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ALUHEAT - A superconducting approach of an aluminium billet heater

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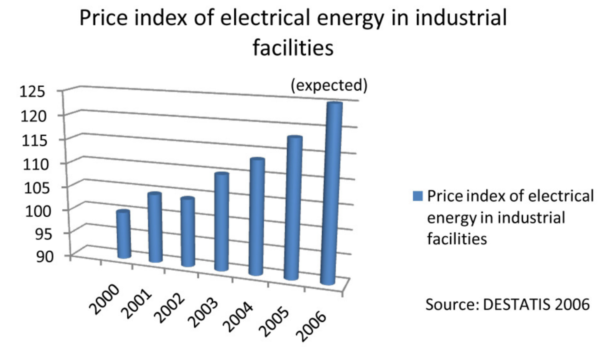
Abstract

Aluminium profiles are a widely used product in today's world. For the production of these products gas based ovens and electromagnetic induction heaters are used at aluminium plants to preheat aluminium cylinders, so called billets, before extruded to profiles. Efficiency in both processes is rather poor which leads to new approaches to save energy. During the 80s the efficiency of classical induction heaters was improved from 50 % to 55 - 60 %. More potential for improvements is not given. A new approach to increase efficiency is to generate a DC magnetic field by DC currents in a superconducting coil. The electromagnetic field is applied in that manner that by rotation of the billet currents are induced in the workpiece. Due to Joule losses the billet is heated up. The magnetic field is generated losslessly by superconductors so that the efficiency of the system is determined by the efficiency of the main drive rotating the billet. An efficiency of 90 % is estimated for the process. In this paper the principles of the heater and an overview of the system are presented as well as a discussion about current scientific results.

Introduction



Source: DESTATIS 2006

Fig. 1: Trend of electrical energy costs

Nowadays the market offers a wide range of aluminium products. Different aluminium alloys are used to extrude aluminium cylinders (billets) into various profiles for further manufacturing in industry. These aluminium billets usually have a length of about 1m and a diameter of 0.3 m. Aluminium alloys have to be preheated before the extrusion process can be applied. The billets are heated up to a temperature level between 350°C and 500°C (depends on alloy and extrusion process). In general the heating process can be done in several ways. Gas burners are used as well as induction heaters. In comparison to gas heaters, the heat is created directly in the workpiece. Electromagnetic induction heating is a fast and clean possibility to heat. The process can be controlled precisely and reproducable. Since energy costs are growing, efficiency of heating processes becomes a more and more important issue. Heating of non-magnetic metals with low electrical resistivity like aluminium or copper is connected with a low efficiency if done in conventional way.

Since the year 2000 the prices for electrical energy increased by more than 20 % (Figure 1). With an efficiency of $\eta = 50\%$ and an amount of 4,000 operating hours per year for a 400 kW installation and energy costs of 0.06 €/kWh the electrical losses would cause yearly financial costs of € 100, 000 per billet heater unit. If the trend of energy prices holds on the losses per year will increase to €130,000 at miniumum. With growing energy costs the need for energy conservation becomes more and more critical issue. With the new approach of an DC billet heater more than 80 % of the energy losses, compared to an AC installation, can be saved.

Basic principles

Conventional AC induction heaters consist of one or more water cooled copper AC induction coils. The billet is placed statically inside of these coils. In Figure 2 the principle of a conventional heater is illustrated. The vector of the magnetic field is orientated in parallel to the billet axis.

Figure 3 shows the configuration of the new DC heater. The billet is mounted pivotable in a magnetic field with a field vector orientated perpendicular to the rotation axis. The rotation of the billet causes a circulation of induced currents at the billet surface which leads to Joule heating effects in the billet.

In general currents are induced in a loop when the magnetic flux enclosed by the loop is subjected to a change (as described by Lenz law). Usually a change in magnetic flux can be obtained on two ways. As described by Eq. 1 the change in magnetic flux can be applied by a change in magnetic field over time. This method is used at conventional heaters by allplying an AC magnetic field to the material.

$$U_i = -\frac{d\phi}{dt} \quad \text{with} \quad \phi = \int_A \mathbf{B}(\mathbf{r}, t) \cdot d\mathbf{A} \tag{1}$$

If the magnetic field is kept constant an other possibility to change the magnetic flux is by moving the loop in the static magnetic field as done in the new approach of the superconducting (SC) DC heater. This method is described by Eq. 2. As $\mathbf{v} \times d\mathbf{s} = d\mathbf{A}$ the induced current is at maximum level, if the loop is moved perpendicularly to the magentic field. In the new heater the billet is rotated in a static DC field. When a loop is rotated with constant speed in a DC magnetic field, the enclosed flux varies sinusoidally in the same manner as a static loop in a sinusoidal magnetic field.

$$U_i = -\frac{d}{dt} \int_A \mathbf{B} \cdot d\mathbf{A} = -\oint_S \mathbf{B} \cdot (\mathbf{v} \times d\mathbf{s}) \tag{2}$$

In AC heaters the magnetic field is orientated in parallel with the billet axis. A rotation of the billet would not induce further currents. For the DC heater the magnetic field has to be orientated perpendicularly to the billet axis to change the magnetic flux by rotation. For any given loop in a plane parallel to the rotational axis the magnetic flux enclosed by the loop will change as the billet is rotated, which will induce currents in the workpiece. The induced currents are sinusoidial with a rotation speed dependent frequency. With increasing rotational speed the frequency increases and leads to skin effects which cause current flows at the surface and eliminates currents in the core of the workpiece. The induced currents cause Joule heating in the billet. As the billet is rotated by a motor, mechanical energy from the motor is converted into heat in the billet. The final axial temperature profile of the billet depends on the profile of the magnetic field along the billet axis. The radial temperature profile will be adapted by the rotational speed as consequence of the skin effect which is linked to the electro-magnetic penetration depth. The penetration depth in general can be calculated as:

$$\delta = \sqrt{\frac{1}{\pi f \mu \kappa}} \quad \text{with} \quad \mu = \mu_{r,Alu} \cdot \mu_0 \quad and \quad \mu_{r,Alu} = 1 \tag{3}$$

For different rotational speeds of the billet the following depths are calculated and presented in the following table. With a minimal rotational speed of 5 rps 86 % of the induced power is dissipated in the outer third of the billet (if a radius of 150 mm is assumed). The inner zones will be heated by heat conduction effects.

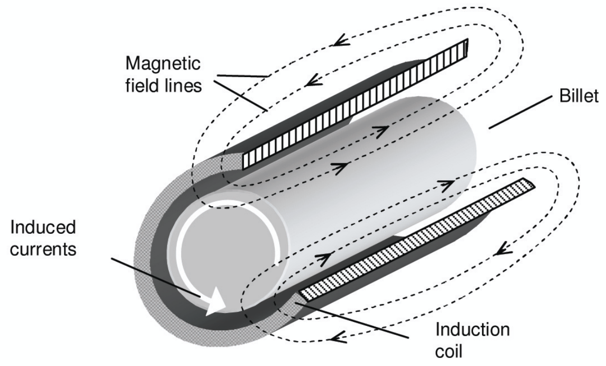


Fig. 2: Principle of conventional induction heating

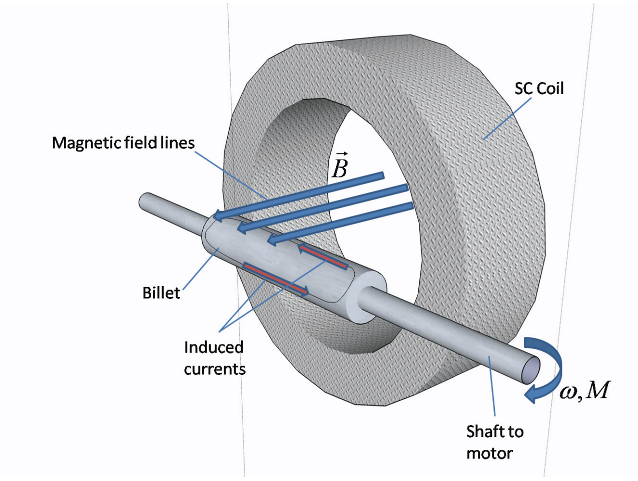


Fig. 3: Principle of rotating billet superconducting induction heating

f[rps]	δ[mm]
1	100
5	45
10	32
25	20
50	14

For different aluminium alloys the specific electrical resistance varies between $3 \cdot 10^{-8}\,\Omega$m and $5 \cdot 10^{-8}\,\Omega$m. An average value of $4 \cdot 10^{-8}\,\Omega$m has been selected for calculation of the electro-magnetic penetration depth.
Within the penetration depth, 86 % of the total power are dissipated in the workpiece.

From heating point of view a lower rotation speed of the billet should be preferred due to a deeper heating. Limitations come from the maximal permitted torque, which increases with decreased rotational speed as presented later.

The DC currents are generarated losslessly by coils consisting of superconducting tapes, if cooled down below the critical point of the superconducting material. To keep the coils at the low temperature level, the coils are placed in a cryostat, which is connected to a cooling device to remove heat from the system.

The efficiency of the installation is determinded by the main drive unit and the cooling system. Asynchronous electric motors in the 500 kW class operate with efficiencies above 90%. The overall efficiency of the heater is expected with $\eta = 90\%$. [2], [1]

Demands of the process

To beware of cracking effects during the extrusion and for high quality and high speed extrusion an isothermal extrusion process is preferred. In these processes the temperature of the billet in the die is constant during the extrusion. This leads to a very strict limit of permitted temperatures inside the aluminium billet. A temperature accuracy of $\pm 2\%$ is necessary to fulfill all requirements. A predefined temperature gradient (also labeled as taper) along the length of the billet is reqired in many extrusion processes. The gradient depends on the aluminium alloy, the shape and size of the die hole in the press and on the billet size. The heater should be able to provide a taper of $0 - 10$°C/dm. By adaption of the axial field distribution the taper can be controlled concisely.

The energy needed to heat the billet is converted from mechanical energy generated by the motor drive. The interface between the shaft and the billet is a crucial point. It needs to be reliable and have the ability to take up the large torques associated with the transfer of power into the billet. At larger torques than the stiffness of the material allows, smearing effects can occur which have to be prevented. In Figure 4 the distribution of the mechanical moment in dependence of the rotational speed is illustrated. With lower frequencies the mechanical moment increases definitly. Finding the right angular speed is finding a tradeoff between optimal heating and mechanical limitations of the system. To assure an optimal heating process the main drive should operated within the range of 5rps . . . 50rps. Flexibility for various control algorithms is given with this range of angular speed. To fulfill the industrial requirements the heating time is designed for 150 s.

Process control

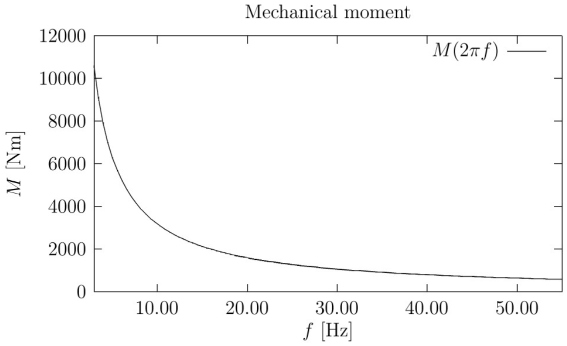


Fig. 4: Mechanical Moment

The temperature accuracy is a very critical point in extrusion processes. Therefore the temperatute distribution in the billet has to be controlled very strictly. Sensors have to be operated to give necessary feedback of the process. In statical systems without rotation of the workpiece the surface temperature can be measured by contact systems like thermocouples. The temperature sensors are pressed at different locations at the billet surface. By heat conduction from the workpiece to the sensor the measurement value is transfered and translated into a voltage signal in the thermocouple. In rotational systems contact measurements would cause friction effects and lead to damages at the workpiece surface as well as at the temperature sensor. Contact less methods like the radiation thermometry (see [4]) have to be applied in this case. Further approaches of system control are presented in [3].

Radiation Thermometry

Every physical body with a temperature higher than 0 K sends out radiation in infrared spectrum. This radiation can be used to determine the temperature of the IR-radiating body. For bodies with temperatures below 500°C all radiation lies in the for the human eye invisible spectrum. In many configurations the spectral radiant intensity is measured by a radiation thermometer:

$$M_\lambda = \varepsilon(\lambda) M_{\lambda b}(\lambda, T_S), \tag{4}$$

where $\varepsilon(\lambda)$ is the spectral emissivity of the surface of the measured object and T_S is the true surface temperature. This radiation is measured by an electrical detector and converted to a voltage. Emissivity is often dependent of the temperature of the considered body as well as the considered wavelength. In the majority of cases metals have a higher emissivity at shorter wavelengths. Aluminium reflects the majority of incoming radiation and owns a very low emissivity. Therefore a very low power is emitted which leads to the need of very sensible measurement sensors. The temperature is calculated based on the measured radiant intensity and the emissivity of the aluminium body. As emissivity changes with temperature and oxidation effects a measurement in only one waveband cannot determine the change in emissivity which leads to inaccurate computation of the surface temperature. For this reason the measurement is done at least in two wave bands.

Pyrometer and Surface Scanning Unit

In the ALUHEAT Project a pyrometer operating at 2 wavelengths with a measurement range of T = [350°C . . . 600°C] is used to measure the surface temperature of the rotating billet. The minimal response time lies at 50 ms. At a distance between pyrometer and target of 1m the measured surface spot has a diameter of 25 mm. So evaluate the temperature distribution along the billet axis a line scanning unit is combined with the pyrometer. Incrementally the

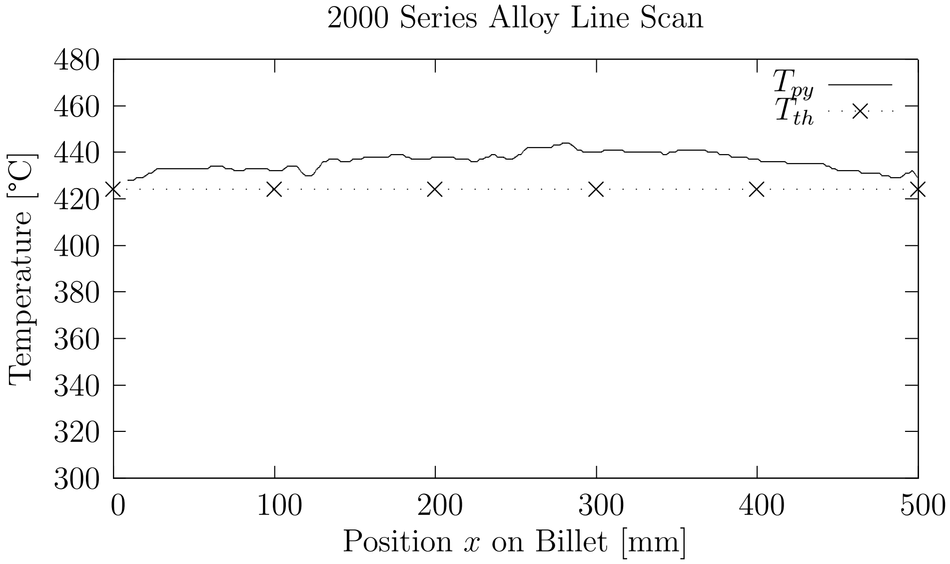


Fig. 5: Temperature distibution on a billet of 2000 series alloy with constant temperature distribution on surface: T=425°C

billet surface is evaluated to get the temperature information for multiple points. For every point the surface temperature has to fulfil the requirements of the heating process according to the defined accuracy. Based on these metered values the control system will adapt the process to be in the defined limits.

Line Scan Measurements

To verify the correct operation of the temperature measurement system in ALUHEAT, test measurements at stationary billets have been performed. Aluminium billets of 200 mm in diameter and a length of 500 mm served as subject to testing. Comparing measurements by a thermocouple acting on the surface of the regarded body serve as verfication of the contact less measurement by the pyrometer.

An alloy of series 2000 has been used for the verification tests. Figure 5 illustrates the results of the measurement. The scanning unit was positioned at the center of a 500 mm billet. The surface of the aluminium billet was slightly oxidised. The standard calibration for series 2000 alloys has been used for the surface measurements. The reference measurement of a thermocouple yields a constant surface temperature of 425°C at every point. At the left and right end of the billet the difference between the measurements of thermocouple and pyrometer differs by less than 5 K. Between $x = [130\,\text{mm} \ldots 450\,\text{mm}]$ the measurement error between reference pyrometer value exceeds the level of 5 K to a maximum error of 18 K. At every point the value of the pyrometer is more than the reference value of 425°C.

With a standard setup of the measurement system influences of viewing angle effects are not compensated, which lead to varying calculated temperatures by the pyrometer. At the points of optimal calibration the measurement error is less than 5 K. It is expected that an viewing-angle dependent calibration will reduce the error level at any point below 5 K.

Status of the ALUHEAT project

To investigate the possibilities of realizing the rotating billet superconducting induction heating technique a European project with the name ALUHEAT was launched in 2005.
ALUHEAT aims at designing and building a 200 kW rotating billet heater prototype. The project is currently at the end of the design phase. The drawings for the mechanical system are delivered and ready to be realized. The cryogenic system is built and tested. The temperature of the working system is expected to be in the range of 10 - 15 K. Thirty-two double

superconductor coils have been wound with an efficient wet winding technique. The temperature measurement sytem has been tested and first verification tests have been fulfilled. In a next step all subsystems will be integrated into the overall system. The heater is designed for billets with a fixed diameter of 215 mm and lengths up to 700 mm. The maximal rotational speed is 3000 rpm and the heating time from room temperature to 450 - 500 °C is about 150 s.

Project partners The project involves nine partners from six european countries. The partners and origins are listed in Figure 6. The superconductor is supplied by Columbus Superconductors and then wound to coils by SINTEF. The cooling system is provided by Tampere University of Technology and the power source by Skoda Vyzkum. The mechanical design has been made by Fraunhofer Gesellschaft and the mechanical system is assembled by SMS Elotherm. University of Hannover provides temperature measurement system and system control and runs the laboratory tests. GK Kety provides industrial end user experience. Aluminium quality analyses are done by the Insitute of Non-Ferrous Metals.

Partner	Country
Fraunhofer Gesellschaft	Germany
Tampere University of Technology	Finland
Institute of Non-Ferrous Metals	Poland
Columbus Superconductors	Italy
GK Kety	Poland
SMS Elotherm	Germany
Skoda Vyzkum	Czech Republic
University of Hannover	Germany
SINTEF Energy Research	Norway

Fig. 6: Partners in the ALUHEAT project

References

[1] Morandi A. Fabbri, M. and F. Negrini. Temperature distribution in aluminium billets heated by rotation in static magnetic field produced by superconducting magnets. *COMPEL.*, 24:281–290, 2005.

[2] N. Magnusson and M. Runde. Induction heating of aluminium billets using superconductors. In *Proc. Aluminium Extrusion Techn. Sem.*, pages 389–393, May 18-21 2004.

[3] Rapoport E. Efimov A. Nacke B. Nikanorov A. Pleshivtseva, Yu. Special method of parametric optimization of induction heating systems. *Modelling for Electromagnetic Processing*, 2008.

[4] A. Ulferts and B. Nacke. Contact-less temperature measurements of aluminium surfaces. *Conference: Aluminium 2007, Kliczkow*, 2007.

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