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Recent scientific research on electrothermal metallurgical processes

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A wide range of industrial metallurgical heating and melting processes are carried out using electrothermal technologies. The application of electrothermal processes offers many advantages from technological, ecological and economical point of view. Although the technology level of the electro heating and melting installations and processes used in the industry today is very high, there are still potentials for improvement and optimization due to the increasing complexity of the applications and the strong requirements regarding the performance and quality of the products but also regarding the reduction of time and costs for the development of new processes and technologies.

In this paper recent applications and future development trends for efficient heating and melting by electrothermal technologies in metallurgical processes are described along selected examples like induction heating for forging or rolling of billets, heat treatment of strips and plates, press-hardening processes, induction surface hardening of complex geometries, induction welding as well as induction melting processes.

Key words: electrothermal processes; electrotechnology; metallurgy; induction heating; induction melting; electromagnetic processing

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Introduction. Thermal processing technologies are an indispensable part of many industrial processes in particular in the production and further treatment of products in metallurgical industry. In many cases the processing and in particular the heating of materials can, in principle, be realized by both using electrical energy and fossil energy sources, like gas or oil. However, due to the continually growing demands for the effectiveness of the whole process chain, the level of flexibility and automation, the environmental sustainability of industrial processes, the reliable quality and not at least ~~on~~ the improvement of the total energy and CO_2-emission balance of a process or a product, electrical energy and particularly electrotechnologies in many cases offer excellent future oriented application possibilities in multifarious industrial processes [5].

Electrothermal processes are offering a wide range of industrial applications because of many different principles which cover the whole range from high-power applications in classical areas such as ferrous and non-ferrous metallurgical industry to very modern applications in process-oriented fields such as crystal growing. For high-power applications the main fields of research and development today are the optimal control of processes and the energy-efficient design and operation of processes and installations. In process-oriented applications the energy aspect plays the secondary role while the optimization of the production process is the primary task [12].

Electro processing technologies are suitable for heating and melting any electrically conducting and non-conducting material. A great number of industrial processes including melting, hardening, tempering, annealing, brazing, galvannealing, drying, crystal growing, preheating before rolling, forging or coating are carried out using electrothermal processing technologies. The electromagnetic processing technologies become more and more significant not only for heating and melting but also for electromagnetic controlling, steering, braking or confining of melt flows during casting processes, separating of inclusions or controlling of solidification processes. The increasing use of electric energy for all these processes depends on the special features and the numerous advantages of electric energy, as described below. The major advantages of using electrical energy for thermal and in particular electromagnetic processing technologies can be listed as follows:

- heat can be generated within the workpiece (direct heating);
- high energy density and consequently fast heating;
- demanded temperature distributions within the workpiece;
- very high temperature, if required;

- lower specific energy consumption than other methods;
- flexible operation and low thermal inertia;
- selective, localized heating, if required;
- excellent environmental conditions;
- clean heating in any media including vacuum or a controlled atmosphere;
- high reliability;
- electromagnetic forces on liquid electrically conducting material for stirring, braking, homogenizing, confining, levitating or separating of inclusions;
- electromagnetic processing of materials.

Electrical heating methods, can be used much more effectively and in a much more targeted manner than competitive energy sources. Electrothermal technologies are characterized by high process efficiency and, in spite of having a higher energy price than fossil fuels, by better profitability than other energy sources as a result of lower operating or raw material costs. Electric heating processes are very flexible in operation and they provide excellent possibilities of a high level of automation.

The application of electrothermal and electromagnetic processing treatment allows a desired heating which is easily reproducible which means that defined material properties can be set in order to improve the technical characteristics of the semi-finished or final product. Using electric heating the fast heating-up rate, the exact temperature control as well as the predictable and reproducible spatial temperature distribution result in high thermal efficiency and noticeable saving of raw material, e.g. due to the low combustion losses. This becomes particularly clear in induction, conduction, dielectric and microwave processes where the heat is generated in the workpiece itself. On the basis of the short heating-up period, which is reduced by up to 90 % compared with fossil fuel heated installations, metallurgical modifications of the workpiece surface, such as oxidation and decarbonisation, are considerably restricted and this results in high quality of the products. Also, a flexible and immediate readiness for operation is given and the storing of heated or melted material is not necessary in many cases. Electric heating installations are very compact and require a relatively small floor space, so they can be easily integrated in existing production lines. This results in considerable improvement of the production course.

Resent Developments. Saving of process steps and the reduction of the production line is frequently the key of success for saving energy and costs by the optimization of the total efficiency and productivity of a complete production process. Therefore the development and realization of new innovative future oriented processes and technologies is indispensable. Near net shape production processes are a trend for saving process steps as well as saving ~~of~~ raw material and energy consumption and so finally it yields in the increase of the total efficiency and productivity. Examples, which are still in development or already in practical use are thixo-forming processes, thin strip continuous casting processes or precision forging and forming processes. In those innovative processes an exact temperature distribution in the workpiece to be treated is absolutely necessary. This strong technological requirement can be carried out with electrical heating, like induction heating, where a precise automatic temperature control is possible.

The substitution of conventional production processes by new innovative processes is a general important approach for improvement and optimization of product quality, productivity and overall efficiency in many industrial processes. This includes also the substitution of the final energy sources. Instead of the complete substitution of the customary used thermal technology sometimes the combination of different technologies leads to an overall improvement of the efficiency. A typical example is the combination of different heating methods and processes in hybrid installations, like induction heating in combination with a gas fired furnace, microwave heating integrated in a convective heated furnace, induction heating in combination with laser or an induction stirrer used in gas fired aluminium melting furnaces. Practical examples can be found e.g. in applications for strip heating, where the fast heating up of the strip can be realized efficiently by induction heating and the time dependent metallurgical process, like annealing for re-crystallisation of the material, can be done using a long gas-fired soaking furnace [8].

Research examples: Flexible transverse flux strip heaters. Many production lines in the semis industry include the heating of thin metal strips in continuous operation as an important process step. For heating there is a wide variety of applications ranging from drying tasks after coating and painting, galvanizing, the heat treatment (e.g. annealing) to the heating for hot forming. Nowadays mainly gas or electrically resistant heated furnaces are used for these tasks. They work on the principle of indirect heat transfer. The energy is supplied to the material to be heated by convection and heat radiation to the surface. In this case, there are limitations and disadvantages, such as ~~the~~ limited achievable power density, increased scale attack and grain growth due to the long residence time in the furnace. At the same time, the operational characteristics such as large floor space required, high heat losses and extended up and cool-down by the large volume furnace rooms and the limited flexibility of these systems are very disadvantageous for modern production processes.

An innovative solution to the problems described above can be achieved by the use of the transverse flux induction heating concept [13]. This technology offers numerous advantages such as high power density, high efficiency, high automation and flexibility. The schematic structure of a transverse flux induction heater is shown in Fig.1.

In recent years, extensive research work in the field of transverse flux heating has been carried where the achieved good results are mainly based on two facts. This is both a design concept developed and the other using a combination of numerical simulation and automatic optimization algorithms. In the automatic optimization search the algorithms look for any special parameter set to get the optimal design of the inductors. The focus of developments in recent years in the field of transverse flux technology aimed at the use of heaters for strips of variable width. Fig.2 shows the newly developed and patented concept for heating the metal strips of variable width (VABID). It is ideal for many applications, extremely robust and has now been proven successful in industrial use.

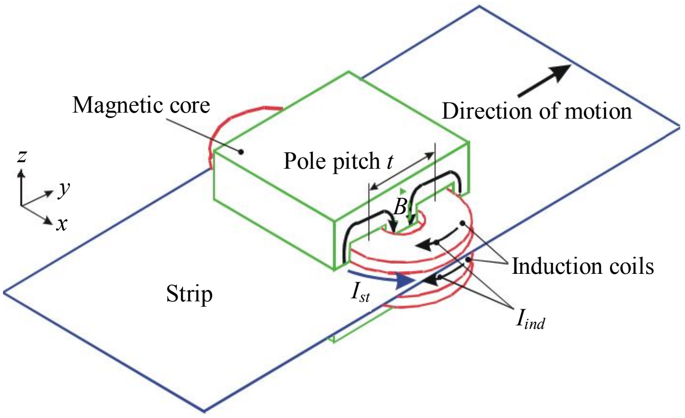

Fig.1. Schematic structure of a transverse flux induction heater induction heat treatment

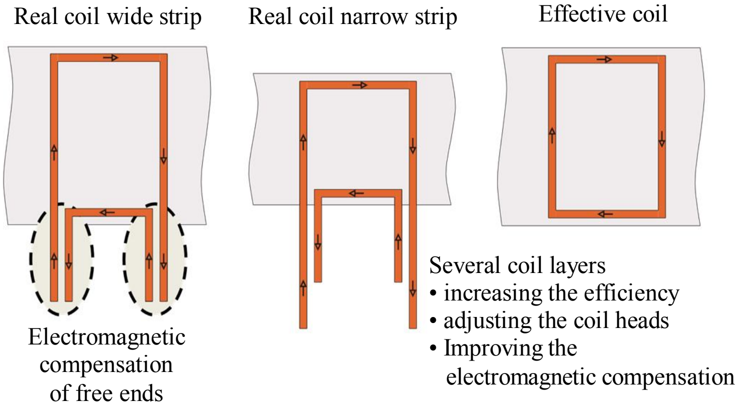

Fig.2. Transverse flux heating concept VABID for strips of variable width

Induction surface hardening and annealing. Inductive surface hardening is also an innovative electro thermal technology which is used for improving the quality of mechanical components in terms of abrasion resistance while preserving the core ductility. To receive these properties, a thin layer of material underneath the work piece's surface is heated up by induction and quenched afterwards. The main advantages of this technology are a very short process time, high power densities, low distortion and low space requirements. Therefore, subsequent machining can often be eliminated and an integration of the process into production lines can be achieved easily.

The design of induction hardening devices, especially the inductor geometry and the choice of the hardening parameters like inductor current and power, are actually carried out by experience and experimentation. However, there are limits to this approach if complex work piece geometries have to be handled or if the hardening parameters become more complex, for example when two simultaneous frequencies are used. Also, a design based on experimentation often means a big financial effort and is time consuming.

The numerical simulation of induction heating processes offers new opportunities for the design of induction hardening devices with complex geometries and time regimes. A new model was developed which can successfully simulate the full in-stationary heating process. The model allows the solution of the coupled non-linear electromagnetic and thermal fields taking into account all relevant temperature and field dependencies of the material properties, which change significantly during heating [11]. A method to simulate the heating process with several simultaneous frequencies was implemented as well. Relative motion of work piece and inductor, for instance rotation of a work piece, can also be simulated. Subsequent to heating, the quenching process and phase transformations within the material are calculated based on the time-temperature profile. All process parameters can be changed easily. Therefore, the simulation tool is able to investigate the influence of different hardening parameters on the hardening profile and to optimize the process.

The simulation tool was used to design and optimize a broad range of processes over the last years. For example, work pieces like worm, spiral and straight cut gears as well as crankshafts were investigated. Experiments were used to validate and improve the simulation tool constantly. In principal, any 3D geometry can be investigated with the new developed model. The complexity is only limited by calculation time.

Fig.3 shows three cross sections of a hardened straight cut gear. The calculated temperature profile after heating, a microsection and the calculated martensite content are displayed. In both cases, the same process parameters were used in the simulation and in the experiment. The computed results and the microsections show good agreement.

A new field of investigation is the development of induction annealing in-line after the induction hardening process [3]. Due to the low temperature treatment at annealing the workpiece is under Curie temperature which needs more attention to the optimal process frequency and to the optimal inductor design. In the current stage a design tool for the numerical simulation of the entire hardening and annealing process will be developed and tested.

Induction heating for hot metal forming. Due to growing challenges regarding crash-performance, CO_2 emission as well as increasing demand for lightweight construction, hot metal forming of car body parts has risen to one of the most important technologies for saving weight of a car body. During hot metal forming shaped blanks of steel, mostly made of 22MnB5, are heated and austenitized at around 950 °C and subsequently quenched for martensitic formation. Currently the heating is realized in roller hearth furnaces which allow only a slow heating and, therefore, a limited production. Additionally, due to the indirect heating principle of such furnaces the energy efficiency is low.

Induction heating of the blanks offers a big potential to increase the production rate dramatically and also to improve the energy efficiency. Only due to the fact, that the heated parts typically are already pre-shaped and mostly have already holes and cut-outs induction heating becomes a very complex task. Beside, induction heating, always accompanied by driven forces, can lead to problems if the blanks are coated by a low melting coating alloy like Al-Si. In previous works different possible induction heating methods (longitudinal heating, transverse flux heating, single stage induction heating, hybrid heating by induction and conventional heating) have been investigated and evaluated regarding the potentials and limitations of induction heating for hot metal forming depending on production conditions. In the frame of a current research project a detailed numerical and experimental investigation of a single

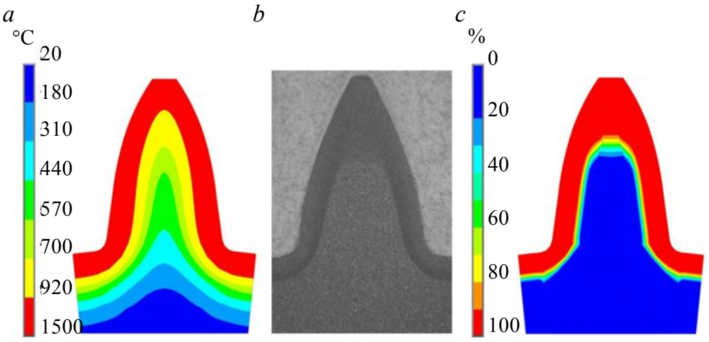

Fig.3. Temperature profile (*a*), microsection (*b*) and martensite (*c*)

stage induction heating has been carried out [6]. The results show the principle potential of a single stage induction heating for hot metal forming. Based on the results an induction heating process for pre-shaped blanks was finally designed. The induction heater is planned to be used in a demonstrator to show effective induction hot forming of a half B-pillar.

Heating for joining. The adequate combination of different heating methods in form of hybrid processes often leads to substantial improvement from technological, energetic and economic point of view [9]. A very innovative example is the combination of laser beam treatment supported by induction heating (Fig.4).

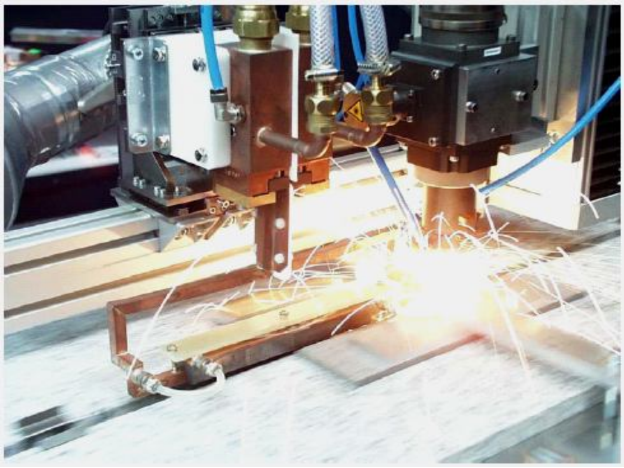

Fig.4. Laser welding process combined with induction heat treatment

The combination of laser processing with induction heating offers new possibilities and allows new areas of application using the advantages of both technologies. Applications are for example the build-up welding of high-alloyed steels, the surface melting of highly stressed components and the welding of plates made of highly alloyed steels. Laser processing is usually associated with high power density and high temperature gradients, which can lead, e.g. during welding processes, to significant thermal stresses and undesirable metallurgical phase transformations. To prevent these undesirable effects induction heating can be used. Induction heating is fully controllable in time and ~~in~~ space, easy to handle and can be applied simultaneously or as post- or pre-heating combined with the laser processing. Reducing the cooling rate, controlling the temperature level during the welding process (reducing the hardness), increasing the formability and toughness as well as increasing the efficiency of the welding processes (due to higher welding speed) are the main advantages of combined induction heat treatment in laser welding processes.

Induction high frequency tube welding. The complex numerical simulation of the induction high frequency longitudinal tube welding process is a research topic for many years. In close cooperation with industrial partner numerous improvements of the induction tube welding process could be obtained [1]. In the frame of a cooperation project the induction high frequency tube welding of cladded pipes, using double or single frequency has been recently investigated. Cladded pipes are used in various applications in natural gas transportation systems, power plants and chemical industry. The combination of two different metals within one pipe offers high corrosion and abrasion resistance in an economical way. Until today the cladded pipes are manufactured by discontinuous arc welding, weld cladding or mechanical bracing with comparatively low production rates.

By the use of developed numerical simulation models (Fig.5), the theoretical capability of an inductive longitudinal seam welding process for cladded pipes have been demonstrated [10]. Industrial scale process windows for both, single frequency and simultaneous double frequency are realized in this project. The verification was performed on a cladding material combination of S355 and Alloy 625 with strongly divergent material properties, where several effects were used to reach the melting temperatures in the joint edges (Fig.6). Potentially, a wide range of metal combinations comprising ferrite alloys as carrier and austenitic alloys as cladding material can be welded by the developed approach [7].

Tailored heating for hot forming. Tailored heating for hot forming is a new approach for heating of bars and billets before forming, e.g. forging. In the frame of this research work numerical and experimental investigations will demonstrate to what extent a tailor-made temperature profile can be realized in a billet for subsequent forming [4]. In this way, a targeted distribution of the yield stress in the workpiece can be adjusted, which can be used for a subsequent forming process to the extent that a desired mass pre-distribution is achieved in the component. Usually, drop forging processes are carried out in several forming steps, at least by preforming and finish forming. In preforming, special forming processes, such as the stretch rolling or cross wedge rolling, are applied.

The required forming units and forming tools are very expensive and therefore often not economical for companies. Tailored heating is intended to offer an economic opportunity to dispense with the preforming units and still produce a suitable complex preform by pressing the tailor-made blank to achieve both energy and material saving effects [14]. For the realization of the temperature distribution the heating by electrical conduction as well as by induction and by direct flame impingement are investigated. Based on numerical investigations for three different materials, the respective heating concepts are tested on experimental setups and compared with each other technically and economically. At the end of the project, based on the results of simulation and experiment, guidelines for the design and application of tailor made temperature profiles for the investigated workpiece geometries and materials will be developed.

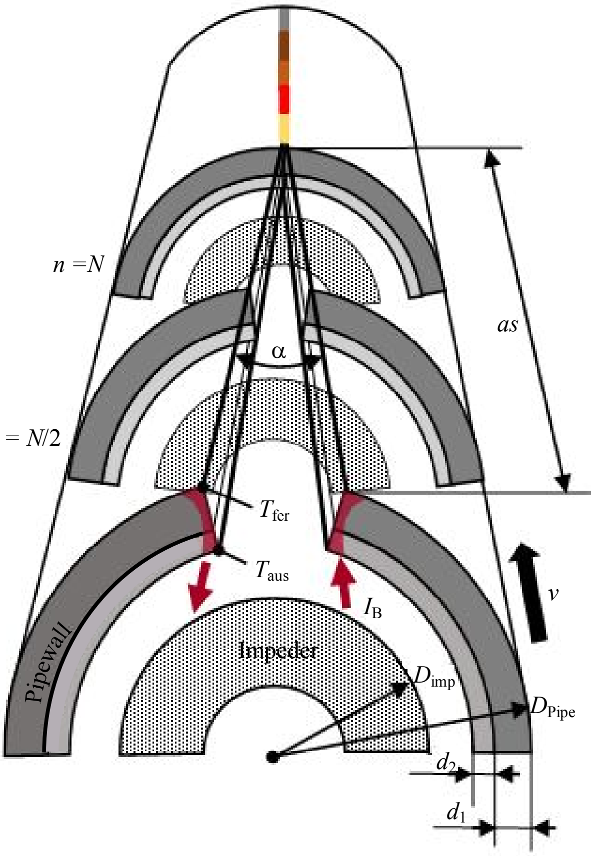

Fig.5. Simulation model of a half pipe cross section, with 2D model steps along the pipe edge move

Magnetofluiddynamics. The magnetofluiddynamics research field is covering projects for the analysis and the optimization of magnetofluiddynamic processes and installations [2]. An important area is the electromagnetic processing of materials including the processing of non-linear electrothermal and magnetofluiddynamic systems. Along with many new developments in the area of common ferrous and non-ferrous metals, there has been an increase research concerning innovative materials for high technology applications, such as semiconductor silicon, titanium-aluminium alloys and oxides with high melting points.

Heat and mass transfer in the melt of induction installations. The process oriented development, design and optimization of induction furnaces for melting and casting of metals is still an important research topic in the field of electrotechnologies. The praxis oriented simulation and

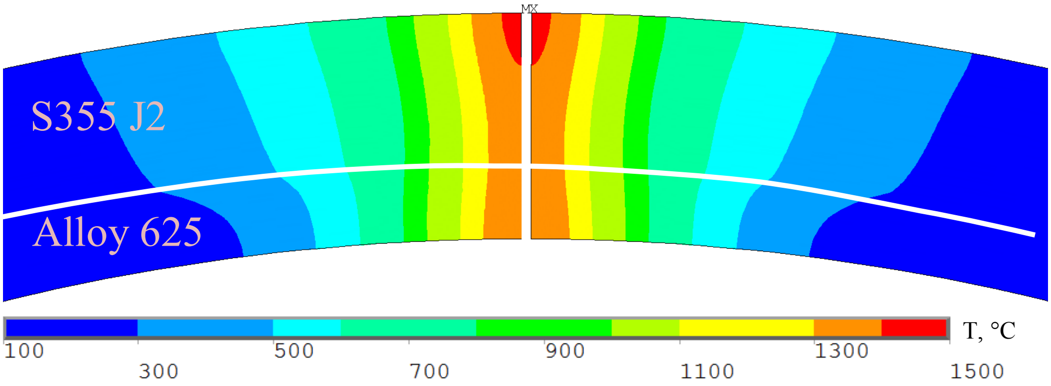

Fig.6. Temperature development at the pipe cross section at a welding speed of v_s = 40 m/min welded at two frequencies of f_{hf} = 220 kHz and f_{mf} = 10 kHz

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analysis of the complex in-stationary turbulent melt flows and temperature distributions as well as the heat and mass transfer in the melt of induction installations today is carried out successfully using the Large-Eddy-Simulation(LES) method, at which the simulation results are in good agreement with corresponding experimental results. Examples for the application of the LES-method in industrial oriented research and development projects are induction crucible and induction channel furnace for ferrous and non-ferrous metals, the cold crucible induction furnace for melting and casting of TiAl alloys, melting and zinc coating installations with crucible and channel inductors as well as electromagnetic steering during continuous casting and solidification processes.

In many melting processes the transport and in-stationary distribution of particles in the melt is very important, at which the particles could have different sizes and densities. For the simulation and visualisation of the particle transport inside the in-stationary melt flow different simulations models have been developed and successfully tested [15]. The transport and mixing of the particles can be calculated in-stationary three-dimensional with particle tracing models. Even electrical conducting and non-conducting particles can be simulated in order to investigate the influence of electromagnetic forces on the particles. The LES-method has been also successfully applied for the simulation of the in-stationary melt flow and temperature distribution in the induction channel furnace. The heat transport from the channel to the melt bath can be calculated with transient three dimensional simulations. Therefore, it is possible to use the LES approach for the design of the channel in order to optimize the heat and mass transfer or to reduce the clogging behaviour of the channel.

Fig.7 shows an example of the transient calculation of the melt flow and temperature distribution in the melt of a channel inductor. Shown are streamlines representing the time averaged velocity. Electrical neutral particles are following these stream lines. The colour of the stream lines characterizes the local averaged temperature.

Electromagnetic levitation melting. Electromagnetic levitation melting offers several advantages, like contactless melting, high purity of the molten material, high temperature of the melt or high efficiency. But in conventional axisymmetric melting furnaces with electromagnetic levitation (EML), the Lorentz force vanishes on the symmetry axis. The melt outflow and leakage can be hindered in this lowest point on the axis of a levitated sample only by the melt surface tension and therefore, the charge weight is limited. Recently, a new technology for the electromagnetic levitation melting of metallic samples with greater weights and axis-symmetrically stabilized positions has been developed [16, 17]. The new method is applying two homogeneous magnetic fields of different frequencies, whose field lines are in absence of a charge horizontally and reciprocally normal in order to exert electromagnetic lift forces also on the axis of the levitated sample. Therefore, the weight of the charge can be increased and the charge can be drip- and leakage-free melted. The method can be used in a melting furnace as well as for the coreless induction valves applied for flow rate control, e.g. in the continuous casting of molten metal. The applicability of the method was experimentally examined and proved by tests conducted with different types of laboratory setups and will be now further developed in industry. In parallel with the experimental investigations a numerical model for simulation and optimization of particular electromagnetic (EM) levitation melting technology has been developed (Fig.8).

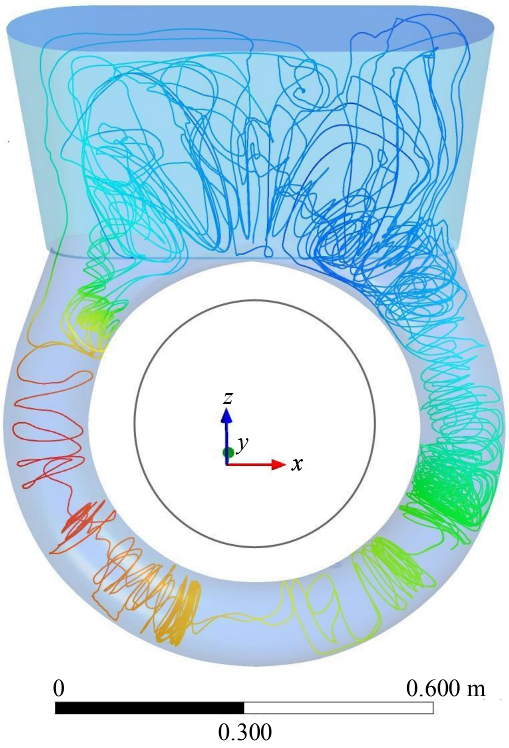

Fig.7. Simulation of stream lines and local temperature inside a channel inductor

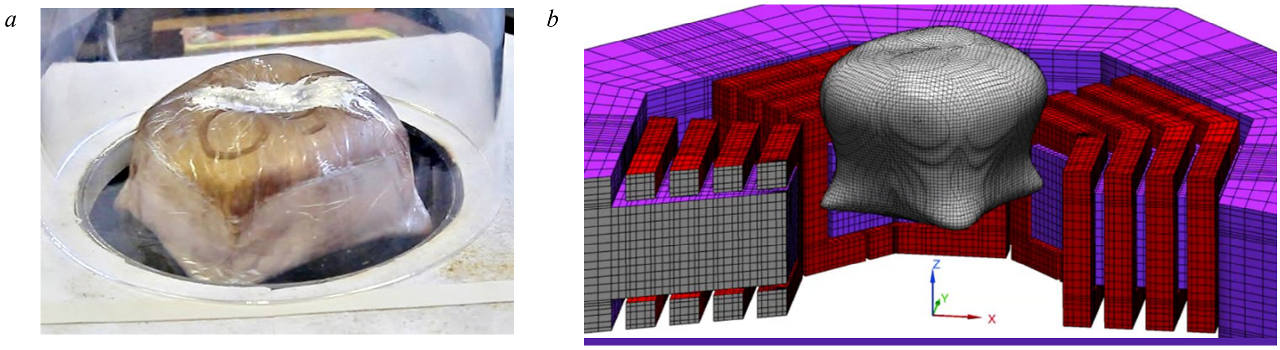

Fig.8. Experimental melting process (*a*) and numerical model of EM levitation melting (*b*)

Electromagnetic induced turbulent flow and free surface dynamics computation is ensured by means of automatic coupling between 3D electromagnetic calculation in ANSYS and 3D two-phase hydrodynamic calculation in FLUENT. Simulation results for single and two-frequency EM levitation melting cases have been compared to experimental measurements, and further scale up possibilities of charge weight which could be applied in industrial scale will be investigated. Further on a cylindrical Cold Protective Wall (CPW) composed of ~~a~~ water cooled copper tube was applied, instead of a cold crucible, for protecting the magnetic core against heating caused by the melted charge. The utilization of the bottomless CPW has, compared to the conventional induction furnace with cold crucible, the following principal advantages: heat losses do not occur through a solidified bottom skull and the melt can be cast through the CPW like a bottom casting method, i.e. without disadvantageously tilting the melting device. This technology offers new industrial possibilities for melting and casting of metals.

Conclusions. The application of electrothermal technologies in metallurgical processes offers many technological, ecological and economic advantages. The use of electroheat will be increased in ~~the~~ future because electro processing technologies in particular meets the continually rising standards with regard to the requirement to the products and the desire for production processes which are both as efficient as possible and have minimum environmental impact. In particular, the manufacturing of new materials and new products offers future potentials for innovative solutions applying electrothermal and electromagnetic processes. From ecological point of view in future the use of electricity for all kinds of industrial and domestic applications including all kinds of thermal processes will lead to a considerable reduction of CO_2-emissions and therefore to a reduction of the carbon footprint, due to the significant increasing share of electricity generated by renewable energy sources.Well established electro processing technologies can be improved and optimized from technological, energetic, and last but not least economic point of view. Future oriented tasks of researchers, producers and users of electrothermal technologies are the development and realization of process oriented customized technologies, where the optimization is not concentrated on a single heating or melting installation, but the whole production line including material transport, overall energy balance and productivity and in particular the total efficiency of the line are taken into account. In the frame of this context the digitalization (Industry 4.0) will play a key role in the future research and development of the electrothermal technologies and processes.

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