International Scientific Colloquium
Modelling for Material Processing
Riga, September 16-17, 2010

Induction Heating for Aluminum Extrusion Process: Concepts, Simulation, Design

M. Zlobina, B. Nacke, S. Galunin, Yu. Blinov, A. Nikanorov

Abstract

Recently the new induction concepts for through heating of aluminium billets before extrusion have been proposed and some installations are under successful operating in industry. The paper is devoted to consider these concepts, their advantages and perspective. The aspect of numerical modeling as a necessary tool to design the induction heating installation is described in the paper and results of investigation by means of numerical simulation are presented.

Introduction

The worldwide market of extrusion products is actually around 6 million ton per year. The European extrusion market is the major market especially for aluminum products with around 2.8 million ton per year. Around 480 presses are actually installed in Europe for extrusion of aluminum billets.

Aluminum billets are heated from ambient temperature up to 450 - 500 ºC prior to extrusion. The primary types of furnaces used for preheating 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 request technique for through 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.

1. Induction Heating Concepts

A main peculiarity of induction heating compared with gas-fired furnaces is the heat generation within the workpiece. When an alternating external magnetic field is applied to a conductor eddy currents are induced within a conducting material. Eddy currents due to alternating excitation tend to cancel the magnetic field within the conductor and, therefore, to increase the effective resistance of the conductor to current flow and magnetic field penetration. This results in skin effect which plays an important role in induction heating systems. Eddy currents are also induced within electrical conductor when the conductor moves in the presence of a stationary magnetic field. Eddy currents also tend to cancel the magnetic field within the conductor and also alter the field outside the conductor. In additional, heat is generated, and $\bar{J} \times \bar{B}$ forces are induced within the conductor which impedes its motion. The high rotation speeds and powerful sources of fields are necessary to provide an effective heating using this approach.

Classical induction through heating, where the alternating external magnetic field is applied to a conductor, is widely utilized for processes of the plastic deformation in the non ferrous metallurgical industry.

Mainly at aluminum extrusions plants longitudinal induction heating (LFH) is widely utilized to preheat aluminum billets before extrusion. Cylindrical solenoid multiturn induction coils are mostly often used in this application (Fig. 1). 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. Aluminum is a low-resistive metal that makes 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. From 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 is greater than all other losses of the induction heating system therefore reduction of losses in coil turns is a main way to improve the total efficiency of an aluminum billet heater.

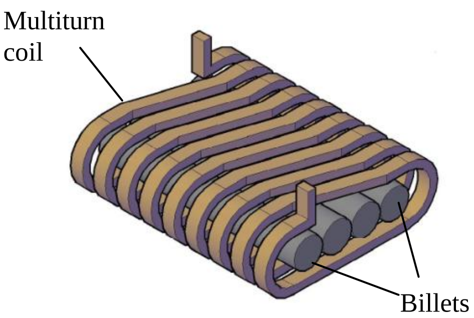

Fig. 1. Conventional induction heating

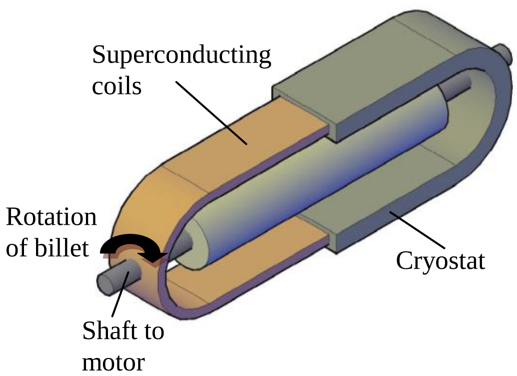

Fig. 2. ALUHEAT concept

To improve the process efficiency innovative induction techniques based on the phenomena of superconductivity have been proposed [1, 7]. The approach is based on generating a magnetic field by DC in superconductive coils (Fig. 2). Rotating of the billet in the DC magnetic field leads to the eddy current induction and heat generation in the billet. The induction system consists of two coils made from superconductive magnets and a billet placed between them so that the magnetic field is oriented perpendicular to the billet axis. The coils are placed in a cryostat to maintain a superconductor at a low temperature. The power loss in the system includes the losses in the electric motor to rotate the billet, losses in the cooling system and thermal losses from the billet surface. This approach should increase the electrical efficiency of the aluminum billet heater up to nearly 90 %. Actually different scientific groups have offered and investigated different shapes of the coils for this concept [2-6].

A similar concept is meanwhile realized for use in industry and the installation operates actually in two companies for extrusion of aluminum billets and in one for copper billets [7]. The concept is operating with a superconducting coil as well. The magnetic flux is guided to the billet by a magnetic yoke and two billets can be heated simultaneously (Fig. 3). The efficiency of this system achieves 85%.

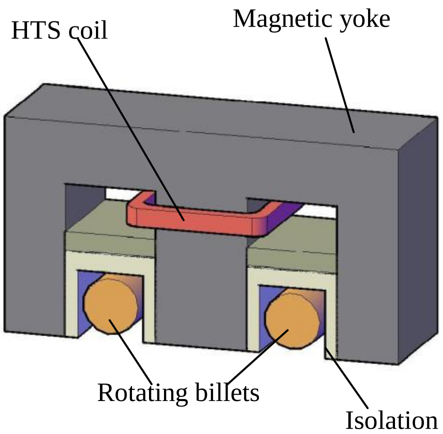

Fig. 3. Energy concept

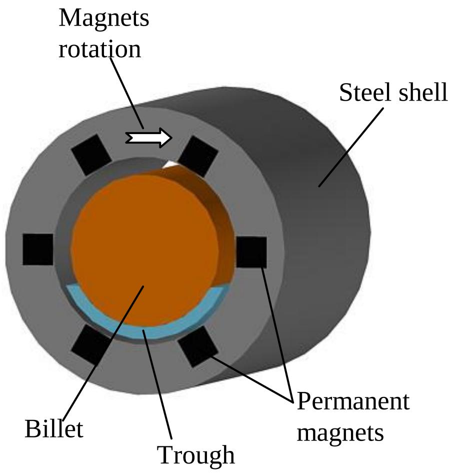

Fig. 4. Permanent magnets concept

Another concept is proposed to use permanent magnets instead of superconducting coils [8]. The permanent magnets are rotating and driven by an electric drive. This concept is actually under development and avoids a rotation of the heated billet. The billet is fixed in a ceramic trough or by axial clamping devices. Diameter of billets should not vary in a wide range because the air gap between the billet and permanent magnets should be small. For this concept electrical efficiency depends mainly on the efficiency of the motor and its driving system. Authors of the concept expect the system to achieve the same efficiency as for ALUHEAT concept.

The physical heating process for all concepts is similar. The optimal heating process needs an accurate design of coils or of permanent magnets. Mathematical modeling is a suitable tool for the optimal design of the heaters. In general strategy of the induction heating installation design consists of several steps, which are common for all engineering problems. The mathematical simulation involves transcribing an engineering description of the problem into well-defined mathematical statement, development of the model using numerical technique, for instance, finite-element method (FEM), which provides an approximate solution.

2. Mathematical Modeling

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 to take into consideration the interrelated influence of different physical aspects so as electromagnetic, heat transfer and metallurgical.

In general, Maxwell's equation for electromagnetic field within the conducting material can be written as

$$rot\bar{E} = -\partial\bar{B}/\partial t + rot(v \times \bar{B}),$$

where E is electric field intensity, B is magnetic flux density and v is conductor velocity.

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 is necessary and should be organized as an iterative loop.

At present different mathematical models to simulate the processes in the induction system for billet heating by rotation in DC magnetic field are available. Group of simplest tools is suitable for preliminary investigations of the system [3]. They are based on analytical techniques for calculation of electromagnetic processes in two dimensions and can be mainly used to optimize the integral characteristics of the heaters. The second group of models includes several specially developed numerical codes for calculation of two- and, especially, three-dimensional electromagnetic and thermal fields [2, 3].

Numerous commercial software packages for computation of electromagnetic, thermal and mechanical processes in induction heating systems can be combined into the third group of models. They are suitable for both two- and three-dimensional analyses of different induction systems. However, high-power computers and skilled engineering staff are necessary for professional use of these tools.

Nevertheless both electromagnetic and thermal analysis of the induction system for billet heating by rotation in DC magnetic field requires building the full three-dimensional numerical model taking into account the rotation speed and all nonlinear physical properties of the materials.

3. Design

As mentioned above the aim of the induction heater design is to provide the required temperature distribution. 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.

ALUHEAT concept has been deeply investigated by set of 2D and 3D numerical codes based on FEM [5, 9]. By means of the 2D model a lot of parameter studies have been carried out in order to investigate the influence of the rotation speed on the Joule heat and temperature distributions in the cross-section of the billet (Fig. 5, 6). The rotation speed influence has the similar physical process as for the conventional heating and with higher rotation speed the temperature becomes non-uniform and the billet cross-section centre becomes colder than the billet surface. Finally frequency of 1000 rpm has been chosen as operating one to provide the balance of the low rotational forces for the hot billet and the homogeneous temperature distribution.

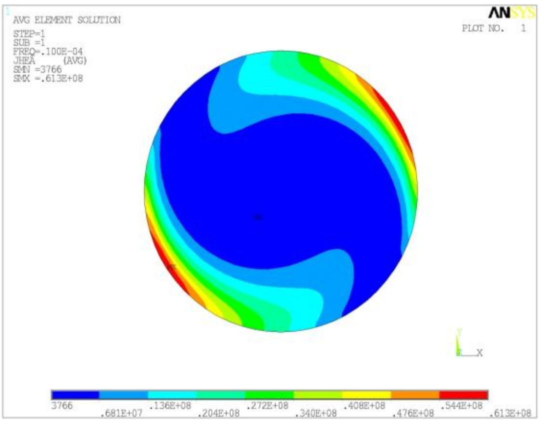

Fig. 5. Joule heat distribution at the rotation speed of 1000 rpm

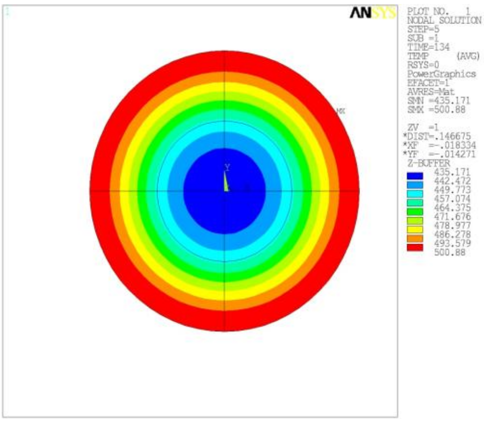

Fig. 6. Temperature distribution at the rotation speed of 1000 rpm

Calculation results by means of 3D codes have shown that the temperature field in the billet is strongly inhomogeneous over the billet length. For considered induction system electromagnetic end effect results in overheating of the billet ends (Fig. 7). Design of a DC superconducting coil is very complicated to be adapted to the required heating process therefore independent measures from coil design have been considered in order to provide the required temperature profile in the billet [9].

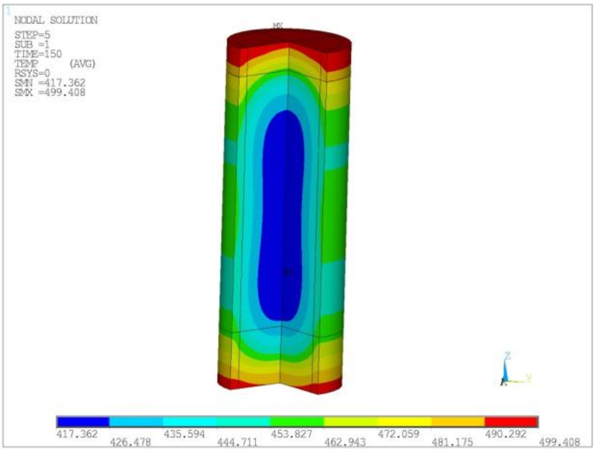

Fig. 7. Temperature distribution in the billet with the length of 600 mm without measures for uniform temperature profile

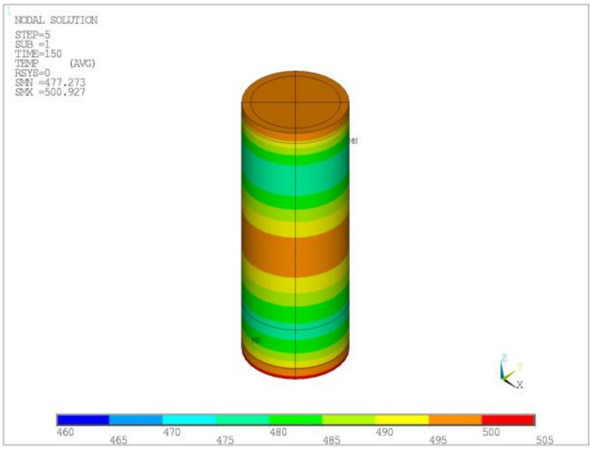

Fig. 8. Temperature distribution over the billet using magnetic rings

The results of 3D numerical investigation have shown that the homogenous temperature profile (Fig. 8) can be obtained by means of special sets of the magnetic rings while the required tapered temperature profile has not been achieved by these measurements. The tapered profile can be achieved by shifting the coils to a certain angle from the billet. In this case the special mechanical tools can be arranged in the system.

Conclusions

Efficient concepts to reduce energy consumption for heating of aluminium billets are available. One concept is already under successful operation in industry. Other concepts offer additional advantages such as higher efficiency (ALUHEAT concept) and simple solution at lower cost (permanent magnet concept).

Numerical modelling is the main tool to design any induction concept and to provide both high energetic parameters of the system and the required temperature profile. By means of developed numerical codes influence of different system parameters such as rotation speed and coils geometry has been investigated. Several concepts to control the temperature distribution in the billet have been proposed and analysed.

Acknowledgment

Financial support from the Ministry of Education and Science of Russian Federation in the frame of the Federal program «Scientific and scientific - pedagogical staff of the innovative Russia» for the years 2009-2013 is gratefully acknowledged.

References

[1] Runde, M., Magnusson, N.: *Induction Heating of Aluminium Billets using Superconducting Coil*. PHYSIC C, 372-376, 2002, pp. 1339−134.

[2] Fabbri, M., Morandi, A., Negrini, F.: *Temperature Distribution in Aluminium Billets Heated by Rotation in Staic Magnetic Field Produced by Superconducting Magnets*. COMPEL, Vol. 24, 2005, No.1, pp. 281–290.

[3] Dughiero, F., Forzan, M., Lupi, S.: *Induction heating of aluminium billets rotating in a DC magnetic field*. Proceedings of the VII International Conference on Problems of Control and Modelling Complex System, Samara, 2006, pp. 171−176.

[4] Magnusson, N.: *Prospects for rotating billet superconducting induction heating*. Proceedings of International Symposium on Heating by electromagnetic sources, Padua, 2007, pp. 479−486.

[5] Nacke, B., Zlobina, M., Nikanorov, A., Ulferts, A.: *Numerical simulation of induction heating of aluminium billets by rotation in DC magnetic field*. Proceedings of International Symposium on Heating by Electromagnetic Sources, Padua, 2007, pp. 497–504.

[6] Araneo, R., Dughiero, F., Fabbri M. and oth.: *Electromagnetic and thermal analysis of the induction heating of aluminium billets rotation in DC magnetic field*. Proceedings of International Symposium on Heating by Electromagnetic Sources, Padua, 2007, pp. 487–496.

[7] Kellers, J., Bührer, C., Hagemann, H., Ostermeyer, B., Witte, W.: *Magnetic billet heating rivals conventional furnaces.* Heat Processing, Vol. 8, 2010, No. 1, pp. 65–70.

[8] Dughiero, F., Forzan, M., Lupi S. and oth.: *A new high effective technology for the induction heating of non magnetic billets.* Proceedings of International Symposium on Heating by Electromagnetic Sources, Padua, 2010, pp. 531–538.

[9] Zlobina, M., Nacke, B., Nikanorov, A.: *Numerical modeling and investigation of coupled electro-thermal processes in induction heating for heating aluminum billets by rotation in DC magnetic field*. Proceedings of the 6th International conference on Electromagnetic processing of materials, Dresden, 2009, pp. 177−180.

Authors

Dr. Zlobina, Marina
Dr. Galunin, Sergey
Prof. Blinov, Yuri
Department of Electrotechnology and
Converter Engineering
St. Petersburg State Electrotechnical University
Prof. Popov Str. 5
St. Petersburg, Russia
E-mail: mvzlobina@eltech.mail.ru

Prof. Dr.-Ing. Nacke, Bernard
Dr.-Ing. Nikanorov, Alexander
Institute of Electrotechnology
Leibniz University of Hannover
Wilhelm-Busch-Str. 4
D-30167 Hanover, Germany
E-mail: nacke@etp.uni-hannover.de