Systematic approach to optimal design of induction heating installations for aluminum extrusion process

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Abstract. An induction heating system has a number of inherent benefits compared to traditional heating systems due to a non-contact heating process. It is widely used in vehicle manufacture, cast-rolling, forging, preheating before rolling, heat treatment, galvanizing and so on. Compared to other heating technologies, induction heating has the advantages of high efficiency, fast heating rate and easy control. The paper presents a new systematic approach to the design and operation of induction heating installations (IHI) in aluminum alloys production. The heating temperature in industrial complexes “induction heating - deformation” is not fixed in advance, but is determined in accordance with the maximization or minimization of the total economic performance during the process of metal heating and deformation. It is indicated that the energy efficient technological complex “IHI – Metal Forming (MF)” can be designed only with regard to its power supply system (PSS). So the task of designing systems of induction heating is to provide, together with the power supply system and forming equipment, the minimum energy costs for the metal retreating.

1. Introduction
The induction method of heating is widely distributed in numerous technological processes for hot forming, surface hardening, annealing, etc. It is extremely effective because of its contactless energy transfer, unlimited power densities and controlled temperature field in the workpiece. However, high potential of induction heating can be fully realized on the basis of numerical simulation only.

New materials are intended for improvements of induction heating equipment for industrial applications. The energy efficiency will be key issues in a contemporary society. In this regard, induction heating is the most energy efficient heating technology in many applications, provided that the technology can be adapted to industrial needs and conditions.

The energy saving effect of electromagnetic heating is more remarkable than traditional heating methods, it saves between 30 and 50 percent of average wattage, and it also has many relative advantages, such as heat stabilities, rapid heating, long service life, convenient maintenance, etc.

This paper shows the result of cross-disciplinary research project and provides great potential application in a new type of induction heating installations (IHI), which are used for heating and plastic deformation of different metals.

By combining new materials with improved manufacturing methods and well-designed control systems, a greatly improved induction heating platform can be achieved. The new technology has the
potential to not only reduce the energy consumption but also to reduce production costs and cycle times compared to traditional methods.

The main purpose of this scientific research is to develop a generic induction heating solution which can be adapted to different industrial applications with a small effort and setup cost.

2. Induction heating concepts for preheating aluminium billets before extrusion

There are many advantages of the electromagnetic induction heating method, such as rapid warming, high thermal efficiency, no open flame, no smoke and no harmful gases, no heat radiation harming environment; it also has a small volume and good security.

The main advantage of induction heating is that a large amount of energy can be introduced into the material to be heated within a very short time. This physical phenomenon allows the plant to be built compactly and with a small footprint. The inductor can be selectively employed in places where temperature increases or temperature adjustment is necessary.

Aluminum billets are heated at ambient temperature of up to 450 - 500 °C prior to extrusion. The primary types of furnaces used for preheating a billet before extrusion are gas fired furnaces and induction heaters. The choice of equipment depends on many factors. The most important criterion is final cost of product and product quality. Also it is important to take into account such factors as installation length, heating time, efficiency at full loaded partial load, cost of energy, operator ease of use, potential for automation, etc. These factors have resulted in induction heating becoming a more demanded technique for heating aluminum billets.

The induction heating system should be designed so that a required temperature distribution in the billet would be provided. An optimal temperature profile in the entire billet depends on requirements of the overall extrusion process. The temperature distribution along the billet length should be uniform or tapered to provide a high quality of product and high speed of the extrusion process [5].

With the induction technology, the aluminum billet is generally surrounded by a coil in which electricity flows and is induced by a magnetic flux in the workpiece.

This magnetic flux in turn generates an eddy current that creates heat due to the specific resistance of the material. As a result, a contact-free temperature increase can be achieved in the workpiece thanks to the flow of electricity. Depending on the power and frequency of the electricity, the temperature in the aluminum alloys can be very precisely influenced.

Aluminum alloys are widely used in various fields of engineering due to their good strength characteristics in combination with low weight. Thus, they have a competitive advantage compared to other materials used in industry. They are also highly resistant to corrosion. It is advantageous to use the insertion of heat-treated aluminum alloys in lightweight constructions as that can reduce the total weight of the product while maintaining its strength [6].

Nowadays the major share of all aluminum production bases on systems consisting of the heating installations and the equipment for metal hot forming which could be represented as a united technological line. The classical structure of the technological line “heating – metal treatment by pressure” includes three technological stages: metal heating, transportation of heated billets, hot forming of pre-heated billets. (Figure 1).

Mainly at aluminum extrusions plants, longitudinal induction heating (LFH) is widely utilized to preheat aluminum billets before extrusion. Cylindrical solenoid induction coils are used most often in this application. The conventional coils have very high energetic characteristics. Basically the electrical coil efficiency of LFH strongly depends on the frequency and the material properties of the workpiece. The power rating of the induction heaters ranges from several hundred kilowatts up to dozen megawatts [1].

Aluminum is a low-resistive metal that makes it possible to apply low frequencies. Utilizing low frequencies at 50 – 60 Hz leads to such benefits as low capital cost of equipment and low energy consumption. On the other hand, the induction heating of low electrical resistive metals is known to have a low coil electrical efficiency. The efficiency of the conventional induction heater does not
exceed 50 – 60 % because 40 – 50 % of total power is transformed into heat in the copper windings and removed by the cooling water. The power losses in the coil windings are greater than all other losses of the induction heating system; therefore, the reduction of losses in coil turns is a main way to improve the total efficiency of an aluminum billet heater.

![Figure 1. Structure of technological line for metal pressing with induction pre-heating](image)

Nowadays a mathematical model and special simulation software, based on Finite Element Method (FEM), have been proposed to improve the efficiency for the induction heating process of aluminum symmetric workpiece. It is difficult to predict temperature accuracy because of multiple nonlinear relationships among induction heating parameters.

Mathematical modeling of local and combined optimization criteria that is used in the research procedures is one of the major factors in the successful design of both induction heating and pressing processes [2]. Initial temperature distribution at the beginning of the billet transportation stage represents final temperature distribution at the end of the heating stage and, at the same time, the temperature distribution before the hot forming represents final temperature distribution at the end of the billet transportation stage. These facts must be considered in the processing cycle “induction heating–metal hot forming” (Figure 2).

The induction heating is a complex combination of electrothermal processes. The electromagnetic and the thermal processes are described by differential equations with non-linear coefficients. Non-linear regularities of the thermal process are the result of the fact that both thermo-physical properties of the materials and the intensity of heat exchange strongly depend on temperature of the workpiece. The mathematical description of the phenomenon requires taking into consideration the interrelated influence of such different physical aspects as electromagnetic, heat transfer and metallurgical [3].

The technique to obtain the solution for electromagnetic analysis depends on the way to solve Maxwell’s equations for the considered region taking into account geometry and material properties and boundary conditions.

The temperature field in the workpiece is formed by several effects: distribution of Joule heat losses, temperature equalization by thermal conduction, thermal losses from the workpiece surface and mass transfer if there is a workpiece rotation.

The choice of the technique for computation and analysis of the induction system parameters depends on the kind of the induction system, tasks and aims of investigation. Analytical methods realized with a computation code offer a very fast computation time, high accuracy and a compact easy way to input data. But the application area of these methods is restricted by simple geometry and linear physical properties of the materials. Therefore, analytical tools are considered to be a simplest tool for preliminary investigation of the system. Numerical tools allow a user to simulate any system geometry taking into account different nonlinearities. In case of the induction heating system, the coupled solution of electromagnetic and thermal problems requires building the full three-dimensional
numerical model taking into account the rotation speed and all nonlinear physical properties of the materials.

**Figure 2.** Mathematical modeling of the processing cycle “induction heating–metal hot forming”

3. **Systematic approach to optimal design of induction heating installations**

The aim of the induction heating installations design is to provide the required temperature distribution. The coil-billet geometry has a significant influence on the temperature distribution due to a distortion of the electromagnetic field in the ends of the billet. The temperature field in the billet is also formed by temperature equalization by thermal conduction and thermal losses from the billet surface.

**Figure 3.** Temperature distribution in the aluminum billet
During induction heating of aluminum billets, the authors have to take account a two-dimensional character of the electromagnetic and temperature fields in cross section, when there is a temperature difference between the surface and the centre (Figure 3).

The 3D model has been carried out in order to investigate the influence of temperature distributions in the cross-section of the billet. Calculation results by means of 3D codes have shown that the temperature field in the billet is strongly inhomogeneous over the billet length.

The degree of manifestation of transverse edge effect depends on the electrical and thermal properties of the heated metal, the cross-sectional size, the frequency of the inductor current and the magnitude of heat losses [4].

The second problem is the fact that electromagnetic processes in the system "inductor-metal" are characterized not only by heat energy in the workpiece and the inductor, but also the volumetric density of the electromagnetic field and its associated electrodynamic efforts.

![Figure 4. Simulation of pressing stage in pre-heated cylindrical aluminum billets](image)

The problem of parametric optimization is solvable if the optimality criterion reaches an extremum at some interior or boundary point of the feasible area.

According to the Weierstrass theorem, the problem of parametric optimization is solvable, if the criterion function is a continuous or semi-continuous from above (in maximum), and the valid area forms a closed bounded set [8].

As the temperature field within the billet is the output data for the optimization procedures, it is necessary to provide the simulation of temperature field evolving over the pressing stage. The temperature distribution during the pressing process stage could be described with the two-dimensional Fourier heat conductivity equation for a cylindrical billet taking into account internal sources of heating such as deformation of treated billet and additional heat flow because of the contact friction (Figure 4).

Computation of temperature distribution appearing in the extrusion process represents the problem that cannot be solved easily. One of the difficulties deals with necessity to solve previously a highly complicated problem of continuum mechanics in order to define velocity field of metal flow and
spatial distribution of plastic deformation energy that should be taken into account in heat transfer equation [7].

The systematic approach in this case allows seeing a new object for research. The main factor, linking both stages of metal processing in a single technological complex is the temperature condition of the metal, based on the achievement of the extremum of the aggregate economic indicator.

In general, it is connected mainly with the design of the treatment area pressure (deformation), which is reflected in the thermal balance of a deformable metal.

The traditional way of solving this problem consists in local optimization separately for the heating installation and deforming equipment in a rigid framework of specified technological instructions generated outside these tasks.

Qualitatively more opportunities appear when there is joint optimization of these processes, pursuing the achievement of the limit values of the aggregate economic performance of the complex as a whole, in terms of the maximum number of degrees of freedom for selecting different options and control actions, which are optimized according to the chosen criterion [9].

The design can be carried out using analytical and numerical methods. The main difficulty when choosing the economic criterion of optimization is due to a desire to have a single generalized indicator that characterizes numerous private aspects. Based on different aspects of economic efficiency, it can be divided into four main factors that, at given prices and the guideline values, uniquely define the values of the vast majority of the remaining indicators. This is the number and quality of products as well as operating and capital costs of its production. As a criterion of optimality, which provides a comparison of all four factors of economic efficiency, it is advisable to use the income.

This research presents a systematic approach to the design and operation of induction heating installations (IHI). A distinctive feature of this approach is that the temperature of the metal heating in industrial complexes "induction heating - deformation" is not fixed in advance, but is determined in accordance with the maximization or minimization of the total economic performance of the process of heating and deformation. It is indicated that the energy-efficient technological complex "IHI – Metal Forming (MF)" can be designed only with regard to its power supply system (PSS) [10]. So the task of designing systems of induction-heating is to provide, together with the power supply system and forming equipment, the minimum energy costs for the metal retreating. The decisive role of the temperature factor allows describing the "IHI-PSS" complex by the behavior of the temperature field of the treated metal at appropriate stages of the process.

4. Conclusions

Induction heating is widely used in industry for heating metals before hot workings (hot rolling, forming, extrusion, forging, etc.). Metal work-pieces (slabs, blooms, bars, and billets) are heated by induction until they reach a high enough temperature which creates proper conditions for plastic deformation. Due to the skin effect, 87% of thermal power injected during the process is produced in a layer located at the surface of the workpiece. While the induction heating of aluminum is fundamentally does not differ from the heating of other commonly induction heated metals; aluminum alloys have distinct material properties that, if unaccounted for, can result in unexpected challenges.

Computer simulation is a valuable tool in the design of aluminum billet-heating equipment and processes. For equipment users, however, better understanding of the unique facets of induction heating aluminum can often be achieved by simply considering the properties that make aluminum alloys such advantageous materials. Powerful finite element modeling (FEM) tools are available to assist in the design of such processes; however, such models should be validated by comparison with analytical solutions or experimental results to ensure accuracy.
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