Computer-aided analysis of induction heating the moving cylindrical ferromagnetic billets

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Abstract — **Mathematical model making allowances for the billet's phase heterogeneity as well as voltage difference in various inductor turns and the current density nonuniformity in the tube section is proposed in this paper. It is shown that proper mathematical modeling the process of moving cylinder ferromagnetic billets induction heating, using the finite element method, requires a solution of the coupled heat and electromagnetic boundary problem, supplemented by additional degrees of freedom, describing the nonuniformity of the voltage distribution in the inductor turns.**

Keywords - induction heating, mathematical modeling

The induction heating unit for moving cylindrical billets made from ferromagnetic material is shown on Fig. 1. The inductor winding is made of a hollow copper tube, the billet being heated is a moving ferromagnetic (steel) cylinder. Externally supplied sine-wave voltage is applied to the winding. The billet is being heated by the currents induced in it.

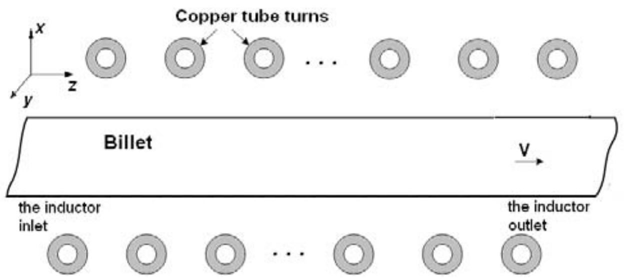

Fig. 1.Diagram of the induction heating unit.

The billet is supposed to be sufficiently long and continuously delivered to the inductor at the constant speed. The problem is to determine the fixed reference frame - related steady-state temperature field in the billet.

Both the billet regions in the ferromagnetic state and those subjected to the phase transition into the paramagnetic state are in the induction heating zone. Specifically, the billet region entering the inductor is cold and, consequently, is in the ferromagnetic phase; the phase transition is in the heating zone inside the inductor, the paramagnetic billet region being closer to the inductor outlet.

There are a number of computer-based models used to investigate the processes of induction heating.

Some studies are based on the assumption of the current density being uniformly distributed over the inductor winding area [1].

The papers [2] introduces the assumption of the voltage drops being equal in separate inductor turns. In modeling the induction heating process of the moving ferromagnetic billets.

However voltage drop in various inductor turns is different, in particular, the voltage drop in the turns spanning the ferromagnetic phase turns out to be greater than that in the turns spanning the paramagnetic phase. Besides, the edge effect caused by the inductor finiteness has a certain impact on the nonuniformity of voltage distribution.

The mathematical model making allowances for the billet's phase heterogeneity as well as voltage difference in various inductor turns and the current density nonuniformity in the tube section have been proposed in this paper. Calculations based on the model proposed are compared with those made using the model where the voltages in the inductor turns are assumed to be equal.

The model is based on FEM analysis of the coupled problem, including the electromagnetic and thermal boundary problem with additional algebraic equations for the voltages in the inductor.

Due to the skin effect, external layers have a screening effect on the internal ones. That is why, heat is produced in the billet's surface layer only. As the billet's internal layer is heated due to the heat transfer, the temperature of the billet's internal part turns out to be lower than that of the external one. This results in the paramagnetic phase appearing on the billet's surface some distance away from the inductor inlet and it grows thicker towards the inductor outlet. The complete transition to the paramagnetic state is not to be observed in any cross-section of the billet.

Fig.2 shows the temperature dependences in the billet centre and on its surface, produced by modeling, Fig. 3 does voltage distribution in the inductor turns. It is seen in Fig. 3 that voltage distribution in the inductor turns is extremely nonuniform. The voltage in the turns which are closer to the inductor inlet is much higher than that in the turns which are closer to the inductor outlet (50-70 turns). This can be explained by the billet being in the ferromagnetic phase in the inlet and by the appearance of the paramagnetic phase in the outlet. Besides, the edge effect is most pronounced; viz. voltage across the edge turns (1st, 2nd, 79th, 80th turns) is lower than that across the successive ones.

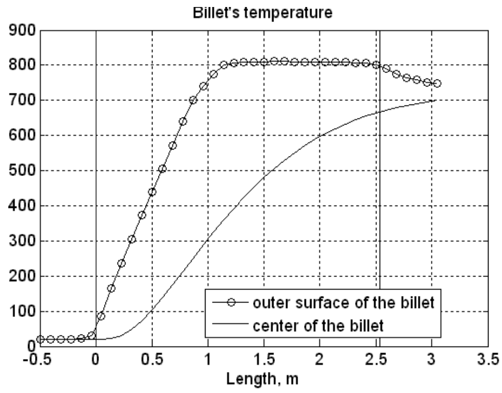

Fig. 2. Temperature distribution along the length of the billet.

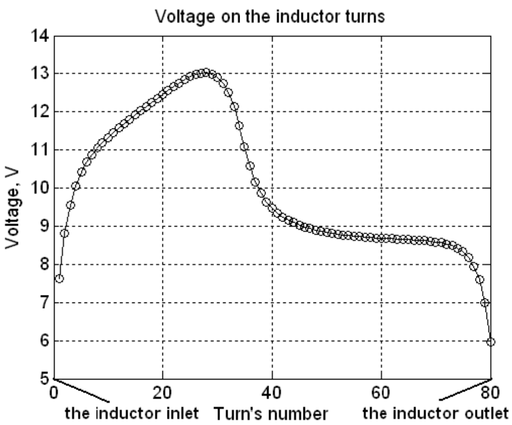

Fig.3. Voltage on the inductor turns

The current density field in the 5th inductor turn from the inlet is shown in Fig. 4. Both the lack of current density isotropy and the current nonuniformity in the tube section are clearly seen. The current flows mainly close to the external surface of the tube turned to the billet. So, in modeling electromagnetic processes of the induction heating, it is necessary to avoid assuming uniform current density distribution in the tube cross-section or its isotropic distribution over the surface, as it was made in [1].

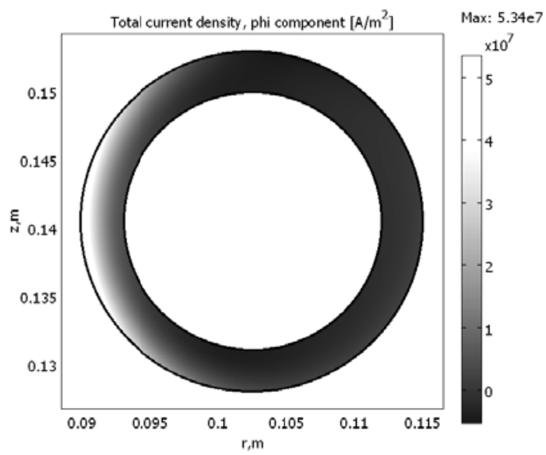

Fig.4. Current density in the 5th inductor turn

The assumption of the voltage equality in the turns leads to underrating the voltage in the turns spanning the ferromagnetic part of the billet and overrating the voltage in the turns spanning the paramagnetic part. To find out the effect of the nonuniformity of the voltage distribution in the inductor turns, we provide the results of calculations, assuming that the voltage is uniformly distributed $U_i = U / n$ (fig. 5, fig. 6). The phase border turn out to be shifted towards the billet outlet from the inductor. As the heating process lasts longer, the temperature difference between the surface and the centre of the billet decreases. Thus, the temperature field pattern changes. The currents in the rings turn out to be significantly different (fig. 6), which is not compatible with the processes occurring in the actual unit. Because of this, a simplified calculation may lead to improper results in designing an induction heating unit.

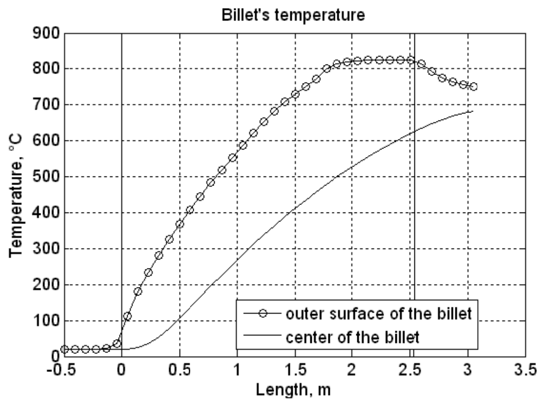

Fig.5. Temperature distribution along the length of the billet (uniformity of the voltage distribution in the inductor turns has been assumed)

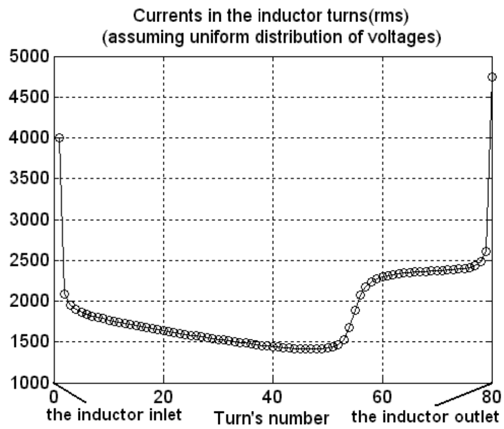

Fig.6. Voltage on the inductor turns (uniformity of the voltage distribution in the inductor turns has been assumed).

Proper mathematical modeling the process of moving cylinder ferromagnetic billets induction heating, using the finite element method, requires a solution of the coupled heat and electromagnetic boundary problem, supplemented by additional degrees of freedom, describing the nonuniformity of the voltage distribution in the inductor turns. The mathematical model described takes into account the billet phase heterogeneity and the nonuniformity of the supply voltage distribution in the inductor turns. Taking into account these two effects significantly influences the calculation results.

References

[1] J. Chen, M. Zhang, "Numerical simulation of electromagnetic induction heating in the material heat treatment", *Advanced Materials Research, Materials Processing Technology*, vol. 291-294, pp 3377-3384, July 2011.

[2] N. Biju, N. Ganesan, C.V. Krishnamurthy, B. Krishnan, "Frequency optimization for eddy current thermography", *NDT & E International*, vol. 42 issue 5, pp. 415-420, July 2009.