

# Finite Element Analysis of Aluminum Billet Heating by Rotation in DC Magnetic Fields

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## Summary

This papers present a multiphysics model able to analyze the heating of metallic billets by rotation in DC magnetic fields. The finite element solution of time dependent electromagnetic and thermal fields taking into account the rotating motion is associated with step by step in time domain method.

## I. INTRODUCTION

The important number of papers related to the subject published in the last years proves the interest of scientific and industrial community for the development of a new heating technology in which the main input energy is the mechanical energy. The eddy currents in the billet to be heated in case of the new technology are the result of the relative motion between the billet and the inductor of the system, DC current supplied. In case of copper or aluminum made billets the proposed heating technology is much more efficient than the classical induction heating technology.

This paper presents the finite element model of the heating process by the relative rotation motion between the billet to be heated and the inductor that generates a DC magnetic field. This model is valid in both cases, billet rotation with respect to a fixed inductor, or inductor rotation with respect to a fixed billet.

The finite element model of metallic billets heating by rotating motion in DC magnetic field is an example of multiphysics simulation with FLUX software by coupling, via transfer files, the transient magnetic analysis with transient thermal analysis, taking into account the rotation motion between the inductor and the billet.

## II. GEOMETRICAL AND PHYSICAL DESCRIPTION

The geometry of the heating device in Fig. 1 includes two components:

(a) the inductor consisting in two stranded coils DC current supplied, symmetrically placed with respect the billet, of rectangular shape 200 mm x 350 mm, round corners radius 70 mm and rectangular cross-section 50 mm x 100 mm. The distance between the center of the device and the center of the two coils is 130 mm;

(b) the billet to be heated by rotation, with diameter 200 mm and height 200 mm. The billet is aluminum made, characterized by a temperature  $\theta$  dependent resistivity

$0.0265(1+0.004 \cdot \theta) \mu\Omega\text{m}$ , a thermal conductivity 220 W/mK and a specific heat  $2 \cdot 10^6 \text{ J/m}^3\text{K}$ . The center of the billet is the origin (0, 0, 0) of the main coordinate system. The billet axis is the Oz axis of this coordinate system and the Ox axis of this system contains the center points of the two coils.

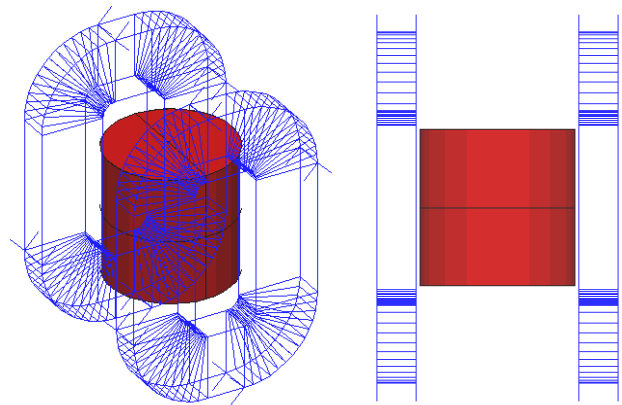


Fig. 1. Device geometry

The physical description of the computation domain of the electromagnetic field, Fig. 2, concerns the following regions: (a) the eddy current volume region that is the billet, a non-magnetic, and thermal conductive region; (b) the air volume region all around the billet, a non-magnetic and insulating region. This region includes the special outer volume, called infinite box, used by FLUX software to simulate the infinite extension of the magnetic field computation domain. The two coils of the inductor are placed inside the inner volume of the air region;

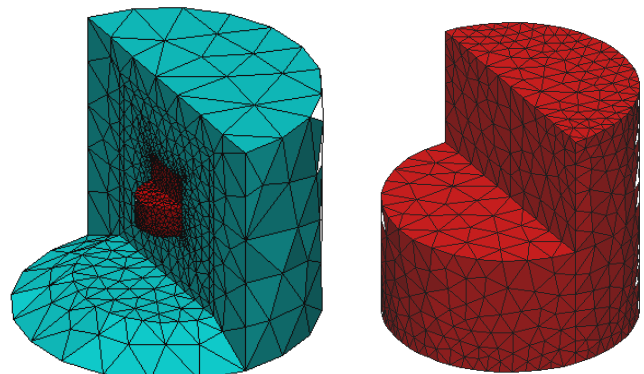


Fig. 2. Volume regions and mesh of the electromagnetic field computation domain

(c) the surface region represented by the billet surface, used in thermal computation, which is the surface of thermal transfer from the billet to the surrounding air whose temperature is 20°C. This surface is characterized by a convection transfer coefficient 20 W/m<sup>2</sup>K and a radiation transfer coefficient 0.8.

### III. MULTIPHYSICS SOLVING PROCESS

The billet rotation with respect to the two inductor coils and the time variation of the billet temperature during the process heating imposes a solving procedure of step by step in time domain type. That means the continuous rotation of the billet is replaced by successive positions of the billet with respect to the inductor. The billet position changes after the time step  $\Delta t$ , the current position differing from the previous one with the elementary angle  $\Delta\alpha = (2\pi n/60)\Delta t$ , where  $n$  is the billet speed expressed in [rpm].

A good numerical solution with respect to the billet rotation is achieved if the elementary angle  $\Delta\alpha$  is not so large, but a very small value determines huge values of the computation time in case of long heating processes. For example, if  $\Delta\alpha = \pi/15$  rad (12 degrees between two successive positions) and  $n = 400$  rpm, it results  $\Delta t = 5$  ms; if the heating time is  $t_f = 180$  s the number of time steps is 36000. In other words, the rotation period  $T = 60/n$  has a very small value in comparison with the time constant of the heating process, and consequently the "thermal time  $t$ " of the heating process is much larger than the "electromagnetic time  $t_e$ " of the induced power generation process.

The solution applied by multiphysics coupling of electromagnetic transient, heating transient and rotation between the billet and the inductor is to consider a hypothetical billet material having a specific heat  $k$  many times lower than the real material. Thus, taking into account the differential equation:

$$\gamma c \frac{\partial \theta}{\partial t} = \left( \frac{\gamma c}{k} \right) \frac{\partial \theta}{\partial (t/k)} = \left( \frac{\gamma c}{k} \right) \frac{\partial \theta}{\partial (t_e)} = \text{div}(\lambda \text{grad} \theta) + p, \quad (1)$$

the heating time scale  $t_e$  of the hypothetical billet with the specific heat  $(\gamma c/k)$  can be similar with the electromagnetic time scale  $t$ . Consequently, the electromagnetic time step  $\Delta t = 60\Delta\alpha/(2\pi n)$  becomes convenient for the numerical solution of heating transient of the hypothetical billet.

### IV. RESULTS ANALYSIS

The numerical experiments whose results are analyzed in this section concern the study of two variants of the coils current supply for heating the billet up to around 600 °C. In the first case the current has the same orientation in the two coils, Fig. 1, of the inductor, and in the second case the two currents have opposite orientations. With respect to the billet the inductor generates a two poles magnetic field in the first case ( $2p = 2$ ), respectively a four poles magnetic field in the second case ( $2p = 4$ ).

The influences of the current intensity supplying the inductor coils and of the billet rotation speed on the characteristics of the heating process are analyzed.

In order to have reasonable values of the computation time a relatively high value  $\Delta\alpha = \pi/6$  was considered.

#### A. Same Orientation of Currents in the Two Coils

The following graphical results correspond to the value 400 rpm of billet speed and to a DC current value of 150 kA in each of the two coils of the inductor. The value  $k = 250$  of time scale factor was considered in these applications. Consequently, the actual values of time, the abscissa in the figures below, must be multiplied by this factor.

After the electromagnetic transient in the range [0 ... 60] seconds, generated by the initial condition of zero value for the state variables, the power induced in the billet, Fig. 3, slightly decreases and the electromagnetic torque, Fig. 4, slightly increases. The explanation of these variations is the increase of the billet resistivity as result of the temperature increase during the heating.

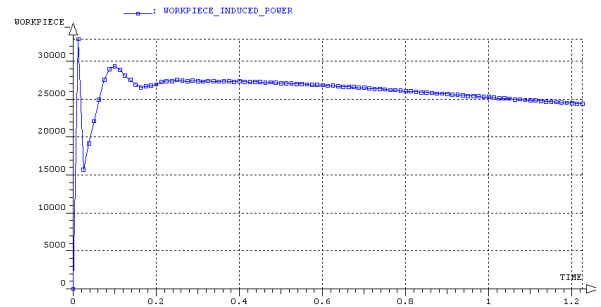


Fig. 3. Transient variation of the power induced in the billet

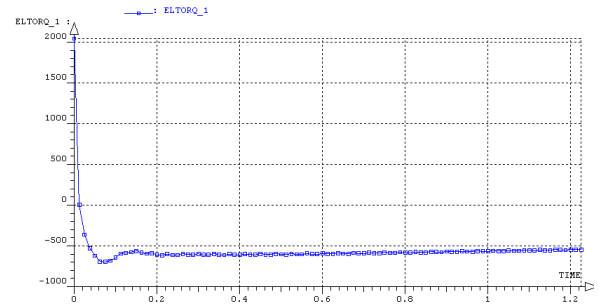


Fig. 4. Transient variation of the electromagnetic torque

The two curves in the Figs. 5 and 6 show the time variation of induced power volume density and of the temperature in the point on the billet surface defined by the coordinates  $x = 100$  mm,  $y = 0$ ,  $z = 0$  in the main coordinate system at the start of the heating, moment  $t = 0$ . The local value of the induced power varies during a half billet rotation between a maximum value and zero value (where the vector velocity is parallel with the flux density vector), Fig. 5.

The thermal losses, whose time variation during heating is represented in Fig. 7, are associated with the thermal flux by convection and radiation through the billet surface.

At the end of the heating, respectively after 306.26 seconds, the induced power has the value 24.48 kW, the

electromagnetic torque 544.36 Nm, the temperature field of the billet cover the range [570.5, 645.1] °C and the thermal losses are 6.945 kW.

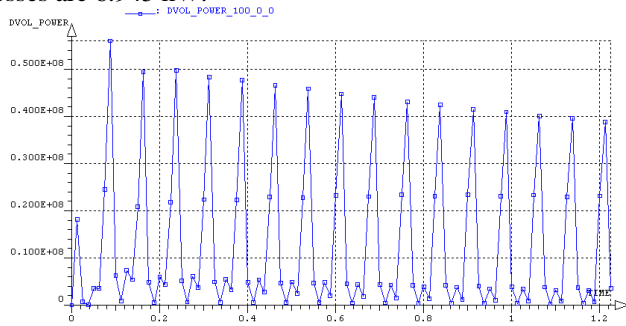


Fig. 5. Time variation of the induced power density in a point during billet heating

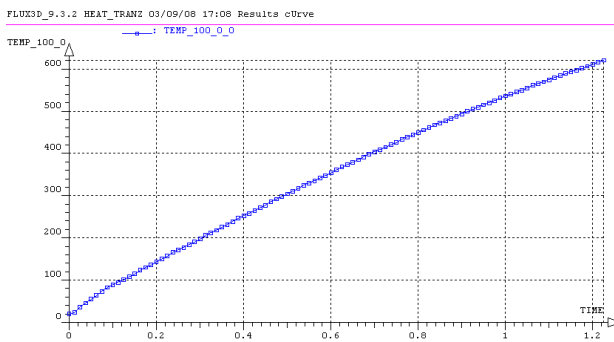


Fig. 6. Time variation of the temperature in a point during billet heating.

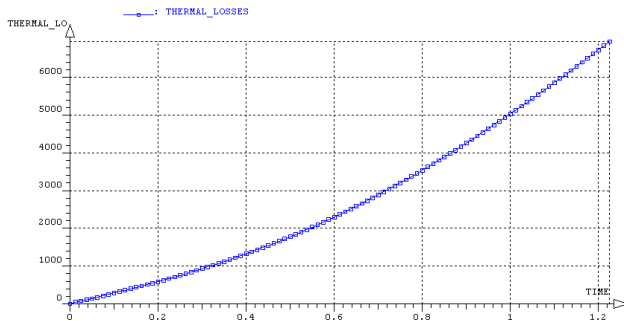


Fig. 7. Time variation of thermal losses during billet heating.

The relative temperature non-uniformity of billet heating is  $\Delta\theta_r = (645.1 - 570.5) / [(645.1 + 570.5) / 2] \times 100 = 12.27 \%$ .

At the moment  $t = 300$  s, the charts of the magnetic flux density in the axial and transversal symmetry planes are presented in Fig. 8, the charts of the induced currents are presented in Fig. 9, the charts of the induced power are presented in Fig. 10, and the chart of billet temperature in Fig. 11.

For 6 successive time steps at the end of the heating, the charts of the billet temperature is presented in Fig. 12. In order to locate the areas with maximum or minimum values, we should notice that the line connecting the centers of the two coils of the inductor, Fig. 1, is parallel with the diameter of the upper circular face, Fig. 12, of the billet.

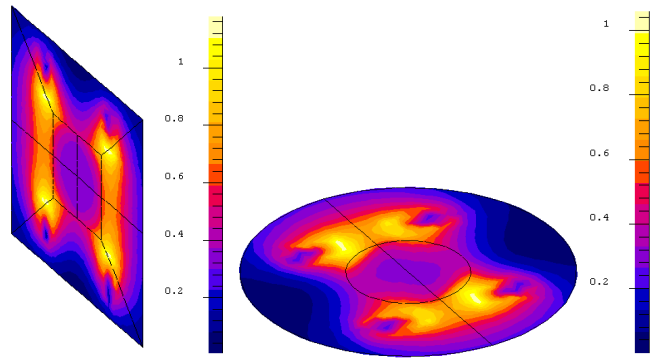


Fig. 8. Charts of the magnetic flux density in the symmetry planes  $y = 0$  and  $z = 0$

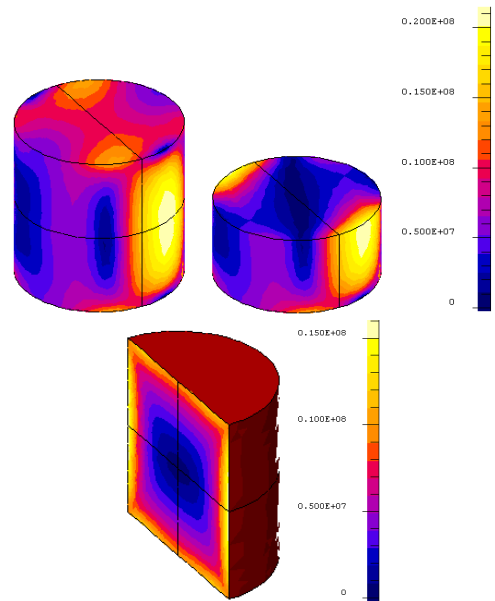


Fig. 9. Charts of the induced currents density

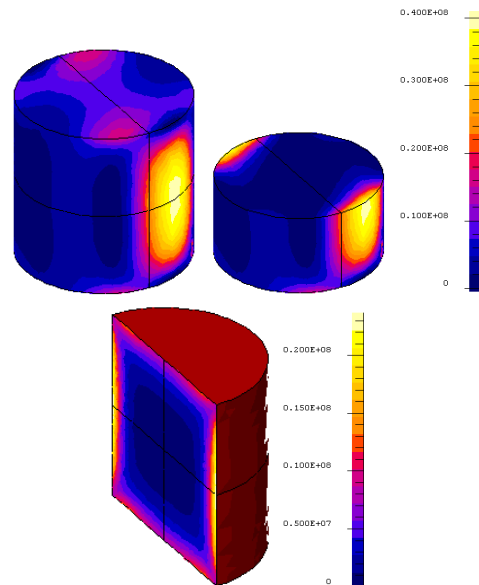


Fig. 10. Charts of the induced power density

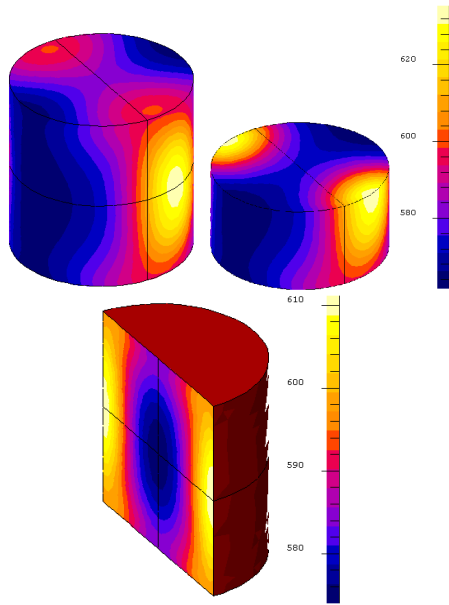


Fig. 11. Charts of the billet temperature

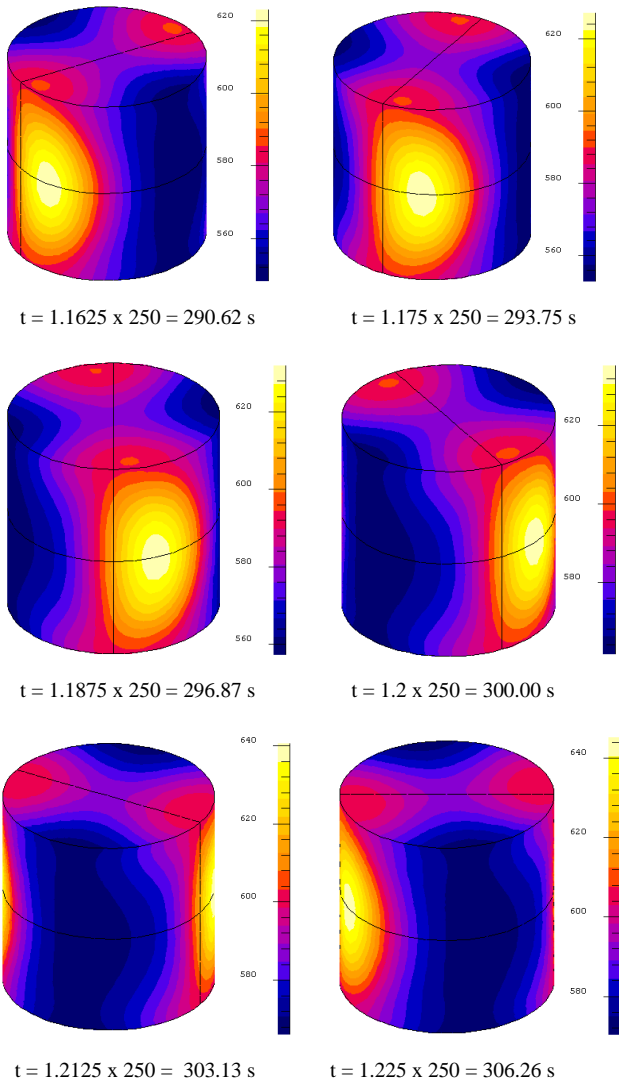


Fig. 12. Charts of the billet temperature for successive time steps at the end of the heating.

The variation at the end of the heating ( $t = 306.26$  s) of the induced power density along the circle on the billet surface placed in the symmetry plane,  $z = 0$ , Fig. 13, shows two points where this quantity has maximal value and four points where this quantity vanishes.

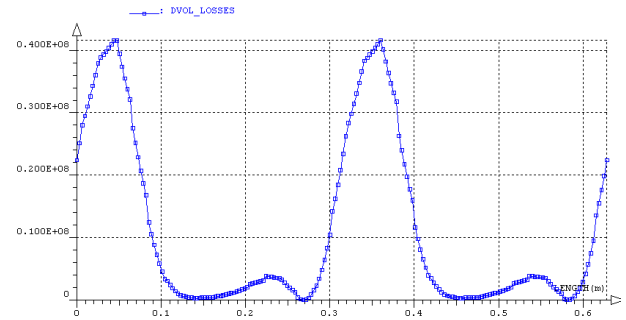


Fig. 13. Induced power density along the middle circle of the billet surface

The variation of the temperature along circles on the billet surface placed in the planes,  $z = 0$ ,  $z = 50$  mm and  $z = 100$  mm (upper surface of the billet) at the end of the heating is shown in Fig. 14 a), b) and c). The relative non-uniformity of the temperature in the symmetry plane  $z = 0$ , Fig. 14 a), is  $\Delta\theta_r = 14.1\%$ .

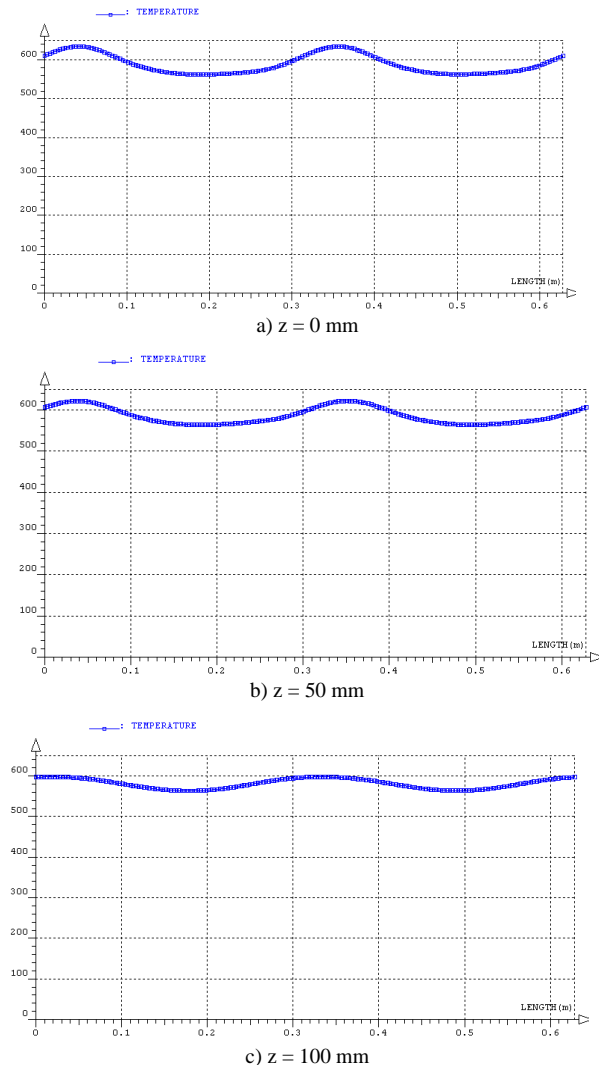


Fig. 14. Temperature variation along circles of the billet surface

Related to the variation along the diameters of billet, placed in the planes  $z = 0$ ,  $z = 50$  mm and  $z = 100$  mm, Fig. 15 a), b) and c), the temperature non-uniformity decreases from the middle to the upper face of the billet.

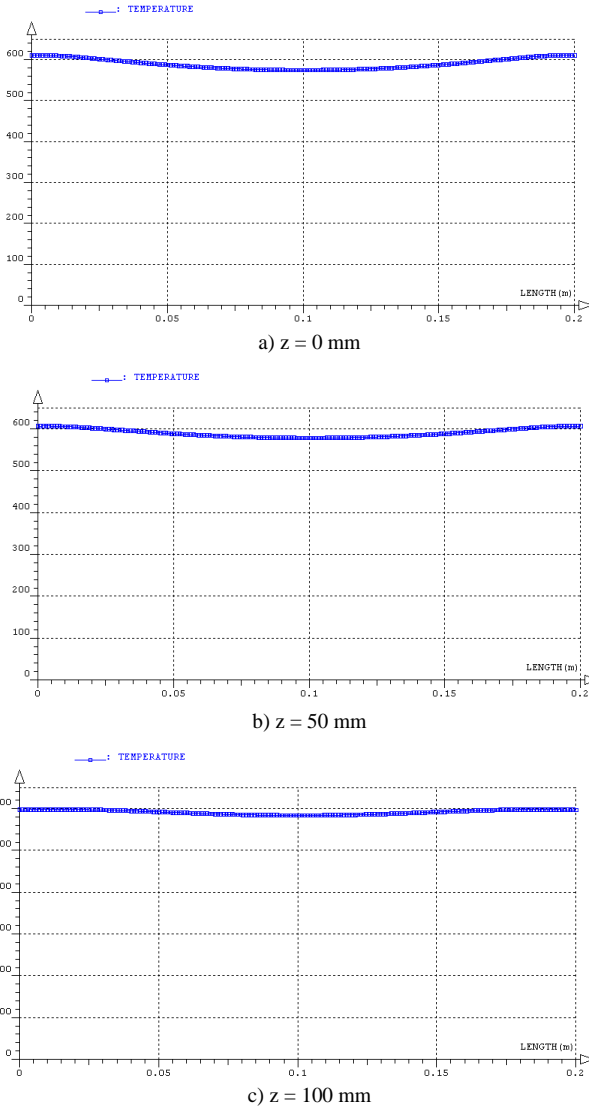


Fig. 15. Temperature variation along diameters of the billet

### A1. Effect of the Speed Increase

The results in Table 1 for three values of the billet speed, the same current 150 kA in each of the two coils and the same mean value (600 °C) of the heating temperature show:

- power is proportional with the power 1.4 of the speed;
- heating non-uniformity is proportional with the speed;
- the advantages of heating time decrease and thermal efficiency increase when the speed increase is counterbalanced by the increase of heating non-uniformity. The quantity thermal efficiency is defined by  $100 \cdot (\text{Induced Energy} - \text{Thermal Losses}) / \text{Induced Energy}$ .

### A2. Effect of the Magnetic Field Increase

The results in Table 2 for three different values of the current intensity in each of two coils and for the billet speed 200 rpm show:

- when the current increases, the heating time decreases, but the heating non-uniformity increases;
- the power is proportional with the square of electric current;
- the heating non-uniformity is also proportional with the square of electric current;
- the advantages of heating time decrease and thermal efficiency increase when the current increase is counterbalanced by the increase of heating non-uniformity.

Table I  
BILLET SPEED AND HEATING CHARACTERISTICS

Speed [rpm]	200	400	600
Induced Power [kW]	8.363	24.53	40.61
Heating Time [s]	1187.5	300.0	184.4
$\theta_{\min}$ [°C]	583	562	544
$\theta_{\max}$ [°C]	616	635	655
$\Delta\theta_r$ [%]	5.50	12.20	16.85
Thermal Efficiency [%]	61.7	89.8	93.7

Table II  
CURRENT INTENSITY AND HEATING CHARACTERISTICS

Current [kA]	220	260	300
Induced Power [kW]	18.15	25.39	34.39
Heating Time [s]	367.5	250.0	180.5
$\theta_{\min}$ [°C]	568	559	541
$\theta_{\max}$ [°C]	629	645	656
$\Delta\theta_r$ [%]	10.19	14.28	19.21
Thermal Efficiency [%]	86.7	90.7	93.4

### B. Opposite Orientations of Currents in the Coils

The results analyzed in this section correspond to the value 400 rpm of billet speed, to the value of DC current of 150 kA in one of the two coils and -150 kA in the second coil.

The power in the billet slightly decreases also, but this power is only 65 % of the value in the case of the same orientation of currents in the coils, section A. At the end of the heating, respectively after 306.25 seconds, the induced power is 15.56 kW, the temperature field of the billet covers the range [378.2, 417.9] °C and the thermal losses are 3.026 kW.

The time variation of volume power density, Fig. 16, is different from the one presented in Fig. 5 in the same point.

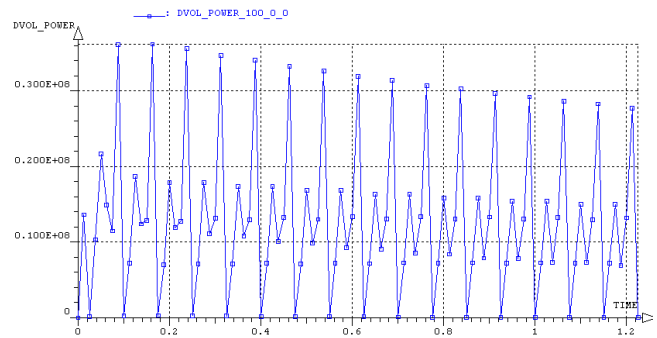


Fig. 16. Time variation of the induced power density in a point during billet heating

The relative temperature non-uniformity of billet heating is  $\Delta\theta_r = 9.97$  %, 19 % less than in the case of the same orientation of currents in the coils.

The time variation of the temperature in the same point as in Fig. 6 is represented in Fig. 17.

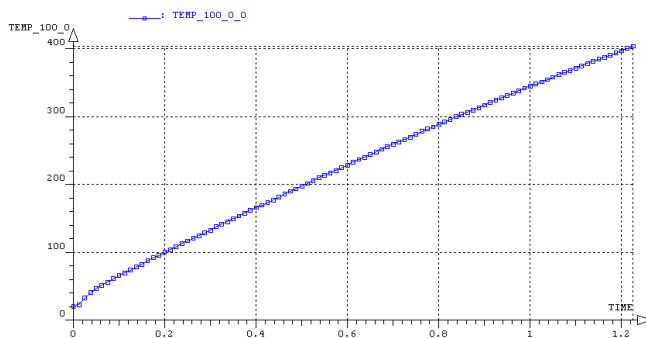


Fig. 17. Time variation of the temperature in a point during billet heating

The charts of the magnetic flux density in the axial and transversal symmetry planes and the chart of billet temperature at the moment  $t = 300$  s, are presented in Figs. 18 and Fig. 19 respectively.

The variation at the end of the heating of the induced power density along the circle on the billet surface placed in the symmetry plane,  $z = 0$ , Fig. 20, at the end of the heating ( $t = 306.26$  s) shows four points where this quantity has maximal value and four points where this quantity vanishes.

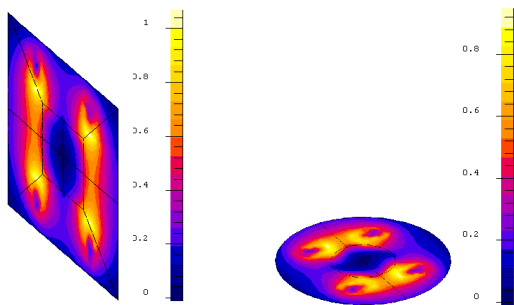


Fig. 18. Charts of the magnetic flux density.

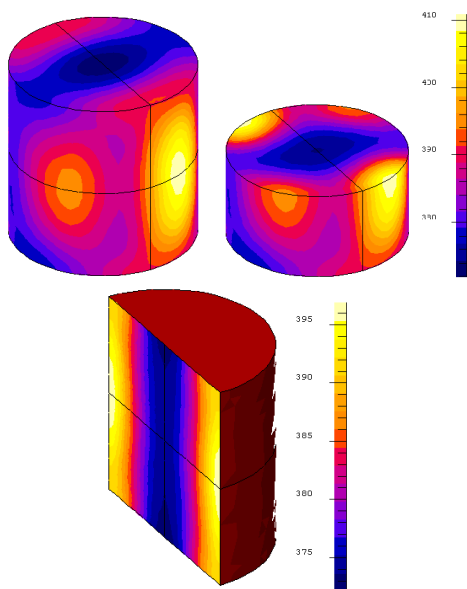


Fig. 19. Charts of the billet temperature.

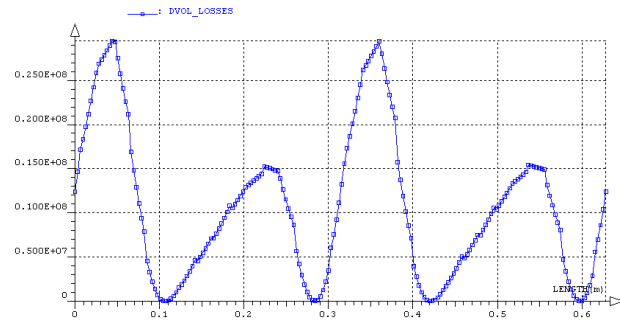


Fig. 20. Curve of the induced power along the middle circle of the billet surface

The variation of the temperature at  $t = 306.26$  s along a circle on the billet surface placed in the symmetry plane  $z = 0$ , Fig. 21, where the maximum value is  $417.48$  °C and the minimum value is  $398.58$  °C, emphasizes a reduced temperature non-uniformity of 8.15 % in comparison with 14.1 % for the case of the same orientation of currents in the two coils.

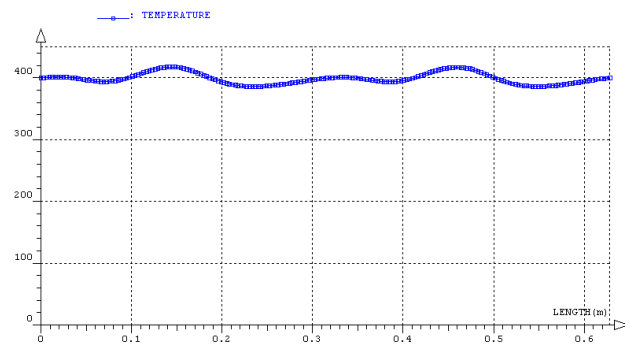


Fig. 21. Curve of the temperature along the middle circle of the billet surface

## V. CONCLUSIONS

The volume heating of aluminum or copper billets by rotation in DC magnetic fields is a good and more efficient alternative compared with the classical induction heating technology.

The electromagnetic and thermal results in this paper confirm the multiphysics module of FLUX software as well adapted tool for finite element analysis of both electromagnetic and thermal characteristics of billet heating by rotation in magnetic field.

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