).
- Ability to use an additional heat source (electronic, laser beam or plasma).
- Vigorous stirring of metal by electromagnetic field.
- Possibility of introducing alloying additives into a liquid drop.
- A favorable ratio between the surface of the droplet and its volume for the passage of heterogeneous reactions.
- Achieving extremely high crystallization rates up to 10^5 – 10^6 °C/s.

Perhaps the disadvantages of the method include a small mass of metal, not exceeding several tens of grams, which to some extent limits the wide industrial application of the method. However, there are known applications of EML in the application of thin coatings in electronics, or the production of fine powders for additive technologies. By the way, for most physical and physicochemical studies, a small mass is not an obstacle.

EML techniques enable the noncontact study of thermophysical properties over a wide temperature range. In this regard, an overview on measuring enthalpy through the method of levitation dropping calorimetry for 30 years is of interest [11]. The results of these measurements of melting enthalpies and melting entropies really amaze with the breadth of coverage (three subgroups of refractory metals) and the complete novelty (obtained for the first time due to EML). For these three subgroups of the periodical table: IVb (Ti, Zr, Hf), Vb (V, Nb, Ta), and VIb (Cr, Mo, W), a group similarity was discovered. Accordingly, the melting entropy of metals of the fourth group is 6.8 – $8 \text{ J mol}^{-1} \text{ K}^{-1}$, the fifth group is 10 – $11 \text{ J mol}^{-1} \text{ K}^{-1}$, and the sixth group is 13 – $14 \text{ J mol}^{-1} \text{ K}^{-1}$, although earlier these data simply did not exist. As for possible industrial applications, the promising process of deposition of thin films of light metals on metal and plastic surfaces, based on the levitation of conductive materials in a high-frequency electromagnetic field, has been studied [12]. The authors focused on the design of the inductor, which ensures the achievement of high specific powers, and the system of rational distribution of vapor, which contributes to the production of a uniform thin coating. According to the authors of [12], this method is most optimal when applying thin coatings of metals with low vapor pressure, such as Al, Ni, Cu and their alloys. It seems quite natural and reasonable to use EML as a part of new technology for high rate physical vapor deposition of coatings onto metallic strip. Many publications are known in which, at a good theoretical level, specific technical problems were solved, for example, increasing the mass of levitated metal or spraying liquid metal [13–22].

During EML, the sample quickly melts, the melt undergoes strong mixing, and as a result, the melt becomes completely homogeneous [23–33]. EML has become widely used to study the refining processes in obtaining metals of high purity, active and with high melting points. EML of metals means the electromagnetic interaction of a sample and a magnetic field. For this, metal samples are placed in an inductor

with a high-frequency alternating current, forming an electromagnetic field in which the sample rises and then melts. Induction current, as a rule, arises on the surface of metal samples, and the interaction between the induction current and the high-frequency magnetic field forms the Lorentz force, which is in equilibrium with the gravity of a solid metal sample in a magnetic field of a certain configuration. As a result, the metal sample hangs in the inductor and levitation is realized. The simultaneous action of the induced current or eddy currents generates Joule heat, which leads to heating and melting of the sample.

The lifting power of levitation, temperature and stability are important factors in the state of EML. At different times, the researchers modeled the influence of the design and arrangement of inductors on the dynamic deformation and stability of metal melts, as well as the vibrations of metal droplets at different points in time, for which arbitrary Lagrange-Euler equations and the finite element method were used. The effect of the second (transverse) magnetic field on the stability of rotation of the experimental samples was also investigated. In the process of EML, the samples are simultaneously subjected to heating and levitation, and EML creates a high temperature distributed on and around the levitated melt. The factors affecting the temperature characteristics of EML, the melting of samples with low conductivity and high density at relatively low temperatures are investigated. It seems interesting to study the influence of the structural dimensions of multi-turn inductors and the sizes of a metal sample on the temperature characteristics of EML, analyzed with the aim of correctly choosing a suitable inductor for various applications.

EML of melts is a progressive and universal method for conducting high-temperature physical and physicochemical studies necessary to improve metallurgical processes, as well as a means for producing miniature parts and samples from high-purity metals. Due to its unique characteristics, noncontact levitation provides obvious advantages in the field of research of new materials. Compared to traditional studies using crucibles made of refractory materials, noncontact technology is a unique research technique, and only it opens up the possibility of completely avoiding contaminants entering the metal melt from the refractory material of the crucible. Noncontact levitation is also used to crystallize samples of objects, measure physical and chemical properties, and produce ingots of highly pure crystalline and amorphous materials. Noncontact measurement of the physical and physicochemical properties of liquid metals made it possible to observe thermal and surface vibrations during the levitation of metal melts not only in terrestrial conditions, but also in zero or microgravity [34–38]. Significant underheating of the sample can be one of the advantages of the noncontact method of levitation. Undercooling means the nonequilibrium state of a liquid sample at temperatures below its equilibrium melting point. The noncontact of a liquid sample is the essence of EML, especially when combined with an ultrapure process medium. In addition, EML is one of the oldest noncontact methods of levitation used for material science experiments for decades. New levitation methods include aerodynamic and acoustic levitation, as well as electrostatic levitation. In these methods, levitation forces arise from electrodes located above and below a sample containing a surface charge, while heating is performed, for example, using a laser. EML is the most mature of all noncontact melting methods and has been used for decades in ground-based experiments, as well as in experiments with microgravity with a wide range of alloys.

Thus, surface tension, density and solubility of various gases in liquid metals were measured, as well as decarburization parameters were established, and features of the Fe desulfurization ability of slags in a wide range of carbon concentrations were studied.

2. Physical features of electromagnetic levitation

2.1 Liquid metal floating in an electromagnetic field

A metal with diamagnetic properties can freely hang in a constant magnetic field in the presence of a potential well in it, that is, a region where the tension decreases from the edges to the middle [4–7]. The interaction of a high-frequency magnetic field with a metal leads to the appearance of eddy currents in the latter, which displace the field from the space occupied by the metal, or, in other words, the field inside the metal is weakened by eddy currents. As a result of this, in a variable magnetic field, a nonferromagnetic conductor behaves like a diamagnet in a constant field. Due to the force interaction of eddy currents and the field, the metal is pushed out of the zone with a higher field density to a region with a lower density, that is, into a potential well. If the indicated forces are sufficiently large, then the metal can be raised up despite the action of gravity and held in space in suspension. The simplest field diagram of an inductor system consisting of three parallel wires is shown in **Figure 1**.

It is of interest to consider qualitatively the physical processes that occur during metal levitation. In **Figure 1b**, the location of the metal in the potential well of the magnetic field of three wires with currents is shown. The direction of eddy currents in the surface layer of the metal is opposite to the current in the wires. On the surface of the molten metal, there are special areas characterized by the absence of eddy currents. This is due to the weakening of the magnetic field in these areas. During levitation, in the lower part of the molten metal sample, such areas necessarily exist with almost any configuration of the magnetic field. The absence of eddy currents in such areas eliminates the appearance of electromagnetic pressure, which should lead to the flow of liquid metal through these places, but this does not happen, since the existing surface tension forces compensate for the weakening of the power shell near points 1–4. It should be noted that these forces can balance only a small part of the hydrostatic pressure of the metal and contribute to the retention of the latter at a small height of the liquid column above the indicated surface area. To partially compensate for the weakening of the interaction of eddy currents of the metal with the field, use a two-frequency power supply system of the inductors, which allows you to periodically shift the weakened magnetic field on a larger surface of the metal. Due to the rapid redistribution of the weakened magnetic field and the large inertia of the molten metal, its outflow through singular points does not occur. This technique also contributes to an increase in the mass of the metal. However, the increase in mass is limited by the formation of folds in the lower part of the liquid metal column. The direction of the folds coincides with the magnetic field lines of force, and the depth of the folds is commensurate with the penetration depth Δ .

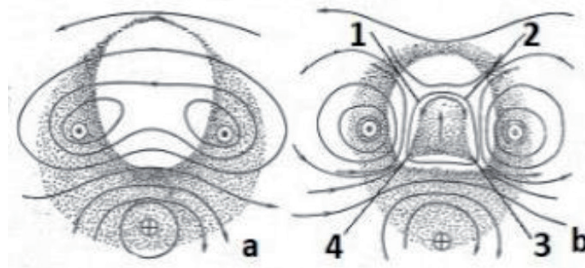


Figure 1.

The magnetic field of three wires with currents (the density of the field lines is shown by the degree of blackness of the shading and fixes the hydrostatic pressure). a—without metal; b—with metal; the numbers 1, 2, 3, and 4 are singular points on the surface of the metal melt.

Along with the indicated limitations of the levitation of metallic melts, there are two more. The first is associated with a given vibrational power in the inductor circuit or, in other words, the limiting field strength corresponds to the limiting metal height h . The second is due to the presence of a minimum volume of liquid metal, which may still be in a levitation state in the cap, close to the penetration depth or skin layer $h_{\Delta} = \Delta$. This was confirmed experimentally by melting Al, Sn, Fe, Ti and Cu using frequencies of 500–2500 kHz. It should only be noted that the surface tension coefficient α and the penetration depth Δ depend on temperature. Currents flow in the upper wires in the same direction, so the field between them is weaker than around each. A particularly strong field is created near the lower wire, through which the current flows in the opposite direction.

In addition to the above-considered features of the interaction of a high-frequency electromagnetic field and a liquid metal during levitation, there is a group of phenomena associated with the stability of the metal [4–7]. The swaying of a droplet hanging in a magnetic field is not a specific property of the liquid state but is caused by the electromagnetic interaction of the metal with the field. Change in the position of the metal relative to the inductor at a constant emf affects the value of the current flowing through the inductor, which causes a change in the force acting on the metal. When conducting experiments with balls of aluminum floating in air, water and oil, the following features of their behavior were discovered:

- Stable equilibrium with respect to finite disturbances in a more viscous medium than air
- Stable undamped oscillations with a small amplitude of constant magnitude (ball in water)
- Increasing oscillations with an amplitude exceeding the size of the inductor (ball in the air)
- Quickly established stable equilibrium (for all studied balls) in oil

The presented nature of the phenomena does not depend on the current value in the inductor (10–30 A) and on the degree of compression of the balls by the magnetic field. The stability of the metal is ensured if the center of curvature of the surface of the melt in its stable state lies outside the volume of the melt. However, this is impossible, since in acute angles, the value of the Laplace pressure of the curved surface of the liquid would reach infinity. The presence of a special configuration in the electromagnetic field of the potential well, as well as a relatively large volume of metal, leads to the extension of the lower part of the ball, and a drop of metal takes the form of a pear hanging from the cuttings down [7].

A characteristic feature of liquid metal during levitation is intensive mixing inside the drop. A model study carried out with liquid sodium placed in a glass flask, which was in an electromagnetic field (**Figure 2**), showed the existence of turbulent motion of the metal inside the flask [4–7]. Using pitot tubes, as well as photographing methods, melt velocities were measured. It can be seen that the bulk of the liquid in the floating flask moves up. Along the walls of the flask, the metal moves at a much greater speed down. To determine the dependence of the metal velocity on the magnetic field strength, the flask was fixed and the vertical velocity component was measured for various current values. Special experiments without a flask made it possible to conclude that the mixing of the melt during levitation in vacuum or an inert gas is more intense than that described above, since the velocity of the metal on the surface of the drop is not equal to zero. With an increase in the current value in

the inductor, the metal velocity increased. The stability of the metal largely depends on the speed of its rotation. This is usually observed with a spherical shape.

The complete process of heating and melting a sample can consist of four stages. At the first stage, the solid sample rises to fixation in a certain stable position (**Figure 3a,b**). This part of the process completely depends on the location of the inductor, field currents and the initial position of the sample. With incorrect levitation parameters, the behavior of the sample may turn out to be unpredictable. The next step is to heat the sample to the melting temperature (**Figure 3b**). At this stage, with increasing temperature, a change in the physical properties of the material itself is possible, which can affect both the change in the electromagnetic field and the stability of the position of the sample. Therefore, this stage is central to the duration and overall effectiveness of the levitation process. The third stage consists of melting the sample (**Figure 3c**). It is known that the melting model is

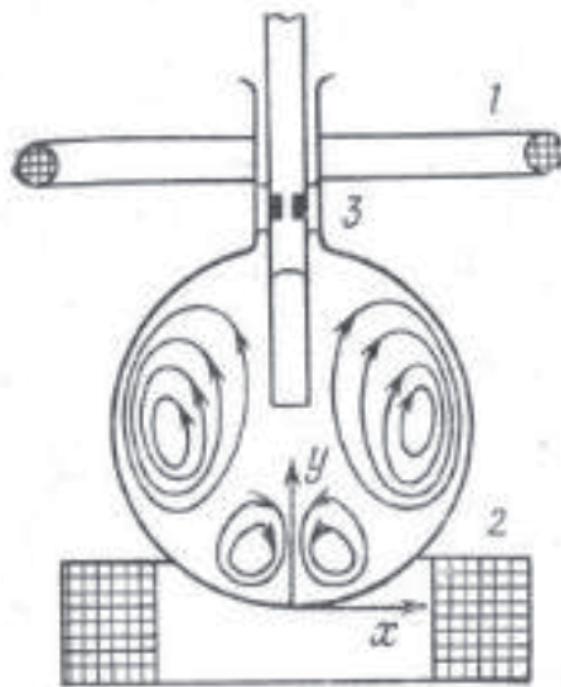


Figure 2.
The motion of the melt in a flask with liquid sodium. 1, 2—inductors with 50 and 700 turns, 3—diaphragm.

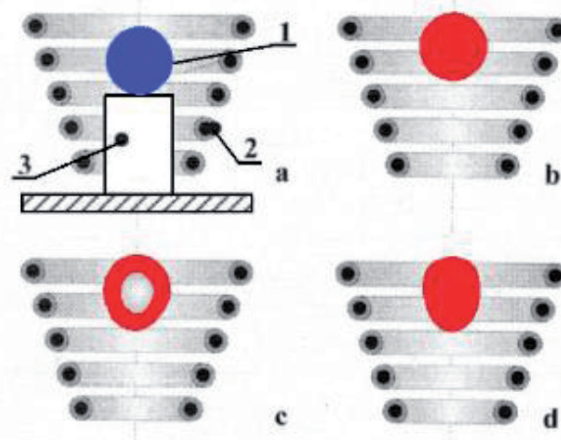


Figure 3.
Simplest arrangement of induction melting with one inductor: 1—solid charge, 2—inductor; 3—ceramic stand. a—the solid sample is fixed in a certain stable position in an inductor; b—the sample is heated to T_m ; c—melting the sample; d—the sample is melted, and the melt can be heated to a given temperature due to intensive mixing.

not easy even from a geometric point of view, but it is characterized by the fact that the internal volume of the sample remains solid, while the surface of the sample is covered with a liquid film due to the surface nature of the implementation of Joule losses. At the fourth stage (**Figure 3d**), the sample is melted, and the melt can be heated to a given temperature due to intensive mixing.

2.2 Solid and liquid metal levitation

The main problem of levitation is the development of a theory and its applications to the problem of the retention of liquid metal during EML, although over the past decades there have been many studies that are somehow related to the theoretical basis of levitation. The significant advantages of EML compared to other methods of metal melting have led to the rapid spread of this method; however, this had to be done almost by touch, without sufficient theoretical justification. More recently, more or less adequate theoretical foundations of the method have been developed that can be used to optimize the setup parameters for levitation. Historically, for example, in Russia, the development of levitation occurred along the path of using two-coils and multi-coil inductors. This significantly affected the development of the theory. The main reason for using two types of inductors is the different power of high-frequency generators used for levitation. Two-coil inductors require increased power (26–100 kW), while multi-coil inductors are able to operate at lower power (8–15 kW). Theoretical prerequisites and experimental possibilities for using two-coil inductors (with parallel turns) were developed by Alex Vogel and his lab [6, 39]. In accordance with the development of this lab, the effect of an idealized uniform electromagnetic field on the metal half-space is summed up from the electromagnetic force (F) and the power absorbed by the metal (P_s), which goes to heat it. Analytically, this is expressed as the following relationship:

$$F = \frac{1}{2} \sqrt{\mu / \pi \rho f} P_s S \quad (1)$$

where F is the electromagnetic force acting on the metal and equal to its mass; μ is the magnetic permeability of the vacuum; ρ is the electrical resistivity of the metal; f is the field frequency; and P_s is the power transmitted to the metal and referred to a surface unit:

$$P_s = \frac{1}{2} \sqrt{\pi \mu \rho f} H^2 \quad (2)$$

where H is the amplitude of the magnetic field on the surface of the half-space. As a result of solving the system of Maxwell equations for a plate in a longitudinal plane-parallel magnetic field, the dependence of the magnetic component of the field on its frequency is established for

$$\beta x = \operatorname{Re} \left[\frac{\delta y B_z}{2} \right] = \text{Const.} \quad (3)$$

and a constant plate thickness. This dependence was hyperbolic in nature. Therefore, with a fixed size of the metal sample, there is a well-defined frequency range at which the metal theoretically levitates in an electromagnetic field. The choice of a specific frequency value is determined by the required sample temperature. In addition, it is also necessary to take into account the configuration of the field in order to determine the nature of the dependence of the lifting force on its parameters. Several similarity criteria were theoretically established (conditions for the equality of electromagnetic pressure and mass, equality at specific points of hydrostatic and Laplace forces, and equality relating the skin effect, circular

frequency, etc.) and experiments were conducted to simulate the vaporization of liquid aluminum on molten sodium. In an elongated two-coil inductor “with a parallel reverse coil,” a group of droplets that did not merge with each other due to the existence of repulsive forces between them was stably held, which is obviously explained by the interaction of currents of the opposite direction flowing at the ends of the droplets. For levitation, when the field is inhomogeneous and the metal moves in it, falling into zones of various configurations, coefficient A characterizing the configuration of the field is introduced into Eq. (2), and then Eq. (2) takes the form:

$$F = \frac{1}{2} \sqrt{\mu / \pi \rho f} A P_s \quad (4)$$

The validity of this equation is verified experimentally, provided that the inductor has a coefficient value $A = \text{Const}$. The power supplied to the copper, molybdenum and niobium balls with a diameter of 15 mm at different field frequencies using the same two-coil inductor “with side parallel coils” was calorimetrically determined. This power was compared with the calculated one [6, 39]. The difference between P_s obtained by calculation and experimentally was 23%, which proves the good reliability of Eq. (4), in which the values of coefficient A are determined experimentally for each type of inductor. For a two-coil inductor “with two side parallel coils,” the values of A vary from 0.7 to 0.9, whereas for a two-coil inductor “with two parallel coils,” these values vary from 0.4 to 0.7. For a two-coil inductor “with sequential switching of coils,” the values of coefficient A are in the range of 0.2–0.7. Ensuring the transmission of a given power P_s depends on the mass of the metal, the surface of the sample, the frequency of the field and a certain coefficient A . Coefficient A characterizes the degree of heterogeneity of the electromagnetic field. It was experimentally established that the greater its heterogeneity, the smaller the coefficient A , which theoretically can tend to zero, but it is practically impossible to get it less than 0.2. The heterogeneity at the surface of the melt is different; therefore, the value of A also depends on the position of the melt in the inductor and on the size and shape of the sample. When considering the behavior of a metal ball in the field of a two-coil inductor system, the functional dependence of coefficient A on the position of the sample was determined [6]. All investigated metals are divided into three groups in accordance with the interval of fixed temperature:

Group 1: Al, Fe, Co, Ni, Cu, Rh, Hf, Ir ($t_r > t_m$); Group 2: Ti, Zr, Nb, Mo, Ru ($t_r > t_m$, depending on I and U); Group 3: Ta, W, Re, Os ($t_r < t_m$).

For a two-coil inductor, the dependence of r/A on the volume of various metals is obtained, which varies similarly to the previously described [6]. The increased temperature range corresponds to the optimal volume of the metal, so that depending on the frequency, a different temperature of the metal melt is set, and in vacuum, the temperature is always higher. It is promising to obtain a stable melt temperature using two fields: holding and heating, but not for all metals equally. For Group 1 metals, the use of two-frequency heating is excluded, since the confining field overheats these metals much higher than t_m . For metals of Groups 2 and 3, two-frequency heating is practically possible.

The interdependence between the values of the function F characterizing the skin effect and the power P transmitted to the metal is extremely important. Obtaining a given metal temperature is achieved either by changing the frequency of the generator or by choosing the shape of the inductor. A change in the current in the inductor cannot lead to a direct change in the P/F ratio, since both quantities depend on I^2 . With increasing current, the metal in the inductor rises and falls into the area with a lower electromagnetic field strength and a large gradient of it. This means that temperature can only be controlled to a limited extent.

In addition to the dependences of the lifting force described above on the frequency and intensity of the electromagnetic field, as well as on its configuration, there are specific conditions for a limited choice of the field frequency for holding a liquid metal, which is characterized by a change in shape. It was previously noted that metal during levitation is located in a potential well in which at least one singular point or area of a weakened field necessarily exists through which the metal does not pour out only due to surface tension on a curved surface. In areas of a weakened field, the pressure of a liquid metal column is balanced by the difference in surface tension values on the curved surfaces of the lower and upper parts of the metal [6]. The use of a two-coil inductor at the selected frequency and configuration of the electromagnetic field revealed the need to study the relationship between the voltage applied to the inductor and the behavior of the liquid metal during levitation. Experimentally, the lowering of a drop was recorded with a decrease in voltage. When a certain value was reached, the metal began to flow out of the inductor. The release of the melt can be controlled by increasing the area of the weakened field while maintaining the strength of the magnetic component of the field, necessary to hold the bulk of the metal. It was experimentally established that in a two-coil inductor there are three zones of the electromagnetic field [6]. In the first zone, the solid metal hangs, and the liquid merges independent of the capillary constant. In the second zone, the liquid metal hangs unstably; its degree of stability depends on the volume of the metal and does not depend on the capillary constant. In the third zone, the position of the metal in the inductor is associated with the presence of volume dependence. The use of a multi-coil inductor at the selected frequency and configuration of the electromagnetic field revealed the need to study the relationship between the voltage applied to the inductor and the behavior of the liquid metal during levitation.

2.3 Temperature of the levitated melt

Along with the retained metal melt, the production and regulation of its temperature are of great importance. For two-coil inductors, the theoretical foundations and technological designs that provide the necessary heating of the samples were considered in [6, 7]. The validity of the functional dependence (4), which relates the electromagnetic lifting force to the power absorbed by the metal, has been proved experimentally. In the steady state in vacuum, the power transmitted to the metal is equal to the radiated power. For most metals, the temperature dependence of the power P_s radiated from a unit surface is well known (**Figure 4**). This power is usually determined by the reverse calculation. It is known that ensuring the transmission of a given power P_s depends on a number of factors: the mass of the melt, the surface of the sample, the frequency of the field and coefficient A . The mass of the melt during levitation in a multi-coil inductor can be determined by knowing the minimum frequency of the electromagnetic field that implements the levitation of a metal melt with a given height and physical properties.

Obtaining high temperatures during the levitation of metal melts has no fundamental obstacles. In practice, this is accomplished by choosing, for example, a multi-coil inductor, the conical part of which is open at a small angle and whose field has a small tension gradient. To obtain the necessary lifting force, a sufficiently large current is needed, due to which the metal is heated. Due to the fact that the power increases proportionally with frequency, and the lifting force is much less dependent on it, the field frequency is increased to obtain a higher temperature. In each case, the field frequency must be chosen so that the value $X = R/\Delta$ (here R is the radius of the sphere and Δ is the thickness of the skin layer) is more than 10 and the value of F does not depend on the change in ρ . Otherwise, during heating, the

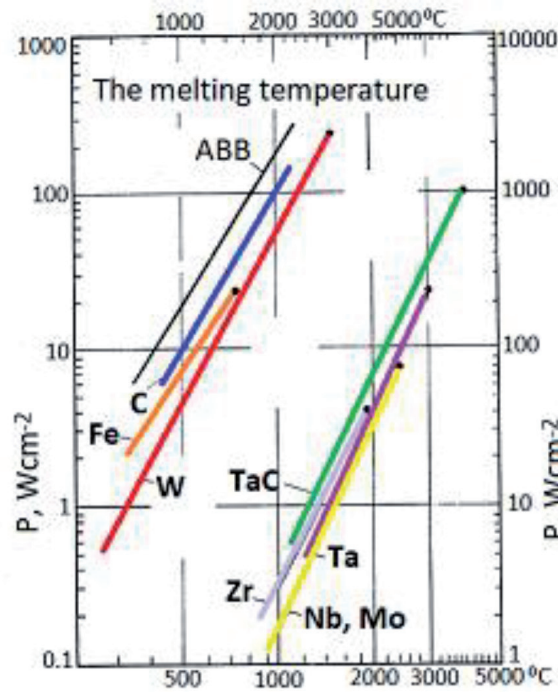


Figure 4. Dependence of the specific radiation power on the temperature of refractory metals. ABB—the absolutely black body.

value of X may become less than 10, and the value of F at $I = \text{Const.}$ will decrease, which will lead to the discharge of the molten drop. Low temperatures of the melt can be obtained at such a frequency and diameter of the spherical sample, when the value of X is more than 10. In this regard, F should be about 50% less than its full value (when X is more than 10). As mentioned above, the current in this case is regulated within certain limits, and the shape of the inductor must be such that the intensity gradient is maximum. In this case, the stabilizing forces become very small.

Temperature control can be done in two ways. The first is the selection of such an inductor shape in which there is a strong dependence of the P/F and F ratios on the position of the sample inside the inductor. An inductor is suitable for this, in which there exists a possibly large linear decrease in field strength along the axis of the inductor. In this case, P also depends linearly on the position of the sample. If the current is increased, the sample rises to the upper part of the inductor and its temperature decreases. The second method consists in the separate action of two inductors fed by currents of two frequencies: the lower one—for levitation of the metal at the lowest temperature—and the upper one—only for heating and melting the sample with regulation of current and frequency. In EML, samples simultaneously participate in heating and soaring, so that the power of EML unambiguously indicates a high temperature distributed around the soaring sample. This explains the interest in studying factors regarding the influence on the temperature characteristics of EML with the final goal of gaining additional knowledge in order to not only fully realize the levitation and melting of samples with low conductivity and high density at relatively low temperatures, but also fully use the primary role of inductors on the temperature characteristics of the electromagnetic field. So, in [6, 39] for the first time, using the finite element analysis, the influence of the design of inductors and the mass of samples on the temperature characteristics of levitation were studied. The modeling capabilities are confirmed experimentally as a result of a detailed analysis of the effect of the inductor on the temperature characteristics of levitation when choosing the optimal inductor in various applications. The shape of the metal

melt depends on the degree of compression of the melt by an electromagnetic field, which is largely determined by the configuration of the inductor. In a multi-coil inductor, the limiting melt height can be approximately two times smaller than in a two-coil inductor [6].

To obtain a given stable steady-state temperature, not only two-frequency levitation, cooling gas mixtures, but also other heating sources (electron beam, light beam, electromagnetic beam with a frequency corresponding to the centimeter and millimeter wavelength ranges) can be used. Refractory metals are known (Group 3), which, under experimental conditions, levitated in an inductor, but were not melted. Therefore, for their additional heating, a source of thermal energy—an electron beam—was used [6, 7]. Indirect heating is also used due to the relatively low efficiency of induction heating, which is mainly due to the presence of a large gap between the inductor and the metal sample and, in fact, depends on the design of the inductor. The use of additional heating is shown by the example of tungsten, which should melt at a frequency of 440 kHz, a power of 160 kW and a mass of 28 g. **Figure 5** shows experimentally determined temperatures depending on their mass and voltage at the inductor (40–90 V). Obviously, an increase in the mass of the sample cannot lead to a significant increase in the temperature of the metal ($\sim 3000^{\circ}\text{C}$). At this temperature, the power emitted by the melt surface ($\sim 7.5\text{ cm}^2$, the shape of the melt is a spinning top) is 1.7 kW, which corresponds to 1.7% of the power consumed by the generator. This complicates the cooling of the inductor with water and significantly increases the voltage (up to 300 V). The arrow in **Figure 5** shows the temperature rise of a metal after being heated by an electron beam ($\sim 3700^{\circ}\text{C}$). Radiated power increases to 3.4 kW, that is, 1.7 kW is additionally transmitted, which is 68% of the total power of the electron beam unit (2.5 kW).

Similar results were obtained with EML of a 30 g Nb sample in a multi-coil inductor at a voltage of 30 V, a generator power of 25 kW and a frequency of 80 kHz. The metal temperature was 2100°C , which in terms of absorbed power is 0.5 kW or 2% of the power consumed by the generator. The metal was heated by an electron beam to a melting point of $\sim 2415^{\circ}\text{C}$, and the power was 1.2 kW. The melt surface emitted $\sim 1\text{ kW}$. This means that the electron beam additionally transmitted at least 0.5 kW or 40% of the power consumed by the electron beam setup. By the way, electromagnetic levitation of the Nb melt without additional heating can be carried out in the same type of inductor using a more powerful generator (60 kW) with a frequency of 440 kHz and a voltage of 160 V.

Additional heating may also be necessary in specific cases, for example, with silicon levitation. Pure silicon is known to have an extremely high electrical resistance; therefore, at ordinary frequencies (of the order of hundreds of kilohertz) and power (tens of kilowatts), silicon cannot be levitated. With increasing temperature, the electrical resistance of silicon decreases, especially sharply at the melting temperature; therefore, for silicon levitation, it is necessary to pre-heat it with an electron beam. If the field frequency during silicon levitation is about 200 kHz, then the sample should be heated to $10,000^{\circ}\text{C}$, and at frequencies of 70–80 kHz, up to $14,000^{\circ}\text{C}$.

Two-frequency heating has been studied in less detail. The experiments with aluminum were carried out in air. An inductor for EML was connected to a machine generator with a frequency of 8 kHz, and an inductor for heating, from a generator with a frequency of 440 kHz. Five different two-coil inductors were tested, producing a two-frequency field. The most rational were (1) an inductor with a single coil for holding the sample, placed above the main heating coil; (2) an inductor with a single holding coil placed between two main heating coils; and (3) an inductor with a single holding coil placed above the main heating coil.

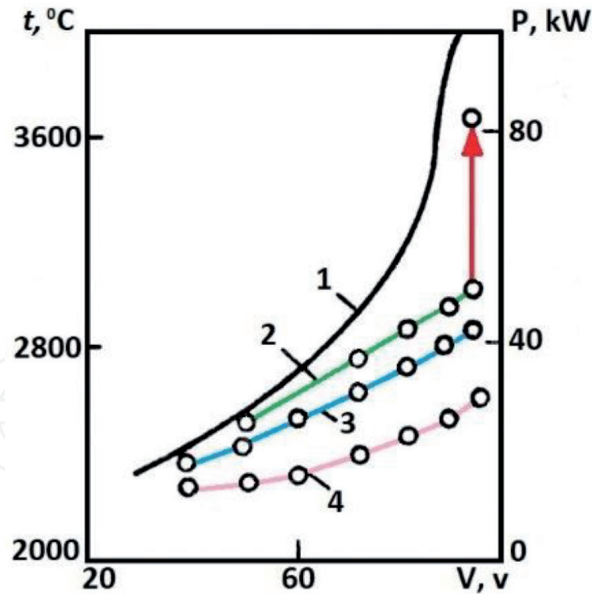


Figure 5.

The dependence of the power of the generator and the temperature of tungsten of various masses on the voltage at the inductor; the arrow shows the temperature of the metal after additional heating by an electron beam: 1—P, kW; 2—28.5 g; 3—20 g; 4—10 g.

In axisymmetric EML, the Lorentz force vanishes on the axis of symmetry. At the lowest point on the axis of the levitated sample, only the surface tension of the melt prevents the flow of the melt, which affected the limitation of the mass of the melt—not more than 50–100 g. With electromagnetic two-frequency levitation, lifting forces also arise along the axis of the levitated sample. Digital models developed to optimize EML were implemented in [13–18]. At the same time, data were obtained on the electromagnetic flux and the dynamics of the free surface, for which calculations of the electromagnetic force, as well as modeling of the melt volume and restoration of the shape of the free surface, were made.

2.4 Setups for EML of melts

Depending on the voltage at the inductor, its design and the conditions of the technology and experiment, all setups for EML are divided into two groups: with an internal inductor and an external inductor relative to the reaction vessel. The first group includes setups powered by quenching circuit generators and equipped with two-coil or multi-coil inductors of all known types when operating in a vacuum or inert gas environment. The second group includes setups with multi-coil inductors, powered by generators without a quenching circuit for operation at atmospheric pressure or low discharge. The setup with a two-coil inductor, designed to obtain samples used in metal research, appeared in the middle of the last century [6, 39]. The metal vessel housed an inductor for levitation, a rotary table with copper molds, a table for initial samples and a manipulator. Later, the same authors [6, 39] developed a 27-position setup for levitation, consisting of a high-frequency generator, a reaction vessel and a vacuum unit. Another reaction vessel is shown in **Figure 6b**. A sample with a manipulator was placed in a double-coil inductor, where levitation and melting of the metal took place. A transparent shutter 6 protected the sight glass 8 from condensation of metal vapors on it. After a given exposure, the melt was poured into the mold 2, located coaxially with the inductor 4. A characteristic feature of such setups was the presence of a rotating table with molds and a manipulator.

Another feature of such setups was devices for various physicochemical studies, for example, the interaction of elements in the melt-slag-gas system. The reaction vessel shown in **Figure 6** is made of copper, and the flanges of the vessel are closed with plexiglass covers. Water cools the inductor and the stabilizer ring, located directly above the conical multi-coil inductor. A copper pin crystallizer cooled by liquid nitrogen is intended for crystallization of the drop with a liquid slag (in the lower part of the drop). The mold could be moved in vertical and horizontal planes without violating the tightness of the reaction vessel. The setup was powered by a 10 kW generator with power regulation at the inductor by lowering the primary coil, which provided finer regulation.

Typical for setups of the second group with an external inductor relative to the reaction vessel is the use of multi-coil inductors, quartz glass for the reaction vessel and various means for instant crystallization of metal melts (**Figure 7a,b**). This is explained by the fact that such plants were used for high-temperature studies of the solubility of gases in melts, in particular, nitrogen in iron-carbon melts and the pressure of saturated iron vapor. The body of the reaction vessel is made of quartz glass with polished joints of individual elements. The location of the reaction vessel in the inductor is characteristic-its configuration repeats the internal shape of the inductor, which led to a slight increase in the diameters of the upper and lower coils of the inductor and, as a result, to a decrease in the efficiency of the inductor and an increase in the used power of the generator. At the bottom of the reaction vessel was a turntable with molds for melt crystallization. The turntable was rotated in such a way that there was a free socket on the same axis as the reaction vessel, which made it possible to measure the temperature of the melt using an optical pyrometer. Depending on the purpose of the experiment, some elements were changed in the setups of the second group and additional devices were introduced, for example, to crystallize the melt when oxygen was falling in the atmosphere or to crystallize at an increased velocity using the hammer-anvil device.

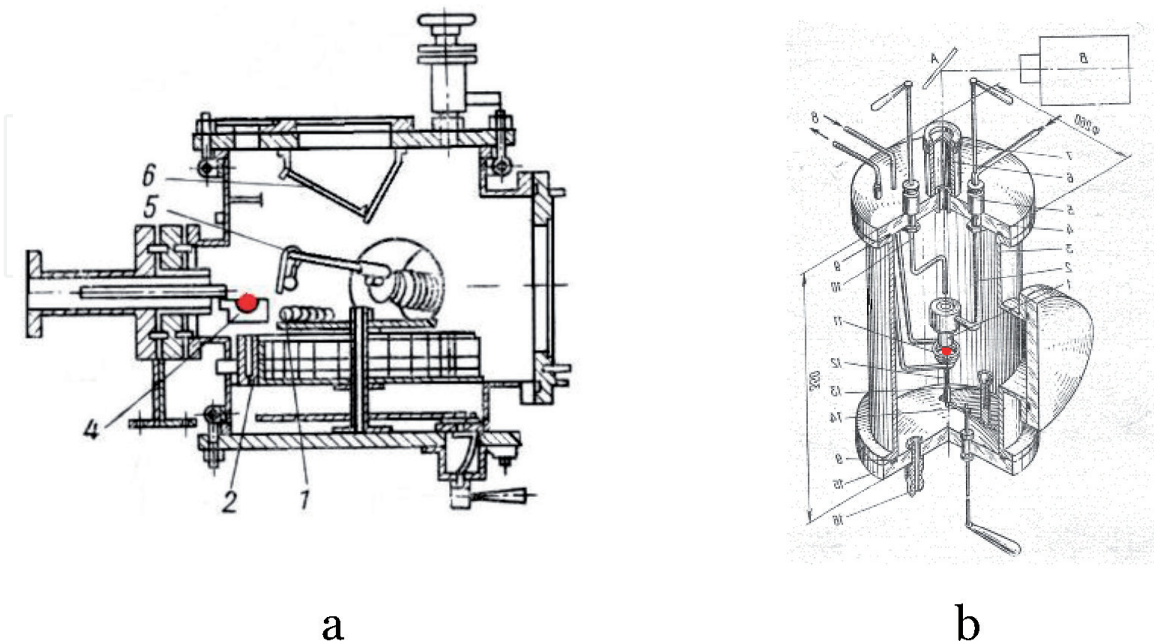


Figure 6.
 a—Multi-position setup for levitation and studies in systems “melt-gas”; b—Levitation setup for physicochemical studies in “melt-gas” and “melt-slag-gas” systems.

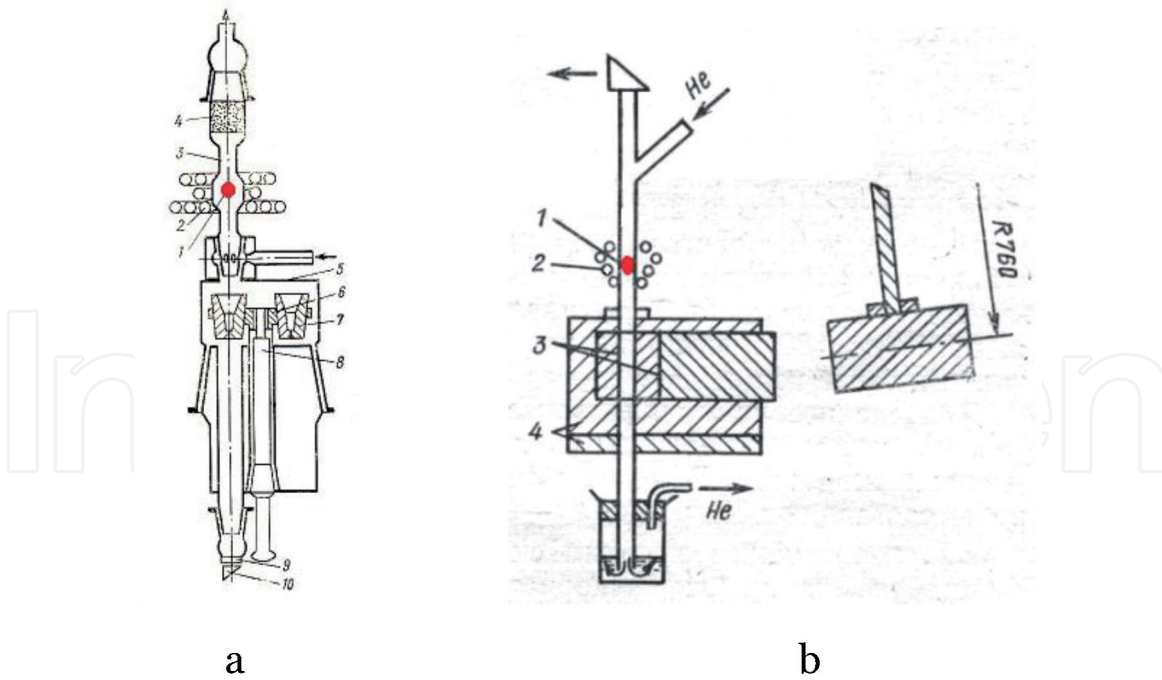


Figure 7. Schemes of levitation quartz setups for studying the solubility of gases in liquid metals with fixation of dissolved gas using: a—Crystallization in molds; b—crystallization with a hammer and anvil.

2.5 Inductor designs

The inductor and the heated metal sample form a single electromagnetic system, similar to a transformer in short circuit mode. However, the functions of its parts are clearly separated in the transformer: electric current passes through the windings, magnetic flux through the magnetic circuit. In contrast, the surface layer of the heated sample is simultaneously a secondary electrical winding and part of the magnetic circuit. Therefore, in the general case, when calculating the parameters of the inductor, it is necessary to take into account not only the magnetic flux passing in the gap, but also the flux in the metal. In addition, the consideration is also complicated by the fact that the values of ρ and μ at different points of the cross section of the heated metal are different and change over time. The heating process (cold, intermediate and hot modes) during electromagnetic levitation and the assumptions made to simplify the relationship between ρ and μ for subsequent calculations ($\rho \times \mu = \text{Const.}$) are studied in detail and are available in the reference literature. The values of μ are determined as a function of the magnetic field strength at the interface, using the magnetization curve. Due to the fact that the magnetization of the magnetic field depends on the specific power in the heated sample, the magnetic permeability is its function. Examples of the general calculation of the inductor are quite possible, and the necessary relations can be obtained from solving the electromagnetic field equation as applied to the propagation of electromagnetic energy inside a flat conductor of infinite thickness. Examples of calculating a single-coil quenching cylindrical inductor, with which the diameter of the inductor and its width, voltage and current, the efficiency of the inductor and the power supplied to it could be determined. However, it is impossible to use this calculation to determine the parameters of inductors for EML, since it does not take into account the main difference between EML and known heating methods—the existence of a force supporting a metal sample in solid and liquid states.

In this regard, the most important and necessary feature of EML is the use of special inductors, the electromagnetic field of which holds and heats the metal

sample. As noted above, the great merit of Alex Vogel [6] and his lab consists in the development of two-coil inductors, consisting of two parallel coils connected in parallel. The inductor design is shown in **Figure 8**. The vertical bends of the profiled copper tube are made for stable melt levitation. One of the important operating parameters of two-coil inductors is the relationship between the power referred to the mass of the metal and the square of the amplitude of the magnetic field.

In addition, a feature of this inductor is the presence of two critical voltages: the first and second, indicating a limitation of stability in the lower and upper positions. It also has some disadvantages: manufacturing difficulties (profiled copper tube); the maximum achievable temperature of the melt is always lower than in the inductors of two other designs; the need to place an inductor inside the reaction vessel. However, this inductor has several advantages: its dimensions are relatively small; the field is symmetrical; potential difference is minimal; the bottom of the inductor is at the same potential; and the mass of the sample is greatest. Two-coil inductors of two other types differ significantly in their characteristics from the inductor described above. Their designs are presented in **Figures 9** and **10**. In both cases, the P/G values monotonically increase with increasing power supplied to the inductor. A higher temperature of the metal melt is achieved as a result of a larger compression of the melt by the field. However, this leads to an increase in hydrostatic pressure in the melt and levitation of a smaller volume of metal compared to the first inductor.

The inductor of the second type has the following characteristic features: (1) the maximum potential difference between the inputs is lower than in the third inductor; (2) the bottom of the inductor is not equipotential, although the low voltage at the lower coil and the large contact resistance between the inductor and the sample exclude melt welding; (3) higher losses in current leads than in the third inductor; and (4) the limiting temperature of melt during levitation is always less than in the third inductor. For the inductor of the third type, the characteristic of the inductor of the second type is valid with the difference that: (1) the potential difference between the inputs of the inductor is maximum; (2) losses in current leads are minimal; (3) the highest sample temperature; (4) the smallest sample mass [7].

Multi-coil inductors having a reverse coil or a stabilizing ring are most widely used in the practice of electromagnetic levitation. **Figure 11** shows the multi-coil inductor with a stabilizer ring, which was used for several physical studies with Nb, Mo, Fe, Co and Ni [7]. The main advantages of these inductors are as follows: (1) the possibility of using generators of low (8–15 kW) and medium (30–60 kW) power; (2) obtaining an electromagnetic field of almost any configuration; (3) a small

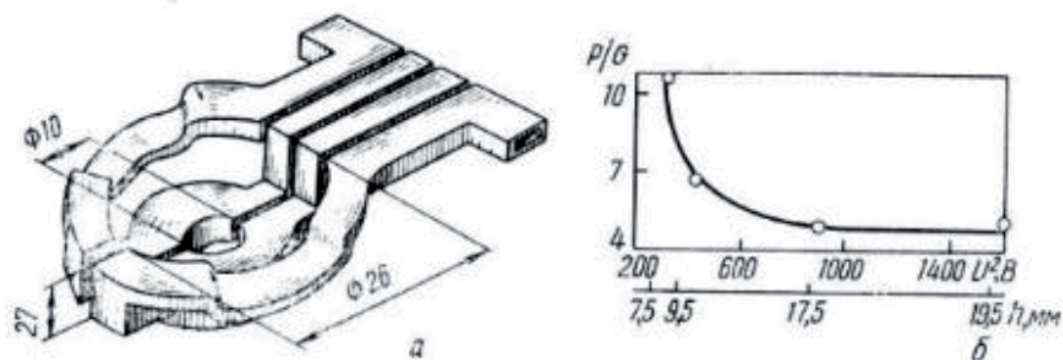


Figure 8.
 Type 1 (a) inductor and the dependence of the power transmitted to the sample on the voltage across the inductor (b); h is the distance from the center of the sample to the upper plane of the lower part of the coil, and the field frequency is 200 kHz.

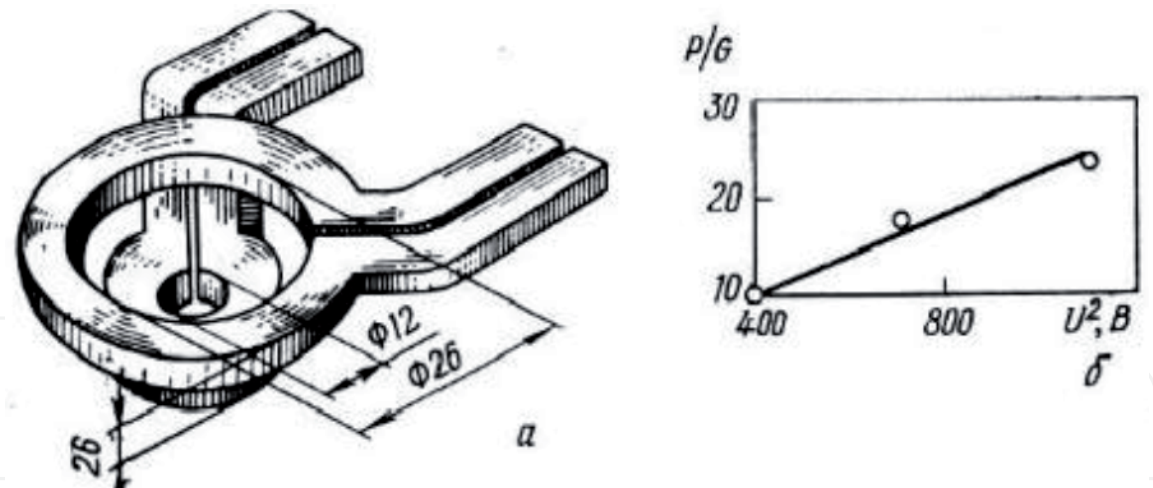


Figure 9.
Type 2 (a) inductor and the dependence of the power transmitted to the sample on the voltage across the inductor (b); the distance from the center of the sample to the plane of the lower coil of the inductor is constant, and the frequency is 200 kHz.

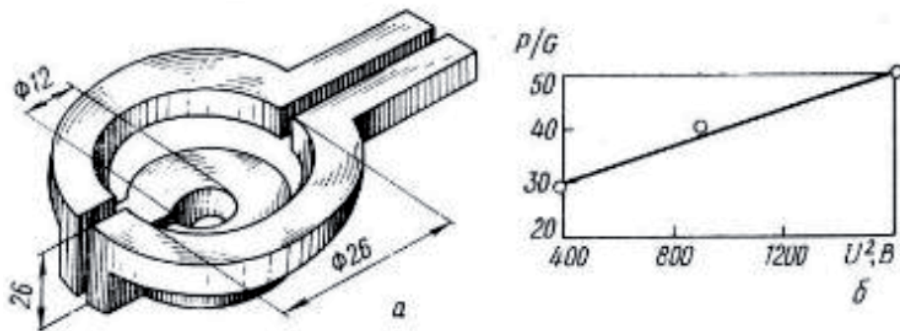
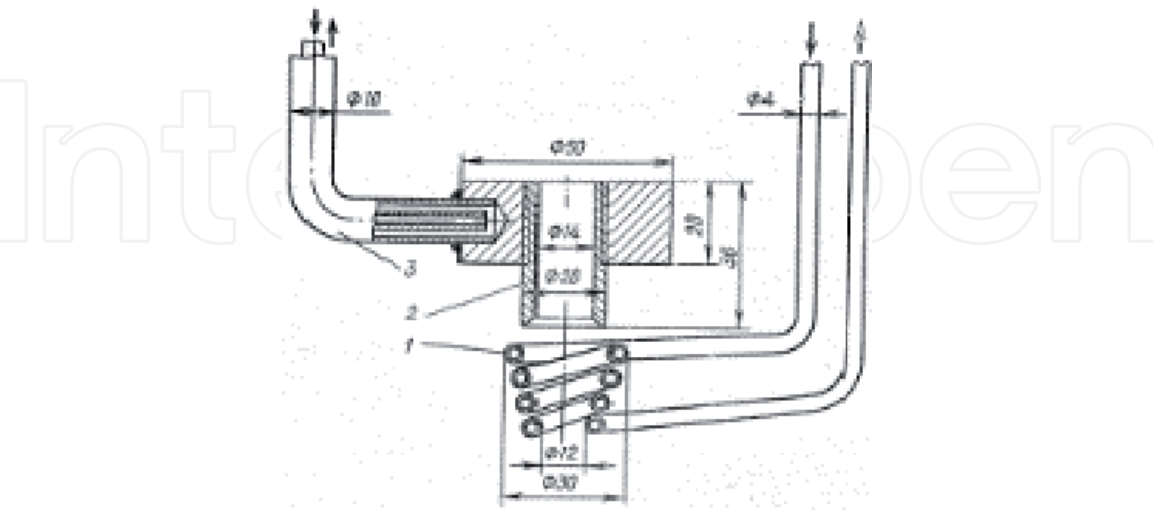


Figure 10.
Type 3 (a) inductor and the dependence of the power transmitted to the sample on the voltage across the inductor (b); the distance from the center of the sample to the plane of the lower coil of the inductor is constant, and the frequency is 200 kHz.



disadvantages are also simple: (1) low mass of the sample; (2) limited temperature control; and (3) the possibility of burning the inductor with the melt.

Previously, the behavior of the melt during levitation in a multi-coil inductor (the number of coils of the conical part, the angle of inclination and the number of reverse coils) and the parameters of the levitated sample (levitation and melt temperature) were examined in detail. A rigorous calculation of a multi-coil inductor for levitation of a melt is still impossible. In this regard, the selection and manufacture of such inductors are carried out empirically, taking into account general ideas about their work. The literature describes more than two dozen designs of multi-coil inductors used for various physical studies. It is almost impossible to classify them according to any criteria, since the tasks solved by their creators were always different. The technique for selecting multi-coil inductors is as follows [7]: the selection criteria are stable levitation (determining the location of the sample in the potential well of the electromagnetic field) and the maximum possible regulation of the temperature of the metal (e.g., solid copper and liquid iron). A generator with a power of 30 kW and a frequency of 230 kHz was used. Inductors were prepared from a copper tube with an outer diameter of 4 and 6 mm. The initial shape, the number of coils of the conical part and the cone angle ($\sim 60^\circ$) were selected in accordance with the data of [7]. The internal diameters of the lower coil of the conical inductor and the upper return coil ($d_1 = 15.5$ mm; $d_2 = 22$ mm) were the same for all multi-coil inductors and were selected in connection with the required metal mass (average weight 3.5 g) and dimensions of the reaction vessel. Stable levitation of the melt was determined visually: the time from the moment of melting to the outflow of the metal from the inductor was noted (the latter phenomenon is associated with the saturation of liquid copper with oxygen, which reduces the surface tension of the copper melt during levitation in air). It turned out that along with the size d_1 , the number of spiral coils affects the lifting force during levitation.

3. EML in physical research

The emergence of new metallurgical processes, such as electroslag melting, electron beam melting, arc melting, induction vacuum melting and plasma melting, revealed the limitations of the available thermodynamic and kinetic data necessary for the correct refining of liquid metal. A characteristic feature of these methods are higher temperatures in comparison with the temperatures at which traditional methods of melting steel and alloys are carried out. The melting temperature of high alloyed steels can reach 1700–1750°C, and temperatures up to 2000–2500°C develop in the reaction zone when the steel is purged with oxygen or air. When melting refractory metals in the arc and electron beam setups, local overheating of the metal is possible at 1000°C above the melting temperature. There are almost no experimental data on the behavior of liquid metals at such high temperatures, which is explained by the limited capabilities of experimental methods. Electromagnetic levitation significantly extends the temperature range of studies related to the solubility of gases in liquid metals, the processes of interaction of metal and slag melts with the participation of the gas phase, etc. It is known that such studies are impossible due to chemical reactions developing between the melt and the refractory material of the crucible.

3.1 Physical properties and chemical reactions studied by EML

The study of heterogeneous systems with the help of EML encounters a number of difficulties with which it was not necessary to deal with the study of liquid

metals by traditional methods. One of the main difficulties is the strong evaporation of the metal. This process arises due to two characteristic features of the electromagnetic levitation method: high temperature and a large specific surface of a molten metal drop (**Figure 12**). Evaporation is particularly active when the liquid metal is held in a deep vacuum. For example, the temperature of the carbon iron melt can reach 2000–2100°C in a few seconds, and its five-minute exposure in vacuum is 10^{-5} – 10^{-6} mm Hg and leads to a decrease in mass by 3–4 times. Such intense evaporation of metal in a vacuum makes it difficult to study liquid metals by electromagnetic levitation with prolonged exposure.

To reduce the contribution of evaporation processes during electromagnetic levitation, an inert gas or gas mixtures are used at different pressures, which can be changed from a few mm Hg to several atmospheres. Although metal evaporation proceeds more slowly in this case, metal vapors condense not only on cold surfaces, but also in less heated areas of the reaction vessel, forming condensate flakes. Their appearance makes it difficult to observe the liquid drop and distorts the temperature measurements. In addition, chemical reactions can occur between the gas phase and the metal vapor, which distort the results. Since the temperatures of the liquid metal droplet and the gas phase are different, two processes affect the rate of metal evaporation: natural gas convection and vapor condensation. Both of these processes, together or separately, increase the rate of evaporation with an increase in the temperature gradient in the system. Around the drop of molten metal, a boundary gas layer appears, the thickness of which can vary from 0.06 cm at an ambient temperature of 0 K to 0.32 cm at an ambient temperature equal to the temperature of the melt. If the surface of a molten metal, for example, iron, has a temperature of ~2000 K, then at the boundary of the gas layer, it will be 1650 K at an ambient temperature of 0 K. In this regard, when studying heterogeneous processes using electromagnetic levitation, it is necessary to take into account the possibility of reactions between metal vapors and the gas phase in the boundary gas layer at temperatures different from the parameters of the molten metal.

Intensive evaporation of the metal of a liquid droplet leads to strong dusting of the sight glasses. In those cases when the experiment is conducted in a gas atmosphere, the evaporating metal does not pollute them; however, the condensate formed in the chamber, along with the gas flows rising from the liquid droplet, continuously moves along the reaction chamber. For this reason, the temperature of a liquid droplet is usually measured from the side or from the bottom through special devices installed in the reaction vessel. For example, to measure the temperature of liquid iron under conditions of strong evaporation, you can use a

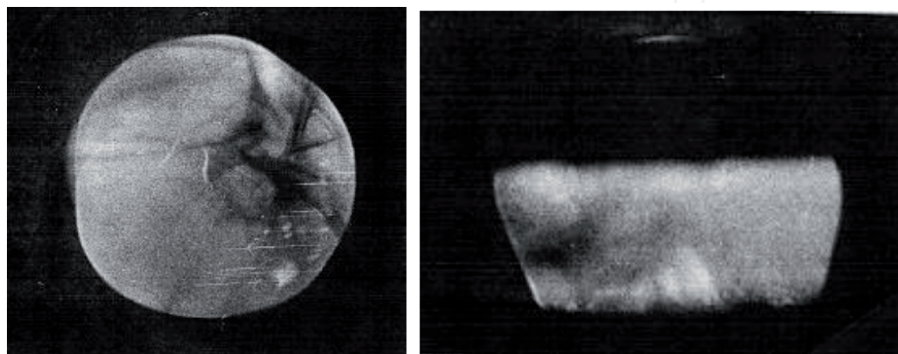


Figure 12.

Top and side views of the same Ø 10 mm liquid iron drop in the multi-coil inductor. The top view is almost a sphere with a disfigured surface, more like a dried apple, but during the shooting on the surface of the sphere, the author observed traces of that “muscle play” under the covers that took place in the volume of the sphere. The side view also contains no evidence of the ideal surface of a metal drop during levitation [7].

movable tube mounted on bellows and brought almost to the melting inductor on the side. When measuring temperature at the bottom of a melt drop, the pyrometer is sighted through an opening in the turntable. After performing several operations to measure the temperature, a mold is placed under the drop, which is installed in another nest of the table.

The microdistribution of temperature over the sample was studied, and the measurement was carried out in the central and peripheral zones of a solid sample heated to premelting temperatures. The difference in temperature measurements of these sections did not exceed 10–12°. Apparently, in the case of molten metal, the temperature difference becomes completely insignificant due to intensive mixing and continuous updating of the surface of the liquid droplet. This eliminates the accumulation of impurities on the surface of the droplet, which could affect the temperature measurement.

The temperature control of liquid metal during levitation can be carried out by optical, radiation and color pyrometers. The use of the first two is allowed in the absence of noticeable smoke or contamination of the sight glasses. The surface of the metal when measuring temperature should be free of oxide or any other film. Color pyrometers are not very sensitive to the appearance of films on glasses; therefore, they are used especially often, although they are difficult to operate. In the case of using a brightness pyrometer, it is necessary to first measure the emissivity of metals in a special setup, since a strong dependence of the emissivity on temperature has been revealed. To determine the temperature dependence of the emissivity of some refractory metals in the solid state, it is desirable to use a model of an absolutely black body. The shape of such samples should be chosen so that the samples had the greatest stability in the inductor and the direction of the hole in an absolutely black body looked vertically upward. The calibration of the pyrometers was carried out on the reference points of pure metals, molten during levitation or in a small ceramic crucible. A drop of metal was slowly melted and then crystallized. To do this, you can take advantage of a change in the gas flow rate or a copper crystallizer cooled by liquid nitrogen, supplied to the drop from above. When it comes into contact with metal, it is possible to observe the crystallization front and make multiple measurements of the melting point. When using pyrometers with automatic recording of the melting and crystallization temperatures, they are fixed with the corresponding areas or bursts (**Figure 13**) [7]. The use of conventional thermocouples is difficult, since it is difficult to eliminate the influence of a high-frequency electromagnetic field on the junction and, secondly, the volume of the metal is usually not large enough to neglect the errors introduced in the temperature readings when a solid junction is introduced into a liquid metal drop.

3.2 Measurement of surface tension and melt viscosity during levitation in zero gravity in parabolic flights and ISS

Volumetric metal glasses or amorphous alloys are a new phenomenon in materials science. The main advantage of these materials is their superior mechanical properties compared to conventional crystalline materials. Amorphous alloys are solid metal materials with a disordered glass-like structure of an atomic scale. They are formed when their cooling from a liquid state occurs much faster than the critical cooling rate. During supercooling of the melt, the increasing thermodynamic driving force of crystallization and amorphous atomic kinetics compete with each other. A strong increase in viscosity during cooling and a high probability of amorphization of the melt also establish boundary conditions for the correct choice of parameters of the process. To justify superplasticity, it is important to know the temperature-dependent viscosity of the alloy. Thus, in order to create technology

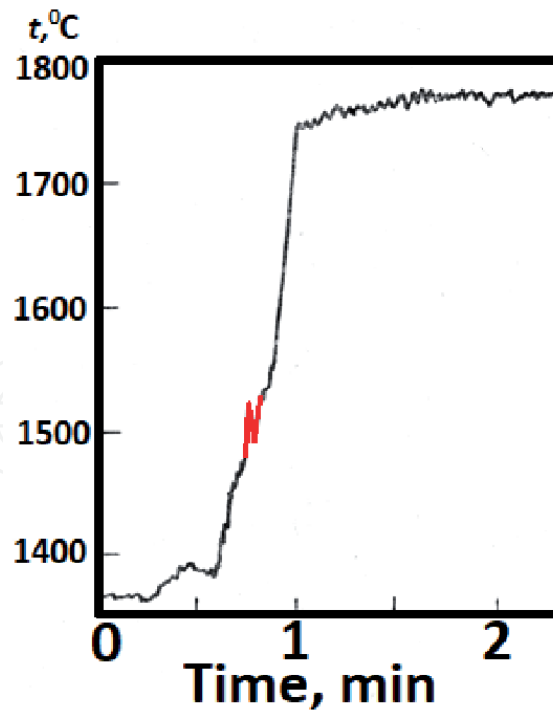


Figure 13.

Temperature of liquid iron in the process of electromagnetic levitation; red—a “zig-zag” at the moment of melting the iron sample.

and theoretical models, it is necessary to know the basic thermophysical properties in a wide temperature range. Electromagnetic levitation is clearly a powerful technique for the noncontact manipulation of electrically conductive samples. This method allows to correctly measure the surface tension and viscosity of metal melts. However, under conditions of gravity of the earth, the melt in natural geometry or raised by an electromagnetic field will be significantly deformed. The simultaneous control of temperature and levitation is limited under normal gravitational conditions of 1 G, since the electromagnetic field needed to lift the samples can heat the sample to significant temperatures, even above the melting point. Flows in a heated, deformed melt drop under terrestrial conditions are poorly controlled (laminar transition to turbulent), which makes it necessary to conduct experiments in zero gravity (microgravity) conditions. One of the possibilities to achieve microgravity in a short period of time (10–20 s) is parabolic flights, for example, performed using the Airbus A310 or International Space Station. The experimental results were obtained during several parabolic flight campaigns in 2016 and 2017 using the TEMPUS EML setup. The surface tension and viscosity of the Pd₄₃Cu₂₇Ni₁₀P₂₀ melt were measured, and it was shown that the temperature dependence of the viscosity of this alloy can be well described by the free volume model. In addition, in [23–33], using X-ray diffraction, it was confirmed the absence of the long-range order characteristic of amorphous samples. The morphology of the samples was analyzed using X-ray computed tomography before and after flights.

The noncontact of a liquid sample is the essence of electromagnetic levitation, combined with an ultra-clean environment. In addition, electromagnetic levitation is one of the oldest noncontact methods of levitation used for materials science experiments for decades. Electromagnetic levitation is the most mature of all noncontact melting methods and has been used for decades in ground-based experiments, as well as in microgravity experiments with a wide range of alloys. Electromagnetic levitation in terrestrial conditions has some problems associated with gravitational forces, so if levitation is performed under microgravity conditions, then only small levitation forces are required to compensate for residual

accelerations. With an inductor optimized for microgravity, heating and positioning of the samples can be carried out almost independently. Since positioning requires minimal effort, the low temperature mode is more accessible, convection is reduced and the deformation of the samples is eliminated. As a result, many additional samples can be processed, and their thermophysical properties can be determined with higher accuracy.

Other factors are the length of periods of microgravity and the ability of the experimenter to interactively control the experiment during a parabolic flight. Electromagnetic levitators have been developed for a wide range of carriers and tasks. Due to the flight duration, which was on the order of 1–2 weeks, it was possible to conduct several experiments lasting several hours each, where each experiment with this sample included several melting cycles with this sample. The experiments were preprogrammed, so interactive access via telemetry is possible. The ISS missions are essentially a continuation of previous Spacelab missions and provide long-term access to a good microgravity environment. Several batches of samples can be loaded onto an object, processed and returned to the ground. The experiments are preprogrammed; interactive access via telemetry is possible.

3.3 Atomization of liquid metals in levitation

The advent of 3D metal printing and other additive technologies has stimulated an increase in demand for spherical metal powders with high rheological flow characteristics. The spraying process consists of feeding a vertical sacrificial rod into a conical inductor, where the end of the rod is melted by eddy currents of an electromagnetic field, resulting in the formation of a stream or droplets of liquid metal that are sprayed with a powerful flow of inert gas. In fact, one of the functions of classical electromagnetic levitation is involved in the process—the melting of the metal, without holding it by a magnetic field. The spraying unit is very simple and consists of a feeder with a sacrificial rod, a melting chamber with an inductor, a spraying chamber with nozzles for supplying an inert gas, a powder storage device and a generator. The proposed method is noncontact and ideal for producing high-purity, reactive and refractory metal powders. All process parameters are known and easily adjusted, which allow full control of the size of the powders. The process is simple, manageable and flexible. Perhaps, this process stands out among analogues for its simplicity and reliability, especially in the production of high-quality pure spherical powders from refractory and rare metals such as titanium, zirconium, niobium and precious metals, which are in great demand in additive technologies in aerospace, medical and other industries [20–22].

3.4 Chemical equilibrium in the system metal-slag-gas during EML

Heating, melting and crystallizing a metal melt with slag occur in a controlled gas atmosphere or in vacuum. The exposure time to the onset of chemical equilibrium in the “iron melt-slag melt-gas” system is usually short and does not exceed several minutes. Slag melting occurs due to levitation and heating of iron, liquid slag initially covers a metal drop with a thin film, which can be observed visually, and then it collects in the lower part of the drop and is held in liquid state by interfacial tension. It is this joint behavior of the molten metal and slag plus convection in liquid iron that ensures the rapid achievement of chemical equilibrium in the distribution of sulfur (the usual or radiochemical sulfur isotope ^{35}S). The initial sample for levitation was a capsule of a specially prepared alloy of iron with carbon weighing

~5 g with an opening in which a slag powder weighing 0.35 g was laid; the hole was tightly closed with a thin foil lid of the same alloy. The initial sample was placed in an inductor for subsequent levitation, which, depending on the task, was carried out in vacuum, inert gases and carbon monoxide. After the generator was turned on, levitation and melting of the sample took place with heating to the experimental temperature, and the metal melt took an egg-shaped form, on the lower half of which slag was collected. At the beginning of the experiment, when the capsule was melted, the slag was in the form of a thin film enveloping the entire drop. The experimental time required to reach chemical equilibrium was determined by diffusion in the liquid slag phase.

Using levitation, the sulfur distribution between iron-carbon melts and lime-alumina slag was studied [7, 28, 32]: the dependence of the equilibrium sulfur distribution coefficient on the C content, gas phase composition and temperature.

Experimental results are shown in **Figure 14**. Comparison of the reduced coefficients of the equilibrium distribution of sulfur, obtained by numerical modeling using known thermodynamic data and the experimental equilibrium values of the reduced coefficient of the sulfur distribution, is shown in **Figure 15**. Since the known data for the equilibrium constant of the desulfurization reaction differ by one and a half orders of magnitude, this noticeably affects the reduced sulfur distribution coefficient. On the whole, it is necessary to recognize such a discrepancy as completely admissible and justified. As can be seen in **Figure 15**, in the logarithmic coordinates, the calculated and experimental curves slightly differ in slope, which is due to tolerances in the calculation and experiment [7].

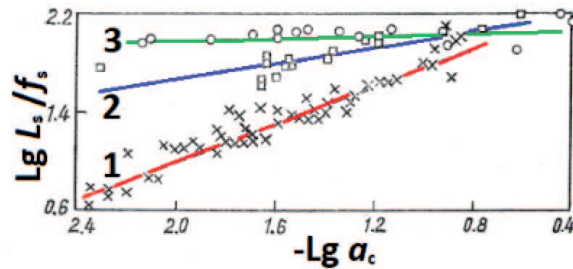


Figure 14.

Experimental dependence of the reduced coefficient of distribution of ^{35}S between Fe-C and oxide slag melts on the activity of C in iron. 1— $P_{\text{Co}} = 1 \text{ atm}$, 2000°C ; 2— $P_{\text{He}} = 1 \text{ atm}$, 1750°C ; 3— $P_{\text{Ar}} = 1 \text{ atm}$, 2000°C .

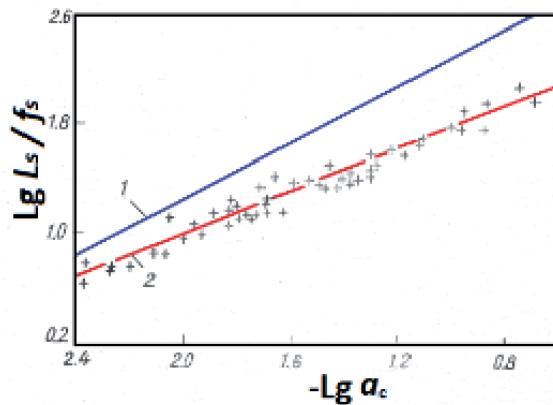


Figure 15.

Dependence of the experimental (2) and calculated (1) coefficients of the distribution of sulfur between liquid Fe-C and slag on the activity of C in iron at $P_{\text{Co}} = 1 \text{ atm}$ and 2000°C .

3.5 Reaction of $C + O \rightarrow CO$ in the melts of Fe and Nb at EML

3.5.1 Melts of Fe-C-O at EML

For comparing EML with crucible melting, the study was made of the influence of the refractory lining on the decarburization kinetics of Fe-C-O samples, which were carried out on melts in corundum crucibles, degassed in vacuum at 1700°C. The data obtained showed that the composition of the products of the decarburization reaction is close to equilibrium; however, the total volume of gases released from the metal depends on the melting method. In melts in a crucible, the gas evolution of CO and CO₂ always exceeded the gas evolution during levitation of similar samples. For stable levitation of samples of this system, a setup was used with an inductor inside the chamber; the working pressure in which was 10^{-7} atm and a metal temperature of $2000 \pm 30^\circ\text{C}$. The received dependence (see **Figure 16**, area 6) is qualitatively confirmed by the data obtained from the smelting of Fe-C-O alloys in an electron beam setup at 1550°C and a vacuum of 10^{-7} atm (see **Figure 16**, area 3). The calculated dependence of the O content on C for 2000°C confirms the disproportionate relationship between the deoxidation capacity of carbon and the partial pressure of CO in the gas phase. The observed decrease in the O concentration in the metal is due to a change in the deoxidizing ability of C due to a change in P_{CO} . Apparently, the data obtained for melting in an inert atmosphere characterize the maximum possible increase in the deoxidizing ability of C at 2000°C.

The increase in the deoxidizing ability of C dissolved in liquid iron, which occurs as a result of a decrease in P_{CO} over the melt, is observed to a certain limit determined by the kinetics of the CO bubble growth. Since the deoxidizing ability of C is usually expressed by the product of the concentrations of C and O in the metal $m = [\% \text{ C}] \times [\% \text{ O}]$, the dependence of the deoxidizing ability on the partial pressure of CO can be expressed by a parabola. Under levitation conditions, when liquid metal does not come into contact with a refractory lining and there is no influence of the lining on the formation of CO bubbles, volume decarburization should prevail, not excluding the evaporation of CO molecules from the surface of a liquid droplet. It is likely that the contribution of evaporation to the removal of CO from a levitated drop of liquid metal should decrease as O adsorption in the surface layer decreases. In low-carbon iron, the formation of CO bubbles in a metal volume is facilitated by thermodynamic and kinetic factors. If the nucleus is comparable in size to large nonmetallic inclusions, the value $2\delta/r$ is much lower than atmospheric pressure. In this regard, as the partial pressure of CO in the gas phase decreases, the

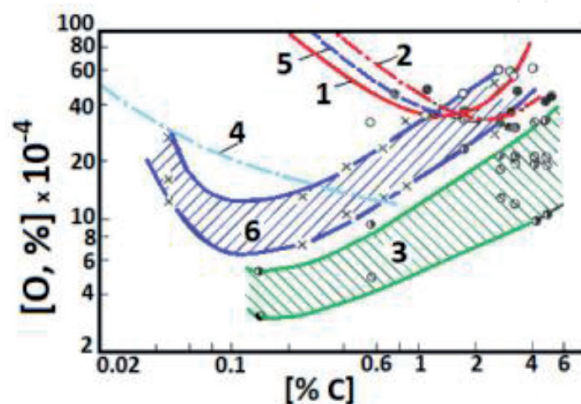


Figure 16.
 Solubility O in Fe-C-O melts. 1— $P_{\text{CO}} = 1 \text{ atm}$, 2000°C; 2— $P_{\text{CO}} = 1 \text{ atm}$, 2000°C; 3— $P_{\text{CO}} = 10^{-7} \text{ atm}$, 1550°C, EBM; 4— $P_{\text{CO}} = 10^{-7} \text{ atm}$, 1600°C (refractory crucible); 5— $P_{\text{CO}} = 1 \text{ atm}$, 1600°C (refractory crucible); 6— $P_{\text{CO}} = 10^{-7} \text{ atm}$, 2100°C.

decarburization reaction intensifies until this pressure is equal to the partial pressure of CO in the gas nucleus and the deoxidizing ability of C becomes constant. The surface decarburization of carbon iron cannot be decisive due to the low diffusion rates of C and O to the metal-gas interface. When bubbles form in the metal volume, the pressure necessary to overcome the forces of surface tension should be two to three orders of magnitude higher than atmospheric. It follows that in iron-carbon melts, in particular at contents $>1.5\%$ C, with a decrease in the partial pressure of CO in the gas phase, the deoxidation ability of C in iron should not change. The description of EML experiments on Co and Ni is not given here because of limited space in the chapter.

3.5.2 Melts of Nb-C-O at EML

The interaction of C and O should be taken into account when obtaining pure metals and studying their surface and bulk properties. However, the study of the behavior of these impurities in solid and liquid metals was often qualitative because of the complex nature of physical and chemical processes in the bulk and on the surface of the metal and because of significant experimental difficulties. A model was created within the framework of which a closed system of equations was obtained [34, 35]. The model allows describing the kinetics of the interaction of C and O during maintaining them in a liquid state in vacuum. It was found that if C and O impurities with initial concentrations of $N_0(0)$ and $N_c(0)$ are uniformly dissolved in the metal volume, then by thermal desorption of CO and MO molecules in vacuum (at high contents of oxygen, MO_2), since the average O concentration $N_0(t)$ decreases infinitely, then, in accordance with the proposed model, the average C concentration $N_c(t)$ should reach a definite threshold level $N_c(\infty)$. It is shown that the ratio between the average concentrations of O and C is uniquely fixed by two parameters, N^* and S . The first of them, $N^* = \omega/G$, is determined by the ratio of the constant of the MO desorption rate ω to the effective constant of the CO desorption rate G and has a certain critical value, which sets the characteristic concentration scale. The effect of one impurity on another becomes high only when its concentration beats this critical value. The parameter S is a dimensionless indicator of the relative intensity of diffusion or surface processes.

The relative simplicity of the model makes it possible to experimentally check the behavior of the average concentrations of carbon $N_c(t)$ and oxygen $N_0(t)$ in time, as far as the created model [34, 35] corresponds to reality and determines the parameters N and S . So, if the model is correct, then in the coordinates $\partial\Delta/\partial(\ln N_c) - \Delta$, regardless of the ratio of the initial concentrations of $N_c(0)$ and $N_0(0)$, the experimental points should be on a common line with the fixed slope and ordinate.

The comparison of the results with the theoretical ones becomes much easier if the S values in the experiment are sufficiently large, which means that diffusion is more intensive than surface processes. In this case, the dependence $\ln N_c = f(\Delta)$ should be close to linear (**Figure 17**). Thus, the experimental points for different ratios of the initial concentrations O and C in the $\ln N_c - \Delta$ coordinates should fit on parallel straight lines with a slope $1/N$.

The kinetics of the interaction of C and O was investigated in a wide range of ratios of their initial concentrations during levitation of Nb and Mo in vacuum. The temporal relationship between the average concentrations of C and O in a wide range Δ follows a simple law. The kinetics of conducting of the average concentrations of C and O was calculated numerically, which showed a good alignment between the digital simulation and the experiment for all studied series. The effective constant of the CO desorption rate and the high-temperature sticking

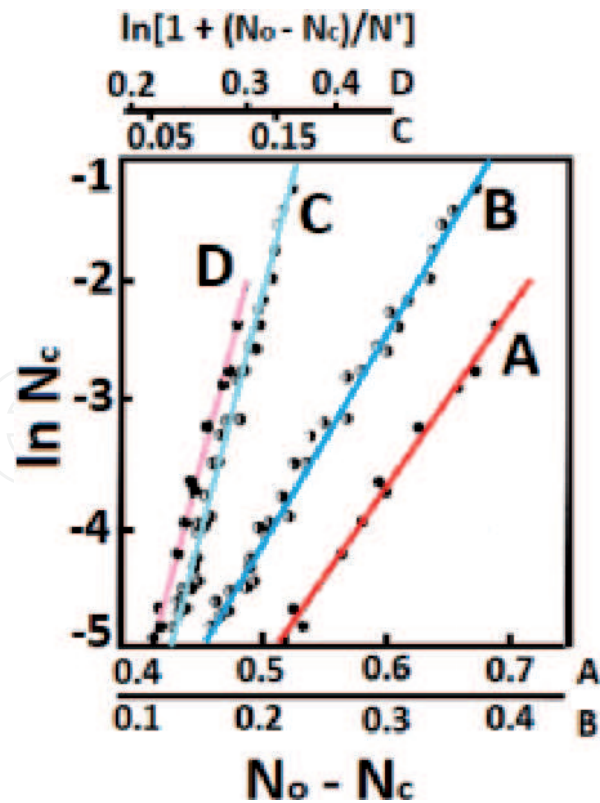


Figure 17.
Mean C concentrations as a function of the value $\Delta = N_o - N_c + N_c^{(\infty)}$, plotted in coordinates $\ln N_c - \Delta$ (lines A and D) and $\ln N_c - \ln(1 + \Delta/N')$ (lines C and B) on the basis experimental data.

coefficient of CO to Nb and Mo were received. The description of EML experiments on Mo is not given here because of limited space in the chapter.

4. Conclusions

The main advantage that attracted the attention of researchers was the lack of contact of liquid metal with refractory lining, which ensured the elimination of one of the main sources of metal contamination by such a harmful impurity, such as oxygen. This is especially important for melting refractory highly reactive metals and semiconductors. Compared to other melting methods, which also ensured the absence of contact of liquid metal with the crucible, EML of liquid metals has a number of significant advantages: adjustable residence time of a drop of metal in a liquid state; controlled gas atmosphere and slag phase; controlled metal temperature (from melting temperatures to boiling); ability to use an additional heat source (electron beam, laser beam or plasma); vigorous stirring of metal by electromagnetic field; possibility of introducing alloying additives into a liquid drop; a favorable ratio between the surface of the droplet and its volume for the passage of heterogeneous reactions; and achieving extremely high crystallization rates up to 10^5 – 10^6 °C/s.

The noncontact of a liquid sample is the essence of EML, combined with an ultra-clean environment, which is an excellent instrument for researches. In addition, ELM is one of the oldest noncontact methods of levitation used in materials science experiments for decades. EML is the most mature of all noncontact melting methods and has been used for decades in ground-based experiments, as well as in microgravity experiments with a wide range of alloys. EML in gravitational conditions has some problems associated with gravitational forces, so if levitation is performed under microgravity conditions, then only small levitation forces are

required to compensate for residual accelerations. With an inductor optimized for microgravity, heating and positioning of the samples can be carried out almost independently.

Conflict of interest

The author declares no conflict of interest.

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