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Review

The Present Issues of Control Automation for Levitation Metal Melting

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Abstract: This article is a review of current scientific problems in the field of automation of the electromagnetic levitation melting process control of non-ferrous metals and potential solutions using modern digital technologies. The article describes the technological process of electromagnetic levitation melting as a method of obtaining ultrapure metals and the main problems of the automation of this process taking into account domestic and international experience. Promising approaches to control the position of the melt in the inductor in real time on the basis of vision systems are considered. The main problems and factors preventing the mass introduction of levitation melting in the electromagnetic field to the industry are highlighted. The problem of passing the Curie point by the heated billet and the effect of the billet's loss of magnetism on the vibrational circuit of the installation and the temperature of the inductor are also considered. The article also reflects key areas of research development in the field of levitation melting, including: optimization of energy costs, stabilization of the position of the melt in the inductor, predictive process control, and scaling of levitation melting units. The concept of a digital twin based on a numerical model as a component of an automatic process control system for the implementation of inductor control and prediction of process parameters of the melt is presented. The possibility of using vision for visual control of the melt position in the inductor based on video images for its further stabilization in the inductor and increasing the accuracy of numerical simulation results by specifying the real geometry of the melt in parallel with the calculation of the model itself is considered.

Keywords: automation; numerical simulation; induction furnace; levitation melting; vision system; digital twin

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1. Introduction

The metallurgical industry is one of the fundamental sectors of the global economy. The demand for metal products has been growing steadily for several decades. The largest consumers are the following industries: construction, machine building, and the electronic industry. In addition to the growth in non-ferrous and ferrous demand, the global trend towards lower greenhouse gas emissions and a smaller carbon footprint is becoming an essential factor. The current measures on carbon policy regulation also adjust the long-term strategy of the metals sector.

The above factors are driving leading steel companies to introduce new metal production and processing technologies, considering the new energy costs and environmental impacts, while ensuring a stable, continuous supply of products in the context of growing demand. The increasing need for new materials challenges the metal industries to produce metals and alloys with improved technical properties.

One of the tasks of metallurgy is to produce metals with a high purity level. It is well known that the resulting properties of smelting metal are usually determined by the concentration of impurities it contains, which negatively affect the properties of the final product. So, it becomes important to prevent impurities from forming in the melt as a result of chemical reactions with the atmosphere and furnace walls, as well as the dissolution of crucible material components. Furthermore, to obtain a homogeneous material it is essential to ensure a uniform distribution of the alloying components in the melt volume within a certain time (melting time). Among the various techniques for heating and melting metals, induction furnaces are widely used to provide non-contact control of melt mixing by electromagnetic field, temperature, and surface shape. Instead of a common ceramic crucible for the electromagnetic treatment of high-purity materials, an induction furnace with a cold crucible is used. Their applications range from the production of titanium parts for the aerospace, automotive, or medical industries to photovoltaic purification and crystallization of silicon in semiconductor manufacturing. Because of the air gaps, the sectional metal crucible remains transparent to the electromagnetic field. Here, the pressure of the electromagnetic field strongly compresses the melt, resulting in semi-levitation. The melt hits the bottom of the water-cooled crucible. Thus, the contamination of the melt with the crucible material is reduced.

However, the huge heat losses through the water-cooled crucible and the melt contact areas seem to be a limiting factor for achieving higher melt heating and are reflected in the low energy efficiency of this process. The high energy costs of floatation are balanced by the high degree of purification of the metal, but in any case, they represent a significant proportion of the cost of metal produced using this technology.

An alternative method of non-contact metal melting is electromagnetic levitation melting. Its distinctive feature is that the melt is suspended throughout the melting process and does not contact either the surface of the crucible or the surface of the heating elements. The metal is kept suspended in the inductor by an electromagnetic field generated by an alternating current and induced current within the billet, which is repelled from the inductor by Ampere’s law. Typically for the electromagnetic melting of metal with levitation, special cone-shaped inductors with a countercurrent at the base of the cone are used. This inductor design creates a so-called “potential pit” in the electromagnetic field, which keeps the melt from vibrating transversely. The Foucault currents generated by the inductor in the metal cause intense heating and subsequent melting.

Induction melting of metals with total levitation has two main advantages over ceramic or induction furnaces. First of all, electromagnetic levitation in an inert atmosphere or vacuum completely eliminates the contamination of the melt with crucible material and results in a significant improvement in melt purity. Secondly, the heat loss of the liquid metal is reduced and limited to radiation and evaporation, allowing the electromagnetic field treatment to be carried out at extremely high temperatures.

At present, induction levitation metal melting is used with considerable limitation in terms of melt mass. This is due to the fact that with the increasing mass of the melt, the amount of energy required to keep the metal suspended increases significantly. Primarily the application of non-contact metal melting is limited to the high-tech sector requiring ultra-pure metal, semiconductor manufacturing (particularly single crystal silicon), and for melting, casting, alloying, and refining of active metals and their alloys such as scandium, yttrium, titanium, molybdenum, uranium, and others.

For ferromagnetic metals, the electromagnetic levitation melting process also has some restrictions relating to the change in properties of magnetic materials when heated. When a magnetic material is heated to the Curie point, it loses its magnetic properties, leading to overheating of the inductor and provoking unwanted vibrations of the sample in the crucible.

The process of induction heating and melting of metals in normal conditions is well automated. Existing control algorithms make it possible to control the heating rate of the workpiece, maintain the set temperature, control the heating and cooling cycle, and stabilize the power consumption of the inductor. However, in the case of heating and melting in suspension, the control task is complicated by the need to control the position of the melt in space. In addition, when working with ferromagnetic metals, it is also necessary to trace the Curie point and change the load on the inductor accordingly to stabilize the levitating melt. This is due to the strong influence of the ferromagnetic workpiece on the oscillating circuit of the inductor, shifting its resonant frequency. The temperature values at the Curie point for various metals and at the Kurnakov point for alloys are known and have been established experimentally. In the case of electromagnetic heating, however, due to the skin effect occurring at the surface of the workpiece, the metal is heated inhomogeneously, which distorts the results of direct temperature measurements.

Thus, the direct measurement of temperature may not be sufficient to build a control loop, which in turn creates the need to build a numerical dynamic model of heating the billet. This paper gives an overview of the current state of research on the problems of electromagnetic levitation melting process control, the construction of numerical models, and the application of digital twins in industrial and experimental control systems, including energy cost optimization.

2. Levitation Metal Melting Technology

The breakthrough changes in the metallurgical industry that occurred in technologically advanced countries in the second half of the last century are related to the rapid development of electrical technology. Metal smelting in electric furnaces (arc and induction) accounted for a small proportion of the total number of pyrometallurgical processes. Induction heating technologies have gained a special role in continuous metallurgical processes of rolling production such as metal casting, continuous heat treatment, slabs and tubes, and forging alloys in a solid state. All of the above technological processes are now quite widespread, deferred, and standardized in both domestic and foreign metallurgical plants.

A new round of development in metal induction melting is non-contact metal melting with levitation, used to produce ultra-pure alloys. Otto Muck in 1923 proposed the electromagnetic levitation of a metal melt, also called non-contact melting in an electromagnetic crucible. He gave the first and simplest theoretical explanation of the phenomenon—suspending or levitation of metal by an electromagnetic field. However, it was not until 30 years later that the first works on the theory and use of this type of melting appeared. Later, research into the expanded application and scientific functions of the levitation melting of metals and alloys, both in the laboratory and on a semi-industrial scale, emerged. Subsequent theoretical research into electromagnetic levitation was accompanied by continuous improvements in the technology itself. In this way, the following important characteristics of levitational melting have been established:

- Optimum residence time of the molten metal drop in the liquid state [1];
- The composition of the gas medium and its effect on slag formation in the levitation melt [2];
- Methods of controlling the workpiece temperature from melting to boiling point [3];
- The possibility of using additional heat sources for heating the workpiece in addition to the inductor itself, including laser radiation and plasma [4];
- The possibility of introducing alloying components into the levitating melt [5];
- The optimum ratio between the surface area of the melt drop and its volume, sufficient for heterogeneous reactions on its surface [6];
- Conditions for achieving ultra-high crystallization rates of the melt [7].

The main challenges in the automation of the levitation melting of metals in the metallurgical industry relate to the development of theory and its applications to the task of keeping liquid metal in a state of levitation despite the numerous studies dealing with the theoretical foundations of electromagnetic levitation. Its huge strengths over other metal melting methods have not resulted in a rapid spread of the method [8]. This is due to the fact that most of the research has been carried out without sufficient theoretical justification. Quite recently, some more or less reasonable methods have been developed that can be used to optimize the parameters of the levitation unit [8]. A cross-sectional view of the five-loop levitation system inductor has been proposed by Paul and McLean [9] is shown on Figure 1.

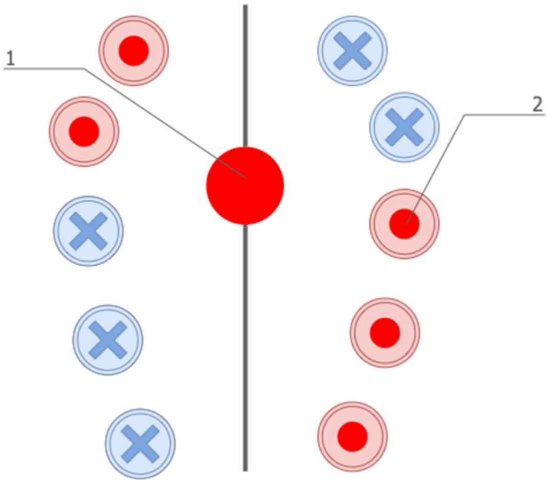

Figure 1. Levitation system inductor. Cross-sectional view. (1) Droplet. (2) Induction coil.

At present, a group of researchers from the University of Latvia, led by Dr. S. Spitans, has made the most significant contribution to the development of electromagnetic levitation metal fusion technology. Their works [10] and [11] present the results of numerical simulations of electromagnetic levitation melting of metals using the packages OpenFoam and Ansys Fluent. This made it possible to reproduce the complex multiphysics processes taking place in the workpiece. Researchers were also successful in numerical simulation of the dynamics of melt drop shape change under the influence of the electromagnetic field of inductor and gravity [12].

Further research proposed a heating plant design consisting of several inductors. The optimum operating conditions of the inductors were also determined for the suggested design, taking into account their relative positioning, using numerical simulation methods. The research carried out by the team headed by S. Spitans was not just limited to a virtual experiment. The researchers also created an experimental setup to test and validate the proposed construction. The results were published in 2017. According to the researchers, the metamorphosis of the melt in the magnetic field (changing the shape of the drop and its position in space during heating and melting) was almost exactly the same as the equivalent characteristics obtained in the numerical model of the process. As a result, the researchers in cooperation with ALD Vacuum Technologies introduced a technology for levitating floating and casting large (up to 500 g) volumes of titanium alloy—the "FastCast" [13]. In contrast to traditional axisymmetric electromagnetic levitation melting approaches, the new solution is based on the application of two electromagnetic fields with different frequencies. Here, the field lines are horizontal and mutually perpendicular. Therefore, it is possible to realize the Lorentz force in the molten charge also on the axis, thus increasing the maximum permissible weight of the levitating sample [14].

The researchers of St. Petersburg State Mining University have also paid attention to the study of induction heating of metals and the construction of numerical models of melting workpieces in a magnetic field. The works, "A combined method of simulation of an electric circuit and field problems in the theory of induction heating" [15] and "Simulation of induction heating of a ferromagnetic plate with a covering inductor" [16], present the results of numerical experiments performed in the Ansys Maxwell software package for the process of induction heating of metals. The current state of scientific research in the field of electromagnetic metal heating technologies is given in the review, "Recent scientific research on electrothermal metallurgical processes", published in the Journal of Mining Institute in 2019 [17].

Another area actively being explored is the production of fine and ultrafine granulated metal powders. The development of 3D metal printing and other additive technologies has driven the demand for spherical metal powders with high fluidity rheological properties. The spattering consists of feeding a vertical sacrificial anode rod into a conical inductor where the end of the rod is melted by the eddy currents of an electromagnetic field. This produces a jet or droplets of liquid metal that are atomized by a powerful stream of inert gas. In essence, this process is one of the classic variants of electromagnetic levitation—the metal melting without holding it up in a magnetic field. The spattering unit construction consists of a feeder with a sacrificial rod, melting chamber with an inductor, spattering chamber with inert gas nozzles, powder storage hopper, and generator. The proposed method is non-contact and is ideal for the production of highly refined, active, and refractory metal powders. All process parameters are known and easily adjustable, giving complete control over the size of the powders. The operation is simple, controllable, and flexible. Perhaps the process has the advantage of its simplicity and reliability. It is presented in the production of high-quality pure spherical powders of refractory and rare metals such as titanium, zirconium, niobium, and precious metals. These metals are in heavy demand in additive manufacturing, aerospace, medical, and other industries.

Electromagnetic levitation is certainly a high-efficiency method for the non-contact manipulation of electrically conductive samples. This method makes it possible to accurately measure the surface tension and viscosity of metal melts. However, under earth gravity, a melt in its natural geometry or lifted by an electromagnetic field will be significantly deformed. Simultaneous control of temperature and levitation is limited under normal 1 G gravity conditions because the electromagnetic field required to lift samples can heat the sample to high temperatures, even above the melting point. Currents in a heated deformed melt droplet are poorly controlled under terrestrial conditions. It is characterized by a transition from laminar to turbulent mode, which necessitates experiments in weightlessness (microgravity) [18]. Among the possibilities to achieve microgravity conditions for a short period of time are parabolic flights, such as those carried out using the Airbus A310 suborbital aircraft or the International Space Station. Experimental results were obtained during missions to the International Space Station in 2016 and 2017 using the TEMPUS EML facility and published in "EML—An Electromagnetic Levitator for the International Space Station" [19]. The results obtained set another direction for the development of levitation metal melting technology in weightlessness as a prospective technology for space exploration.

In addition to metallurgy, electromagnetic levitation melting found its application in the growth of single crystals for the semiconductor industry.

3. The Scaling Task of Metal Levitation Melting

The major drawbacks of the existing levitation melting method describe the small mass of the molten metal. They do not exceed several tens of grams, which narrows the wide industrial application of the method to a great extent.

Increasing the mass of the molten sample is achievable by using a combination of several inductors in the plant, as presented in the work of the group headed by Dr. S. Spitans. However, a larger number of inductors results in higher electrical energy consumption for heating, melting, and holding the melt in suspension [20]. In addition, combining several inductors in a single installation leads to a more complicated control of the condition of the workpiece and the alternators. This study also does not take into account the mutual influence of inductors on each other, resulting in excessive heating of coils under the influence of external magnetic fields created by additional inductors.

Thus, the scaling task of metal levitation melting plants is related to the evaluation of the optimum positioning of the inductor cascade as well as to the development of an automated control system to minimize the negative effect of mutual induction. From the automation point of view, this challenge was not considered at the moment of writing the review and no exhaustive studies on the mentioned problem have been found.

4. Levitation Melting of Ferromagnetic Metals

Practically all of the above-mentioned developments in the field of levitation melting refer mainly to non-ferromagnetic (non-ferrous) metals. The levitation melting technology for iron has significant prospects as a method of purification from phosphorus and other impurities. Suspended melting in an inert gas environment, accompanied by convection of the melt under the influence of a magnetic field, is actively considered a potential method of refining metals. The technical difficulties arising from the ferromagnetic materials melting are due to their distinct magnetic properties and their discontinuous change when heating.

It is well known that ferromagnetic materials magnetize in the absence of an external magnetic field at temperatures below a critical value called the Curie point. Ferromagnetic metals gradually lose their magnetic properties when exposed to external influences and when heated. Once the Curie point is reached, they lose them almost completely. This property of magnetic materials causes certain difficulties in levitation melting in a magnetic field.

When a ferromagnetic workpiece is introduced into an inductor circuit with dimensions comparable to those of the blank, the inductance begins to increase dramatically. This in turn leads to a step change in the natural frequency of the oscillating circuit and its lag from the frequency of the alternator. When the circuit is out of resonance with the oscillator it leads to a sharp increase in resistance, accompanied by a proportional decrease in the energy blown from the inductor to the workpiece. The growing resistance of the inductor leads to overheating and requires additional cooling, which has a negative effect on the energy efficiency of the entire process.

When the workpiece heats up to the Curie point, its magnetic properties disappear, and the natural frequency of the oscillating circuit returns back to the frequency of the master oscillator. The step change in the magnetization of the ferromagnetic passing through the Curie point leads to a sharp drop in the inductor resistance that results in an increase in the current consumption of the inductor. If the plant operator does not react in a timely manner to the increased supply voltage, it can lead to overheating and failure of the equipment. Furthermore, if the furnace is equipped with an automatic control system, it has to monitor the transition of the workpiece temperature through the Curie point and reduce the frequency of the master oscillator proportionally, thus keeping it in resonance with the oscillating circuit [21].

For non-magnetic materials, passing through the Curie point has no significant effect on the inductor circuit. As a consequence, there is no need for automation of the levitation melting process in an electromagnetic field for non-magnetic metals. The same is true when the dimensions of the workpiece are much smaller than the heating inductor.

This is especially relevant to the iron and steel industry because metals such as iron (Fe), nickel (Ni), vanadium (Vn), cobalt (Co), some rare-earth metals terbium (Tb), gadolinium (Gd), and holmium (Ho), and some alloys have strong ferromagnetic properties, which makes levitation technology difficult to apply.

5. The Task of Stabilizing the Melt Position

Apart from the characteristics of the interaction between a high-frequency electromagnetic field and a liquid metal during levitation discussed above, there is a group of phenomena related to the stability of the metal. The motion of a droplet hanging in a magnetic field is not a specific property of the liquid state, but is caused by the electromagnetic interaction between the metal and the field. A change in the position of the metal relative to the inductor with a constant EMF influences the magnitude of the current flowing through the inductor, which causes a change in the force acting on the metal. The following features were found in experiments with aluminum balls levitating in air, water, and oil:

- Stable balance about the axis of symmetry in a more viscous medium than air;
- Sustained oscillations with a small amplitude of constant magnitude;
- Increasing oscillations with an amplitude greater than the size of the inductor.

The nature of the melt oscillations in the magnetic field does not depend on the magnitude of the current in the inductor or on the degree of compression of the melt droplet by the magnetic field. A stable drop position is achieved if the center of curvature of the melt surface in its stable state is outside the melt volume. Another feature of the levitating melt is the mixing inside the drop itself. Experiments conducted with liquid sodium placed in a glass flask in an electromagnetic field showed the presence of turbulent metal movement inside the flask. The velocities of the sodium melt in this experiment were measured using Pitot tubes, as well as photographic methods. Thus, it was found that a significant part of the melt in the flask moves upwards, and along the walls of the flask the metal moves downwards at a much higher speed. To determine the dependence of the metal velocity on the magnetic field strength, the flask was fixed and the vertical component of the velocity was measured at different current values. Separate experiments without a flask led to the conclusion that the mixing of the melt during levitation in a vacuum or an inert gas occurs more intensively than described above, since the velocity of the metal on the surface of the droplet is not zero.

6. Perspective Areas for the Development of Levitation Melting Automation

Stabilizing the oscillating circuit state of the inductor and determining how to remove excess heat from the coil is one of the key control tasks in electromagnetic metal melting. In terms of automation, levitation melting is a complex multi-circuit process. Finding the optimum conditions for heating the workpiece precedes the task of optimizing for several parameters: the temperature of the melt, its position in space (in two or three coordinates), the temperature of the inductor, and the current intensity in the inductor. The temperature measurement of a levitating workpiece is also complicated by the construction of the heating apparatus. The high level of electromagnetic interference and interference from the inductor, and the unstable position of the workpiece in space and its vibrations do not allow any sensitive elements to be placed in the inner space of the inductor. The use of thermocouples is practically impossible, since it is impossible to filter out the noise induced by the high-frequency electromagnetic field of the inductor, and the volume of metal is usually too small for contact measurement. The only possible approach to measure the temperature of the workpiece or melt is therefore non-contact methods, such as pyrometers and thermal imaging cameras.

The temperature of the levitating liquid metal can be measured using various pyrometers: color, radiation, or optical. The last two types of pyrometers can be used only in conditions of good visibility of the object under study. The metal surface during temperature measurement should also not contain impurities and oxides that distort temperature measurements. On the other hand, color pyrometers are practically insensitive to the formation of films on glass; therefore, they are especially suitable for similar applications; although, they are very difficult to operate and maintain. In the case of a brightness pyrometer, it is first necessary to measure the emissivity of metals on a special device, since the principle of their operation is based on determining the emissivity of a hot metal depending on temperature. To find the dependence of temperature on the emissivity of the sample for metals with a high melting point, the absolute blackbody model is applicable. The shape of the samples should be chosen in such a way that they have the greatest stability in the inductor.

The calibration of the pyrometer by reference points made of pure metal is usually performed on a molten levitation or a crucible made of inert materials. To do this, the metal is slowly melted and then crystallized by changing the flow rate of an inert gas supplied to the drop by a directed flow from above, or in a cooled copper crystallizer.

Given all the limitations associated with pyrometers and the complexity of their calibration for adapting to this task, it is advisable to consider thermal video cameras as a non-contact temperature monitoring tool. The main difference between thermal imagers and pyrometers is that they contain a whole cascade (matrix) of sensitive elements that form an image of the measured surface. In contrast to the one-dimensional signal, the video image obtained from a thermal imager is more informative and of greater interest for studying the surface processes taking place in the melt. In conjunction with vision techniques, it can also be used not only to determine the temperature distribution on the surface of the workpiece, but also to track the position of the melt drop in space.

Vision systems with thermal imaging cameras began to appear quite recently in industrial monitoring systems and have already proved their effectiveness for solving the tasks of non-contact temperature control of the surface of industrial objects, products, and workpieces [22]. In particular, they are used in steel-rolling production for slab temperature control, as well as in systems of automatic slag counting in the melt [23].

The use of thermal imaging cameras in similar applications proves the validity of this method. However, they have not yet been used for thermal imaging in levitation melting [24].

The technical challenges of thermal infrared imagery arise in the algorithmic processing and noise filtering phase of the image. The complex technical imaging conditions impose a number of limitations on the application of classical image processing algorithms [25]. In particular, the task of correctly determining the position of the melt drop in space is complicated by changes in the geometry of the workpiece as it melts in the induction furnace and the non-uniform luminosity resulting from convection currents within the melt [26].

The use of vision systems based on neural networks is the current approach for the recognition and tracking of objects with changeable features. The advantages of this approach include the high speed and accuracy of object recognition, which makes it possible to use them as part of real-time systems as well. There are various neural network topologies designed to solve specific specialized tasks. They can be divided into the following groups [27]:

- Classification: determining whether an object of a certain class is present in the image;
- Pattern recognition: identifying an area in the image that is believed to include an object from a known class;
- Image segmentation—separating pixels of the image belonging to objects of the classes of interest from the background;
- Semantic segmentation—matching individual pixels of the image to a specific entity of a recognized class.

For each of the above tasks, there are certain kinds of neural network topologies that will correctly perform one or the other task. Therefore, the main research task is related to the application of neural networks as part of a vision system for melt position monitoring. It consists of adapting the existing topology to handle the multispectral image and preparing a representative training sample [28].

The main disadvantage of neural networks is that they have to be trained on large amounts of data [29]. For example, the most widely known classifier, GoogleNet, has been trained on almost 16 million images. Clearly, the collection of sufficient training data becomes one of the main factors preventing the large-scale adoption of vision to mainstream artificial neural networks in industry. The preparation of the training sample is not limited exclusively to the collection but also requires a significant amount of labor to label the data [30]. Data labeling in machine learning refers to highlighting areas in an image that match the type of object being searched for. This procedure is a rather time-consuming process, and in the case of industrial data, it is also complicated by the higher skill requirements of an engineer [31].

Faster collection of training data and the consequent introduction of vision systems into manufacturing are possible through the generation of synthetic data. Synthetic data are information generated programmatically on a computer using specialized algorithms that simulate the behavior of the object under study and reproduce its various states [32]. For example, in the case of vision systems, the object images can be generated using state-of-the-art computer graphics. The scene with the object is reconstructed from simulation and numerical simulation data, and the melt position and luminosity can be changed programmatically by rendering each variant separately [33]. The images obtained this way can be used to improve the training accuracy of the neural network [34]. In addition to the different states of the object in the image, this approach enables the introduction of realistic process-specific noise into the image. That increases the stability of the trained model.

The next major disadvantage of this approach is the demand for large computational resources to train, to obtain correct and stable results in real-world operating conditions. The training of neural networks is best performed on graphical and tensor processors optimized to handle large matrices representing the weights of the neural network to be trained [35].

The training sample for training neural networks is supposed to combine with photos taken in a field experiment and software-generated images [36]. In addition, noisy copies of images should be added to improve the reliability of recognition and the robustness of the algorithm to noise [37].

Since the real-world operating conditions of the model involve real-time video processing, and the location of the model is assumed to be on-site (on an embedded computer), preference will be given to lightweight topologies such as MobileNet [38].

7. Predictive Control Based on a Numerical Model

In terms of automation, electromagnetic melting is a complex, multi-stage process. It can be roughly divided into three stages: heating the metal, passing the Curie point (stabilization), and cooling the melt (crystallization). Depending on the final goal, the cooling can be replaced by melt casting or extrusion. Either way, it is the changes in the state of the metal, i.e., the transient processes that cause the greatest difficulties in controlling the process. The necessity of using a simulation model as part of the process control system is due to the complex transient response. At this point, the melting process control system has to reduce the current in the inductor coil in a timely manner while keeping the melted sample suspended. The unstable position of the metal drop in the magnetic field is proposed to be predetermined in the simulation model based on the current process parameters coming from the measuring devices [39]. The advantage of this approach over numerical models with no process feedback is that the model, supported by actual measurements, is more relevant and reliable. In addition to this, such a model, unlike a traditional process control system, can be used for predictive process control [40]. New process parameters can therefore be pre-tuned on the digital twin, reducing the failures caused by the operator [41].

As far as the theory of automatic control is concerned, the digital twin is not a fundamentally new concept. Since the second half of the 20th century, regulators with a model block have already been applied in automation and are successfully used in industry [42]. The model block in this case is a simplified mathematical model of the control object and it is used to increase the speed of control systems with a large lag [43]. If you replace the model block with a mathematical model by a simulation model and apply an input force equivalent to that applied to the control object, then the hypothetical response curve of the simulation model should be equivalent to the response curve of the real control object, all other things being equal [44].

The digital twin, which operates in parallel with the real process and is part of the APCS, may become a fundamentally new approach to the construction of control systems based on the digital twin. Combining information from sensors about the object's current state and disturbing influences with a digital model of the process, one can predict with a sufficiently high accuracy the subsequent states of the control system (object) under a given control action of known magnitude [45]. This type of system is applicable to implement predictive process control and as a tool for conducting virtual experiments. With this system, it is possible to create a copy of the model at any time and reproduce an alternative process control scenario without affecting the real equipment that is already in operation. This approach will reduce the error risk of changing the control algorithms in the ACS, debugging them, and assessing their effectiveness, including via the EROI methodology [46].

The economic effect of introducing an automatic control system based on a digital twin will be seen in lower costs for unplanned technological maintenance and repair of equipment. Energy costs will also be cut due to increased equipment productivity through more accurate and timely adjustment of process parameters. Additionally, the digital twin allows the ACS to debug on its own, without the risk of a control room emergency [47].

Another significant advantage of using simulation models as part of a process control system is the potential for medium- to long-term forecasting of energy costs and process energy efficiency for subsequent planning of the energy-saving strategy [48]. This type of system can be applied both to the implementation of predictive process control and as a tool for conducting virtual experiments [49]. With the help of that instrument, it is possible to make a copy of the object model at any time and reproduce in it an alternative process control scenario without affecting the real equipment that is already in operation.

8. Discussion

The presented review gives the current state of the levitation melting of metals in an electromagnetic field. The results of the literature and patent search on the subject of scientific research are given. Existing and as yet unsolved scientific tasks related to the control and complex automation of the levitation melting process and its adaptation to mass introduction to industry are described. The analysis of the most urgent challenges identified in the course of the scientific review was carried out, in particular, in terms of energy saving. This publication presents the most up-to-date and complete review of the current scientific research in the field of levitation melting of metals. The review will be useful for researchers working in related fields.

The most urgent scientific challenges of levitation melting of non-ferrous and ferrous metals have been identified. These include: the task of non-contact determination and monitoring of the temperature and shape of the levitating melt, stabilization of the melt position in the inductor circuit, optimization of the temperature regime of the magnetic levitation unit when ferrous metal billets pass through the Curie point, and the development of methods of melt retention and crystallization in a suspended state. The following challenges have been identified as proposed solutions to these scientific questions:

- The development of a vision system for controlling the position of the melted sample in the inductor and monitoring its surface temperature based on a deep ultra-precise neural network trained on synthetic data;
- The development of a simulation model for heating and melting in an electromagnetic field of a ferromagnetic metal workpiece and a system for monitoring the Curie point transit based on a simulation model calculated in real time (digital twin);
- The development of an electromagnetic grabber system for keeping the melt suspended for cooling and crystallization when the power (heating) inductor is switched off.

Further research in the field of levitation melting of metals involves the scaling of melting furnaces and increasing the mass of the molten metal, as well as the optimization of the consumption of electric power furnaces. In addition, a promising area of research is the solution to the problem of stabilizing the position of the sample in the inductor. As a further work in the framework of this study, we assume the development of a system for monitoring the position of the molten sample in the inductor based on computer vision.

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References

1. Gorlanov, E.S.; Bazhin, V.Y.; Fedorov, S.N. Low-Temperature Phase Formation in A Ti-B-C-O System. *Tsvetnye Met.* **2017**. [CrossRef]
2. Lohöfer, G. Theory of an Electromagnetically Levitated Metal Sphere I: Absorbed Power. *SIAM J. Appl. Math.* **1989**, *49*. [CrossRef]
3. Lewis, J.C.; Neumayer, H.R.J.; Ward, R.G. The Stabilization of Liquid Metal during Levitation Melting. *J. Sci. Instrum.* **1962**, *39*. [CrossRef]
4. Takahashi, K.; Mogi, I.; Onogi, T.; Awaji, S.; Motokawa, M.; Watanabe, K. Materials Processing in Magnetic Levitation Furnaces. *Sci. Technol. Adv. Mater.* **2006**, *7*, 346–349. [CrossRef]
5. Yu, J.; Fu, C.; Liu, Y.; Xia, K.; Aydemir, U.; Chasapis, T.C.; Snyder, G.J.; Zhao, X.; Zhu, T. Unique Role of Refractory Ta Alloying in Enhancing the Figure of Merit of NbFeSb Thermoelectric Materials. *Adv. Energy Mater.* **2018**, *8*, 1701313. [CrossRef]
6. Zhu, X.R.; Harding, R.A.; Campbell, J. Calculation of the Free Surface Shape in the Electromagnetic Processing of Liquid Metals. *Appl. Math. Model.* **1997**, *21*, 207–214. [CrossRef]
7. Palacz, M.; Melka, B.; Wecki, B.; Siwiec, G.; Przylucki, R.; Bulinski, P.; Golak, S.; Blacha, L.; Smolka, J. Experimental Analysis of the Aluminium Melting Process in Industrial Cold Crucible Furnaces. *Met. Mater. Int.* **2020**, *26*, 695–707. [CrossRef]
8. Nycz, B.; Malinski, L.; Przylucki, R. Influence of Selected Model Parameters on the Electromagnetic Levitation Melting Efficiency. *Appl. Sci.* **2021**, *11*, 3827. [CrossRef]
9. Wu, P.; Yang, Y.; Barati, M.; McLean, A. Electromagnetic Levitation of Silicon and Silicon-Iron Alloy Droplets. *High Temp. Mater. Process.* **2014**, *33*. [CrossRef]
10. Spitans, S.; Franz, H.; Baake, E. Numerical Modeling and Optimization of Electrode Induction Melting for Inert Gas Atomization (EIGA). *Metall. Mater. Trans. B Process Metall. Mater. Process. Sci.* **2020**, *51*, 1918–1927. [CrossRef]
11. Spitans, S.; Franz, H.; Baake, E.; Jakovičs, A. Large-Scale Levitation Melting and Casting of Titanium Alloys. *Magnetohydrodynamics* **2017**, *53*, 633–641. [CrossRef]
12. Lee, J.; Xiao, X.; Matson, D.M.; Hyers, R.W. Numerical Prediction of the Accessible Convection Range for an Electromagnetically Levitated Fe50Co50 Droplet in Space. *Metall. Mater. Trans. B Process Metall. Mater. Process. Sci.* **2015**, *46*, 199–207. [CrossRef]
13. Spitans, S.; Bauer, C.; Baake, E. Investment Castings with Unique Levitation Melting Technology. In Proceedings of the 68th Technical Conference & Expo, Grand Rapids, MI, USA, 7 November 2021.
14. Zhang, X.; Trakarnchaiyo, C.; Zhang, H.; Khamesee, M.B. MagTable: A Tabletop System for 6-DOF Large Range and Completely Contactless Operation Using Magnetic Levitation. *Mechatronics* **2021**, *77*, 102600. [CrossRef]
15. Demidovich, V.B.; Rastvorova, I.I. A Combined Method of Simulation of an Electric Circuit and Field Problems in the Theory of Induction Heating. *Russ. Electr. Eng.* **2014**, *85*, 536–540. [CrossRef]
16. Khorshev, A.; Bondar, A.; Streltsova, O.; Chmileno, F.; Rastvorova, I. Simulation of Induction Heating of a Ferromagnetic Plate with a Covering Inductor. *J. Phys. Conf. Ser.* **2021**, *2032*, 012025. [CrossRef]
17. Baake, E.; Shpenst, V.A. Recent Scientific Research on Electrothermal Metallurgical Processes. *J. Min. Inst.* **2019**, *240*, 660–668. [CrossRef]
18. Xiao, X.; Brillo, J.; Lee, J.; Hyers, R.W.; Matson, D.M. Impact of Convection on the Damping of an Oscillating Droplet during Viscosity Measurement Using the ISS-EML Facility. *NPJ Microgravity* **2021**, *7*, 36. [CrossRef]
19. Seidel, A.; Soellner, W.; Stenzel, C. EML—An Electromagnetic Levitator for the International Space Station. *J. Phys. Conf. Ser.* **2011**, *327*, 012057. [CrossRef]
20. Darhovsky, Y.; Mellincovsky, M.; Baimel, D.; Kuperman, A. A Novel Contactless, Feedbackless and Sensorless Power Delivery Link to Electromagnetic Levitation Melting System Residing in Sealed Compartment. *Energy* **2021**, *231*, 120789. [CrossRef]
21. Easter, S.; Bojarevics, V.; Pericleous, K. Numerical Modelling of Liquid Droplet Dynamics in Microgravity. *J. Phys. Conf. Ser.* **2011**, *327*, 012027. [CrossRef]
22. Gagliano, S.; Stella, G.; Bucolo, M. Real-Time Detection of Slug Velocity Inmicrochannels. *Micromachines* **2020**, *11*, 241. [CrossRef] [PubMed]
23. Parchevsky, V.M. Mathematical Support for the Control System for Nitrogen Oxide Emissions in Boilers with Furnaces with Liquid Slag Removal. *J. Phys. Conf. Ser.* **2020**, *1683*, 042060. [CrossRef]
24. Kulchitskiy, A. Optical Inspection Systems for Axisymmetric Parts with Spatial 2D Resolution. *Symmetry* **2021**, *13*, 1218. [CrossRef]
25. Bazhin, V.Y.; Issa, B. Influence of Heat Treatment on the Microstructure of Steel Coils of a Heating Tube Furnace. *J. Min. Inst.* **2021**, *249*, 393. [CrossRef]
26. Ma, Y.; Li, Q.; Chu, L.; Zhou, Y.; Xu, C. Real-Time Detection and Spatial Localization of Insulators for Uav Inspection Based on Binocular Stereo Vision. *Remote Sens.* **2021**, *13*, 230. [CrossRef]
27. Shabalov, M.Y.; Zhukovskiy, Y.L.; Buldysko, A.D.; Gil, B.; Starshaia, V.V. The Influence of Technological Changes in Energy Efficiency on the Infrastructure Deterioration in the Energy Sector. *Energy Rep.* **2021**, *7*, 2664–2680. [CrossRef]
28. Vasilyeva, N.; Fedorova, E.; Kolesnikov, A. Big Data as a Tool for Building a Predictive Model of Mill Roll Wear. *Symmetry* **2021**, *13*, 859. [CrossRef]
29. Ushakov, E.; Aleksandrova, T.; Romashev, A. Neural Network Modeling Methods in the Analysis of the Processing Plant's Indicators. *Adv. Intell. Syst. Comput.* **2021**, *1259*, 36–45.
30. Voronina, M.V.; Moroz, O.N. A Substantiation of Foresight Research of Development Strategy of Descriptive Geometry, Engineering Geometry and Computer Graphics Departments on the Basis of Industrial 4.0 Ideology. *Man India* **2017**, *97*, 375–389.

31. Álvarez-Tuñón, O.; Jardón, A.; Balaguer, C. Generation and Processing of Simulated Underwater Images for Infrastructure Visual Inspection with UUVs. *Sensors* **2019**, *19*, 5497. [CrossRef]
32. Konushin, A.S.; Faizov, B.V.; Shakhuro, V.I. Road Images Augmentation with Synthetic Traffic Signs Using Neural Networks. *Comput. Opt.* **2021**, *45*, 736–748. [CrossRef]
33. Islamov, S.; Grigoriev, A.; Beloglazov, I.; Savchenkov, S.; Gudmestad, O.T. Research Risk Factors in Monitoring Well Drilling—A Case Study Using Machine Learning Methods. *Symmetry* **2021**, *13*, 1293. [CrossRef]
34. Lee, S.Y.; Tama, B.A.; Choi, C.; Hwang, J.Y.; Bang, J.; Lee, S. Spatial and Sequential Deep Learning Approach for Predicting Temperature Distribution in a Steel-Making Continuous Casting Process. *IEEE Access* **2020**, *8*, 21953–21965. [CrossRef]
35. Abakumov, I.I.; Kul'chitskii, A.A. Compensation of the Errors of a Passive Opto-Electronic System for Dimensional Control of Articles. *Meas. Tech.* **2016**, *59*. [CrossRef]
36. Szegedy, C.; Liu, W.; Jia, Y.; Sermanet, P.; Reed, S.; Anguelov, D.; Erhan, D.; Vanhoucke, V.; Rabinovich, A. Going Deeper with Convolutions. In Proceedings of the IEEE Computer Society Conference on Computer Vision and Pattern Recognition, Boston, MA, USA, 12 June 2015.
37. Simakov, A.S.; Trifonova, M.E.; Gorlenkov, D.V. Virtual Analyzer of the Voltage and Current Spectrum of the Electric Arc in Electric Arc Furnaces. *Russ. Metall.* **2021**, *2021*, 713–719. [CrossRef]
38. Silva, B.E.; Barbosa, R.S. Experiments with Neural Networks in the Identification and Control of a Magnetic Levitation System Using a Low-Cost Platform. *Appl. Sci.* **2021**, *11*, 2535. [CrossRef]
39. Vishnuram, P.; Ramachandiran, G.; Babu, T.S.; Nastasi, B. Induction Heating in Domestic Cooking and Industrial Melting Applications: A Systematic Review on Modelling, Converter Topologies and Control Schemes. *Energies* **2021**, *14*, 6634. [CrossRef]
40. Fedorova, E.R.; Vasileva, N.V.; Pupysheva, E.A. Algorithm to Distribute Feed Pulp between Paralleled Thickeners during Red-Sludge Thickening and Washing in Alumina Production. *J. Phys. Conf. Ser.* **2019**, *1333*, 042007. [CrossRef]
41. Pirog, S.; Shklyarskiy, Y.E.; Skamyin, A.N. Non-Linear Electrical Load Location Identification. *J. Min. Inst.* **2019**, *237*, 317–321. [CrossRef]
42. Beloglazov, I.I.; Petrov, P.A.; Bazhin, V.Y. The Concept of Digital Twins for Tech Operator Training Simulator Design for Mining and Processing Industry. *Eurasian Min.* **2020**, *2020*, 50–54. [CrossRef]
43. Koteleva, N.I.; Korolev, N.A.; Zhukovskiy, Y.L. Identification of the Technical Condition of Induction Motor Groups by the Total Energy Flow. *Energies* **2021**, *14*, 6677. [CrossRef]
44. Fizaine, F.; Court, V. Renewable Electricity Producing Technologies and Metal Depletion: A Sensitivity Analysis Using the EROI. *Ecol. Econ.* **2015**, *110*, 106–118. [CrossRef]
45. Knapp, G.L.; Mukherjee, T.; Zuback, J.S.; Wei, H.L.; Palmer, T.A.; De, A.; DebRoy, T. Building Blocks for a Digital Twin of Additive Manufacturing. *Acta Mater.* **2017**, *135*, 390–399. [CrossRef]
46. Savard, C.; Iakovleva, E.; Ivanchenko, D.; Rassõlkin, A. Accessible Battery Model with Aging Dependency. *Energies* **2021**, *14*, 3494. [CrossRef]
47. Vöth, S.; Vasilyeva, M. Potential of Modelica for the Creation of Digital Twins. In *Advances in Raw Material Industries for Sustainable Development Goals*; CRC Press: London, UK, 2021.
48. Kolesnikov, A.S.; Serikbaev, B.E.; Zolkin, A.L.; Kenzhibaeva, G.S.; Isaev, G.I.; Botabaev, N.E.; Shapalov, S.K.; Kolesnikova, O.G.; Iztleuov, G.M.; Suigenbayeva, A.Z.; et al. Processing of Non-Ferrous Metallurgy Waste Slag for Its Complex Recovery as a Secondary Mineral Raw Material. *Refract. Ind. Ceram.* **2021**, *62*, 375–380. [CrossRef]
49. Ilyushin, Y.; Afanaseva, O. Spatial Distributed Control System Of Temperature Field: Synthesis And Modeling. *ARPN J. Eng. Appl. Sci.* **2021**, *16*, 1491–1506.