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Adaptive Induction System for Heating of Aluminium Billet by Rotation in DC Magnetic Field

M. Zlobina, B. Nacke, A. Nikanorov

Abstract

The paper is devoted to investigation of the induction system for billet heating by rotation in DC magnetic field. Induction heating of aluminium billets by rotation in DC magnetic field produced by superconductive coils is an innovative technique. The efficiency of the heater is expected to be up to 90 %. Three-dimensional numerical code based on Finite element method has been developed to investigate the innovative induction system. Independent measures for coil design to obtain required temperature distribution along the billet length have been proposed. The influence of the measures on the temperature distribution in the billet taking into account different billet lengths has been investigated.

Introduction

Nowadays the European aluminium extrusion market is considered to be the major market of extruded non-ferrous metals. Aluminium billets are heated from ambient temperature up to 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 products 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 aluminium billets.

The power rating of the induction heaters ranges from several hundreds kilowatts up to dozen megawatts. Aluminium 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 low electrical resistive metals are known to have a low coil electrical efficiency. The efficiency of conventional induction heaters 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. To improve the process efficiency an innovative induction technique has been proposed [1-2]. A novel approach is based on generating a magnetic field by DC current in superconductive coils. Rotating of the billet in the magnetic field leads to the eddy current induction and heat generation in the billet. Theoretically this approach should increase the electrical efficiency of the aluminium billet heater up to 90 %.

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 axial temperature profile along the billet length should be homogenous; strongly end heating effects have to be avoided.

Moreover depending on type of press die, certain axial temperature profiles, e.g. tapers, are needed to realize.

For the new approach a deep analysis of the induction heating system is necessary to achieve the desired development target. Experience of the last years has shown that only mathematical simulation allows reducing the extremely cost intensive way of experimental trial and error. Numerical modelling offers today an advanced tool to achieve an optimal design of an induction system and to achieve the development targets. Numerical simulation has been used to develop the novel innovative installation based on induction heating concept.

The 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.

1. Theoretical Background and Numerical Simulation of the Innovative Induction Heating Process

Induction heating is a complex combination of electrothermal processes. The mathematical description of the phenomenon requires taking into consideration the interrelated influence of different physical aspects so as electromagnetic, heat transfer and metallurgy. A main peculiarity of induction heating 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 an 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 addition, heat is generated, and $\overline{J} \times \overline{B}$ 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.

In general, Maxwell's equation for electromagnetic field within the conducting material can be written as $rot\overline{E} = -\partial\overline{B} / \partial t + rot(\overline{v} \times \overline{B})$, where E is the electric field intensity, B is the magnetic flux density and v is the 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. According to mathematical theory of the field the magnetic flux density can be expressed in terms of magnetic vector potential A as $\overline{B} = rot\overline{A}$ and $div\overline{A} = 0$. The boundary condition of the considered region is selected so that gradient of magnetic vector potential is negligibly small along the boundary compared to its value elsewhere in the region (Neumann's condition $\partial A / \partial n = 0$).

The volume density of Joule heat generated by the eddy currents is obtained by solving the electromagnetic problem. The distribution of the Joule heat losses plays a significant role to form temperature field in the workpiece. The temperature field 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. In general, the transient heat transfer process in the workpiece can be described by the Fourier's equation: $C_v \frac{\partial T}{\partial t} = div(\lambda gradT) + w$, where T is the temperature,

C_v is the specific heat, λ is its thermal conductivity; w is the volume density of Joule heat losses.

For most engineering induction heating problems, boundary conditions are a combination of the convective and radiation losses. The boundary conditions can be described: $-\lambda \frac{\partial T}{\partial n} = \alpha(T_s - T_a) + \varepsilon(T_s^4 - T_a^4)$, where $\partial T / \partial n$ is the temperature gradient in a direction normal to the surface, α is the convection surface heat transfer coefficient, ε is the radiation heat loss coefficient, T_s is surface temperature, T_a is ambient temperature and n denotes the normal vector to the boundary surface.

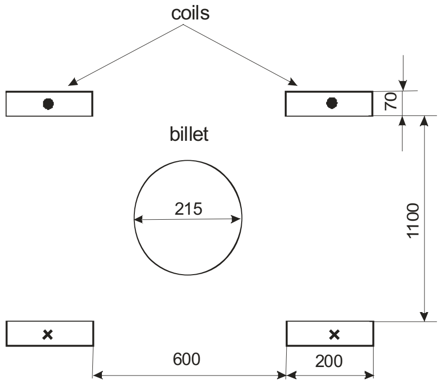

Fig. 1. Cross-section of the billet

Electro-physical properties of conductive materials (like specific resistance) significantly depend on temperature. This dependence has to be taken into account in electromagnetic analysis. The Joule heat, generated by the magnetic field, initiates the growing up temperature in the workpiece. However the thermal process also forms a temperature distribution in the workpiece by thermal conduction in its material and thermal losses from its surface. Both thermo-physical properties and thermal losses depend on temperature as well. The coupled solution of electromagnetic and thermal problems is organized as an iterative loop. The Joule heat obtained from the electromagnetic analysis is used for the thermal calculation and the received temperature distribution is taken to correct the specific resistance of the workpiece material for the electromagnetic calculation at next iteration. Non-linear behavior of a simulated system requires organizing a coupled model based on a numerical technique.

Well-known approach to simulate a traditional induction system can be applied to develop and investigate the innovative induction system to heat by rotation an aluminium billet in DC magnetic field. The investigated induction system consists of two superconductive round coils located at 600 mm from each other (see Fig. 1). The coil diameter is 1100 mm, the thickness and the height is 70 mm and 200 mm correspondingly. The billet is placed between coils so that it rotates in transverse magnetic field. The heater should be designed for billets with diameter 215 mm and lengths up to 700 mm. The heating time should be about 150 s to heat the billet from ambient temperature to 450 – 500 °C.

2. Influence of Coil-Billet Geometry on Temperature Distribution in the Billet

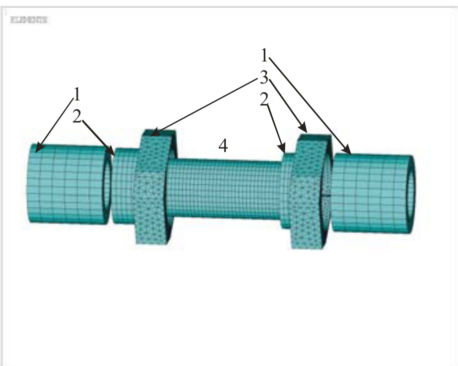

Fig. 2. 3D mesh of the billet and magnetic rings

As mentioned above the aim of the induction heater design is to provide the required temperature distribution which should be uniform along the billet length or tapered to provide a high quality and high speed of the extrusion process. 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 due to thermal conduction and thermal losses from the billet surface. 3D model simulation is required to investigate the temperature field in the billet and to optimize the induction system parameters. A full 3D numerical model has been developed to solve a coupled electrothermal problem taking into account the billet rotation and non-linear material properties.

First calculation results have shown that the temperature field in the billet is strongly inhomogeneous over the billet length. For the considered induction system the electromagnetic end effect results in overheating of the billet ends. The adaptation of DC superconducting coils to the required heating process of the billet by design is very difficult; therefore independent measures have to be considered in order to adapt the temperature profile in the billet to the requirements of the pressing process.

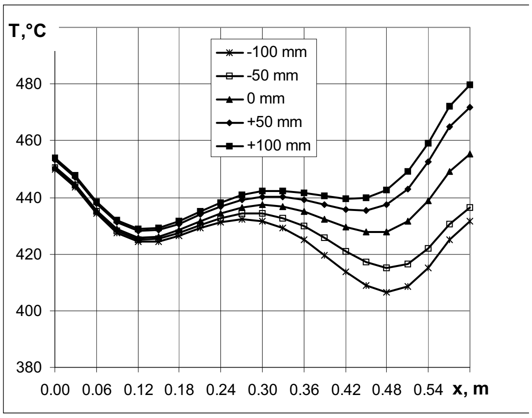

Fig. 3. Temperature distribution at the surface (billet length 600 mm) using fixed rings

One measure is proposed to use magnetic shielding rings at the billet ends in order to guide and to screen the magnetic field with the aim to optimize the temperature for a homogeneous or just tapered temperature profile [3].

The proposed system contents three sets of rings. The first set of rings is to screen the clamping system of heating. The second set of rings is at constant position in order to avoid overheating in the billet ends. The third set of rings is movable and it should provide the tapered temperature profile in the billet. One possible configuration of the billet and ring sets is shown in Fig. 2.

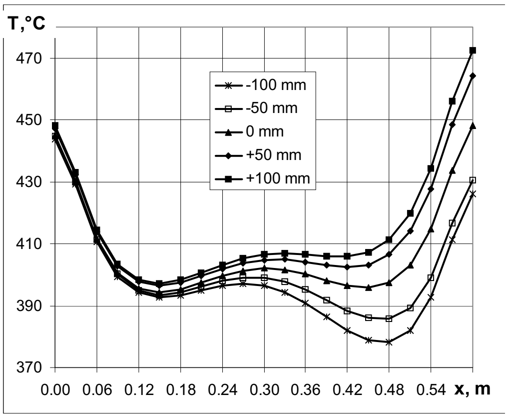

Fig. 4. Temperature distribution in the centre (billet length 600 mm) using fixed rings

The influence of fixed rings to reduce end effects has been studied by numerical simulation as initial investigation of rings influence on temperature profile over the billet length of 600 mm. The fixed ring at the cold side has constant position while the position of the ring at the hot side is changed so that the ring is shifted out of the billet end and to the centre of the billet. The results of the investigation are presented as curves of temperature distribution at the surface and in the centre along the billet length in Fig. 3 and Fig. 4 correspondingly just after 150 s heating time. The results show that fixed rings can be used to reduce overheating in the billet ends but this measure does not allow avoiding overheating at all. The best temperature profile can be obtained when the fixed rings have symmetrical position at 25 mm to the billet centre from both billet ends (–25 mm position). The temperature distribution along the billet length for this position of the fixed rings is presented in Fig. 5. For this case the maximum temperature differences at the surface over the billet length are around ± 10 K.

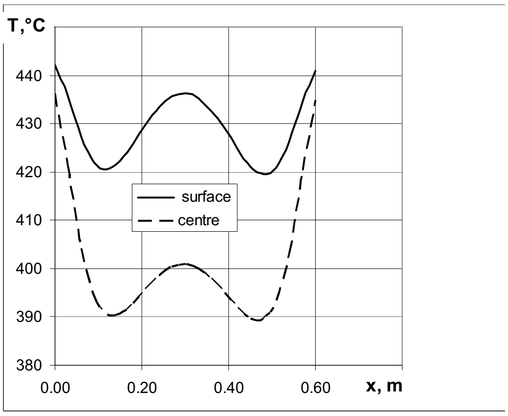

Fig. 5. Temperature distribution over the billet length of 600 mm using fixed rings

Next investigation has been devoted to study the influence of movable rings on the temperature distribution and the taper generation in the billet. Symmetrical position of the fixed rings at 25 mm to the billet centre has been chosen as a basic. At the cold side the movable ring has the same constant position like the fixed ring while the position of the movable ring at the hot side is changed so that the ring is shifted out of the billet end and to centre of the billet.

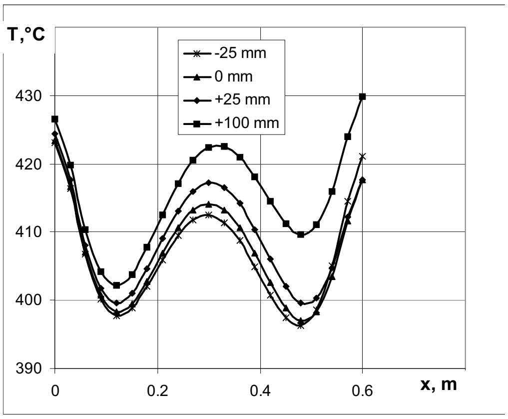

Fig. 6. Temperature distribution at the surface (billet length 600 mm)

The temperature distribution at the surface and in the centre along the billet length for sets of the fixed rings and movable rings are presented in Fig. 6 and Fig. 7 correspondingly. Presented diagrams show the influence of shift of the movable ring at the hot side of the billet (right side) on the temperature profile. When the position of the fixed and movable rings are the same at the hot side of the billet the temperature profile along the billet length becomes more uniform due to the movable rings.

The temperature gradient from the cold side to the hot side of the billet can be provided if the movable ring at the hot side is shifted out of the billet end. The investigated configurations show only small temperature gradients over the billet length due to the shift of the movable rings. For the maximum required taper of 10 K/100 mm additional investigations of ring configuration and probably additional measures are necessary.

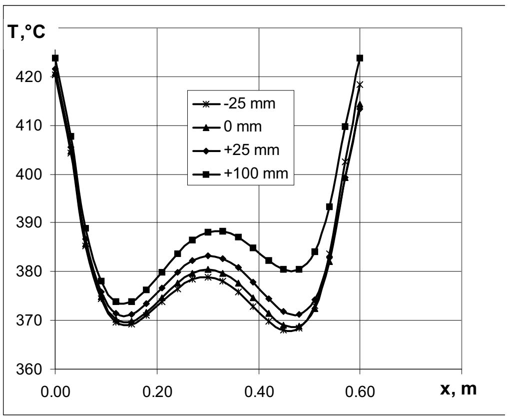

Fig. 7. Temperature distribution in the centre (billet length 600 mm)

Numerical simulations of the heating with a shorter billet of 400 mm length have been carried out in order to investigate the influence of the billet length on the temperature distribution in the billet. It was assumed to use the same configuration of fixed rings at the ends of the billet (–25 mm position). The movable ring at the hot side is shifted as for the billet with length of 600 mm.

Temperature profiles along the billet obtained for length of 400 mm when using only the fixed rings at 25 mm position at both ends of the billet are presented in Fig. 8. It can be clearly seen that the temperature profiles at the surface and in the centre are more inhomogeneous over the length of 400 mm than in the case of 600 mm billet length (see Fig. 5). The maximum temperature difference for 400 mm billet length is roughly double in comparison with 600 mm billet length. The temperature distributions along the billet length for both billets have different shapes. In the case of 600 mm length the temperature gradient at the surface and in the centre is nearly the same for the middle part of the billet. The minimum temperature gradient between the surface and the centre is formed in the 1/6 part of the billet length at the billet ends. In case of 400 mm billet the magnetic field intensity has changed due to the shorter billet length. The overall magnetic field

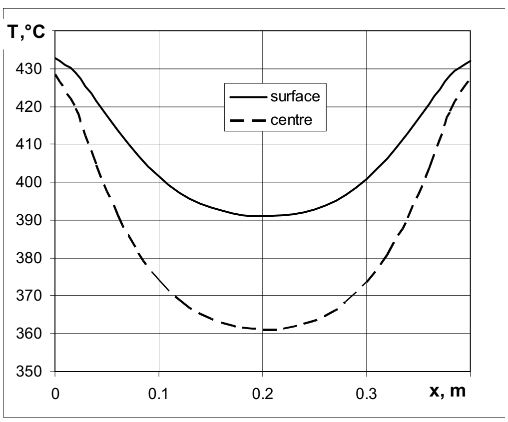

Fig. 8. Temperature distribution over the billet length of 400 mm using fixed rings

leads to the different temperature distribution over the billet with length of 400 mm. In this case the temperature gradient between the surface and the centre reduces to the billet ends and the temperature curves have significant minimum in the billet centre. The electromagnetic field in the central part of the billet with 600 mm length becomes nearly homogeneous due to the fixed rings at the symmetrical position while this measure is not enough in order to obtain similar temperature profile for the shorter billet length.

The simulation of the movable rings application for the billet length of 400 mm has shown a similar influence of the movable rings to generate a tapered profile along the billet length. However the temperature distribution is inhomogeneous because the basic temperature profile provided by the fixed rings has not been optimal as well.

The convection losses take a major part in the heat losses process for low-temperature applications in comparison with radiation losses, but the absolute value of losses are low as compared with induced power in the billet. After the heating process the temperature equalization along the billet length takes place during the time required for transportation of the billet from the heater to the press while the average cooling effect of the billet is small because of low losses. The simulation of both processes has been carried out taking into account that the transportation time lasts 120 s. Results of the simulation show that the average temperature of the billet stays approximately the same but the temperature distribution inside the billet becomes more homogenous after the transportation time.

Conclusions

Models for numerical simulation of the heating process of the rotating billet in DC magnetic field have been developed and successfully applied for electromagnetic and thermal analysis.

The full 3D model shows important 3D effects of the innovative induction heating system. The developed numerical model has allowed investigating the influence of the system configuration on the temperature distribution over the billet. The investigation of the billet length influence on temperature profiles along the billet has confirmed significant influence of the electromagnetic ends effect to form the temperature distribution over the billet. Results of parameter studies have shown that the end effects and overheating of the billet ends can be reduced by the considered measures.

References

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Authors

Dr.-Ing. Zlobina, Marina
Department of Electrotechnology and Converter Engineering
St. Petersburg State Electrotechnical University
Prof. Popov Str. 5
St. Petersburg, Russia
E-mail: mvzlobina@mail.eltech.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@ewh.uni-hannover.de