Modeling of Inductively Heated Copper Cylinder with Water Cooling Based on Turbulent Flow and Instantaneous Mixing

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Abstract

This paper represents the model which shows the temperature distribution of inductively heated copper cylinder after 10 hours with active cooling by making the coil conductors hollow shape with circulating water flow inside. It was observed that for modest flow rates, the coolant flow becomes highly turbulent which makes the heat transfer between conductor and fluid very efficient. This model illustrates a simplified way of modeling water cooling based on the assumption of turbulent flow and instantaneous mixing. For mechanical support and electrical insulation, the cylinder and coil are embedded in FR4 composite material. The current in the coil has amplitude of 2kA while the average temperature of copper cylinder has increased from 293 K to 346 K. Using this model the temperature evolution in the center of the copper cylinder and in the cooling channel is also observed.

1. Introduction

Induction heating is fast, precise, clean, energy efficient, controllable and repeatable. Generally heating due to currents is also called resistive heating or ohmic heating. Induction heating is a flame-free and non-contact heating process that can turn a precisely defined section of a metal bar cherry red in seconds when heating an electrically conducting material by electromagnetic induction. In a thin layer of the workpiece, usually called the skin depth, the alternating electromagnetic field generates a current which is called eddy current. The eddy current generates heat, due to ohmic power losses and is the main heat source in an induction heating process.

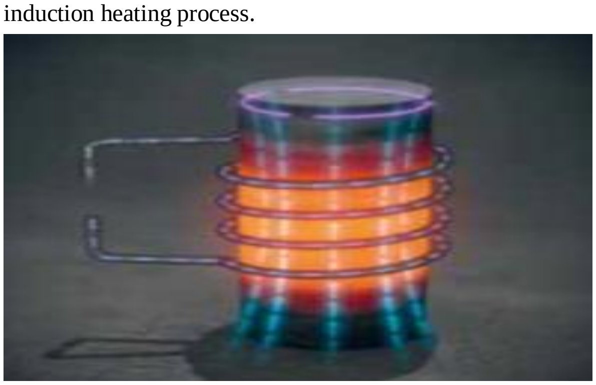

Fig: 1. induction heating

H.Jiang at el. [10] discussed that he skin depth is defined as the depth at which the magnitude of the currents drops e^{-1} from its surface. In induction heating the presence of skin effect causes an exponential heat source distribution within the material as well as a non-uniform temperature profile from surface-to-core. Its depth depends on the electric conductivity of the material, the frequency of the applied electromagnetic field and the magnetic properties of the work piece itself.

The strength of the field varies in relation to the strength of the current passing through the coil. The field is concentrated in the area enclosed by the coil; while its magnitude depends on the strength of the current and the number of turns in the coil.

The eddy currents create their own magnetic field that opposes the original field produced by the coil. This opposition prevents the original field from immediately penetrating to the center of the object enclosed by the coil. The eddy currents are most active close to the surface of the object being heated, but weaken considerably in strength towards the center.

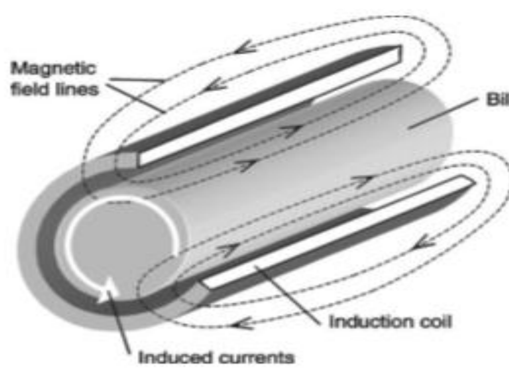

Fig: 2. Principles of induction heating of a massive cylinder (a billet)

The distance from the surface of the heated object to the depth where current density drops to 37% is the penetration depth. This depth increases in correlation to decreases in frequency. It is therefore essential to select the correct frequency in order to achieve the desired penetration depth.

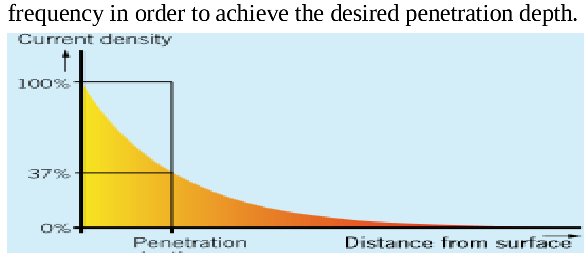

Fig: 3. graph current density vs distance from surface [9]

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Before calculating your energy requirements we first need to know:

- The type of material (steel, copper, brass, etc.)
- Work piece dimensions
- Desired production
- Desired final temperature

First we determine the material's energy absorption rate. Multiply the energy absorption rate by our desired hourly production (kg/hour). The result is our specific power requirement. We can now ascertain the overall efficiency level of the induction equipment. Then we divide the calculated specific power need by the equipment efficiency rate. This gives us the total power requirement.

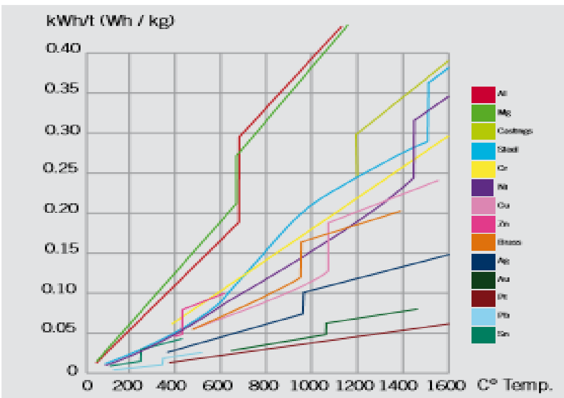

Fig: 4. Energy requirement rate for different materials [9]

The choice of frequency is crucial when using induction heating, as frequency determines the heat's penetration depth. [9]

Table: 1. Some economically beneficial ranges of dimensions for common materials at different frequencies. The frequencies shown are approximate guides only. The shortest heating time for specific materials and dimensions is achieved by operating close to the lowest possible frequency limit. [9]

Material Steel non-magnetic	Steel magnetic	Brass	Copper	Aluminum and aluminum alloys	Frequency
Final temp. 1,200°C Ø mm	700°C Ø mm	800°C Ø mm	850°C Ø mm	500°C Ø mm	Hz
150–500	27–75	110–	50–	50–	50
60–250	8–35	35–440	22–800	22–800	500
40–175	6–25	30–300	15–600	15–600	1,000
25–100	3.5–14	15–180	9–350	9–350	3,000
20–85	2.5–10.5	10–130	7–260	7–260	5,000
14–60	2–8.5	8–100	5–180	5–180	10,000
10–40	1.5–5.5	6–75	3–125	3–125	20,000
5–22	0.7–3.0	3.5–40	2–75	2–75	60,000
4–17	0.5–2.0	2.5–30	1.5–60	1.5–60	100,000
1.8–8	0.2–1.0	1.2–15	0.6–20	0.6–20	500,000

When induction heating a solid cylinder (Fig. 4), there will be high coil efficiency when the applied frequency F > F2. F2 corresponds to a ratio of cylinder outside diameter, OD, to current penetration depth, , greater than three (OD/δ > 3). The use of a frequency which results in a ratio of OD/ δ > 6 will only slightly increase the coil efficiency. At the same time, the use of very high frequencies (>F3 in Fig. 5) tends to decrease the total efficiency due to higher transmission losses and high heat losses, since a long heating time will be needed to provide the required "surface-to-core" temperature uniformity. If the chosen frequency results in a ratio OD/ δ < 3 (frequency <F2), the coil efficiency will dramatically decrease.1 This is due to the cancellation of induced eddy cur- rents circulating in the opposite sides of the solid cylinder.

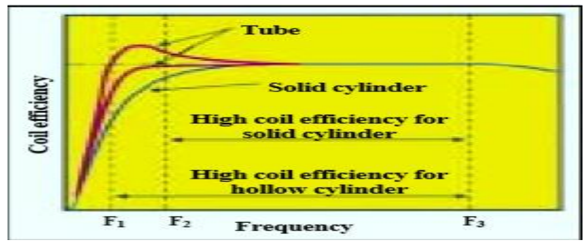

Fig: 5. Graph coil efficiency vs. frequency conditions for maximizing the electrical efficiency of the induction coil are different for tubes and solid cylinders. [9]

Avemann et al. [3] discussed that the induction heating can be utilized in brazing with forming process. The induction apparatus consists of a generator and a cooling appliance from which cooling water flows into the external circuit, the inductor coil and the generator. Both are arranged outside the press and connected to the external circuit by water tubes and electric cables. An inert gas flow through the die is provided to avoid annealing colors and to cool the part down after brazing.

Lee et al· [7] discussed that local induction heating is an efficient way to produce bended pipes of various radii with lower cost and to provide better quality product, bending by radial arm, rapid cooling by water cooling device and continuous feeding by pusher and guide roller.

Runde et al. [2] discussed that for induction heating of aluminium or copper extrusion billets the high-temperature superconducting BSCCO/Ag tapes in the coil windings with liquid nitrogen cooling can be used in place of conventional methods of induction heating.

For a single-layer coil the efficiency of this process, i.e. the ratio between the powers dissipated in the work piece and the overall power consumption is to the first approximation expressed by:

$$\eta = \frac{1}{1 + \sqrt{\frac{\rho_c}{\rho_w \mu_w}}}$$

Where ρc is the resistivity of the coil conductor material, ρw is the resistivity of the workpiece and μw is the relative magnetic permeability of the workpiece. In the case of heating a non-magnetic workpiece with a resistivity comparable to the resistivity of the copper in the coil windings, the root term approaches unity and the efficiency is only around 50% while in case of steel which have high resistivity and permeability the efficiency reaches to 100%. By using multi-layer coils the efficiency can be somewhat improved, but it is still extremely poor compared to almost all other electrical heating processes. Hakim et al. [6] presented a new structure of induction heaters for aluminium billets using a strong DC magnetic field created by a superconducting inductor in which the conducting billet is actuated by a linear movement at a constant velocity and presented magneto-thermal analysis in 2D. Favennec et al. [4] discussed that the complete optimization model coupling heat transfer and electromagnetism process. It is based on a gradient-type method related to an ultra-weak coupling between both non- linear time-dependent problems, and thus makes capable of analyzing the magnetic materials. .Jiang at el. [10] discussed induction heating by studying the conjugate gradient method for thixoforming technique for semi-solid aluminum alloy formimg and. Kang et al. [5] discussed the optimization of inductive coil design by defining the quantitative relationship between billet length and coil length, numerical simulation of the induction heating process using a general purpose finite element analysis to predict the temperature distribution. The proposed objective function based on the computational techniques and numerical simulation model contribute to produce thixo formed parts. Higuchi et al. [8] discussed dynamic and quasi-static behaviors of magneto-thermo-elastic stresses and deformation in a conducting copper or aluminum hollow cylinder subjected to variable magnetic field due to induction heating with time dependent function. One of the most common applications of induction heating is for induction cooking hobs, rice cookers and sealing the anti-tamper seals that are stuck to the top of medicine and drinks bottles. Another common application is "getter firing" to remove contamination from evacuated tubes such as TV picture tubes, vacuum tubes, and various gas discharge lamps. In the semiconductor manufacturing industry induction heating is used in a process called Zone purification in which silicon is purified by means of a moving zone of molten material. Manufacturing industrial applications include metal hardening of ammunition, gear teeth, saw blades and drive shafts, etc

2. Conclusion from Literature Review and Research gap identified

Induction heating problems are mainly optimized and modeled with gradient type method study with time dependent problems. Studying the quantitative correlation of billet/solid geometry with finite element analysis. Also use of superconductive coil with liquid nitrogen cooling (crystat condition) to be maintained is rather very difficult and uneconomical. In some study, magneto-thermal analysis is done in 2D model in induction heating but there is gap since end effects are not considered in 2D model and required full developed 3D model.

The present work mainly deals with the study of frequency transient model with three separate induction heating model features by turbulent water cooling with instantaneous mixing. Thus enabling more detailed, fine and accurate study of induction heating in comparison to previous studies. The current work is aimed to enable modeling of this process and will in turn be useful when defining individual parameters affecting the temperature distribution. This model also simulates the electromagnetic and thermal effect of induction heating.

3. Model description

The model shows a easy way of modeling water cooling based on the assumption of turbulent flow and instantaneous mixing and uses COMSOL with induction heating and model study is based on frequency-transient with single turn coil domain. Model uses three separate induction heating model features. The first one models the temperature dependent electrical conductivity of the metal in the copper using linearized resistivity. The second node, for the FR-4 domain, has a constant conductivity taken from the Material library. Using an induction heating model with a high thermal conductivity to mimic the efficient heat transport in turbulent flow. Water material misses the electric permittivity and the magnetic permeability so add those values.

The system to be solved is given by:

$$J\omega\sigma(T)\, A + \Delta \times (\mu^{-1} \times A) = 0$$

$$\rho Cp\, (\partial T/\partial t) - \Delta.\, K\, \Delta T = Q(T,A)$$

Where ρ is the density, C_p is the specific heat capacity, k is the thermal conductivity, and Q is the inductive heating. The electric conductivity of copper, σ, is given by:

$$\sigma = 1/[\rho_o\, (1 + \acute{\alpha}\, (T - T_o))]$$

Where ρ_o is the resistivity at the reference temperature T_o = 293 K, $\acute{\alpha}$ is the temperature coefficient of the resistivity, and T is the actual temperature in the domain. The time average of the inductive heating over one period is given by:

$$Q = ½\, (\sigma\ \ E^2 | \ |$$

The coil conductor is cooled by turbulent water flow in an internal cooling channel. This is emulated by a combination of a high effective thermal conductivity and a homogenized out-of-plane convective loss term:

$$Q_c = [\, (dM/dt) C_p\, (T_{in} - T)]/\, [\, 2\pi r A\,]$$

Where dM/dt is the water mass flow, Tin is the water inlet temperature, r is the radial coordinate and A is the cross-section area of the cooling channel.

Table 2 lists all the input parameter needed for this model i.e. cooling water inlet temperature, cooling water flow rate, channel radius with section, temperature coefficient, resistivity, current and reference temperature.

Table: 2. Input parameters for model

Name	Experiment	Description
I0	2E3[A]	Current
T0	293 [K]	Reference temperature
r0	1.754e-8[ohm*m]	Resistivity at T=T0
alpha	0.0039[1/K]	Temperature coefficient
Rc	5[mm]	Cooling channel radius
Ac	pi*rc^2	Cooling channel x-section
Mt	1[kg /min]	Cooling water mass flow rate
Tin	10[degC]	Cooling water inlet temperature

Table: 3. includes the material description i.e. water with its relative permittivity and relative permeability values.

Property	Name	Value
Relative permittivity	epsilonr	80
Relative permeability	mur	1

4. Results and discussion

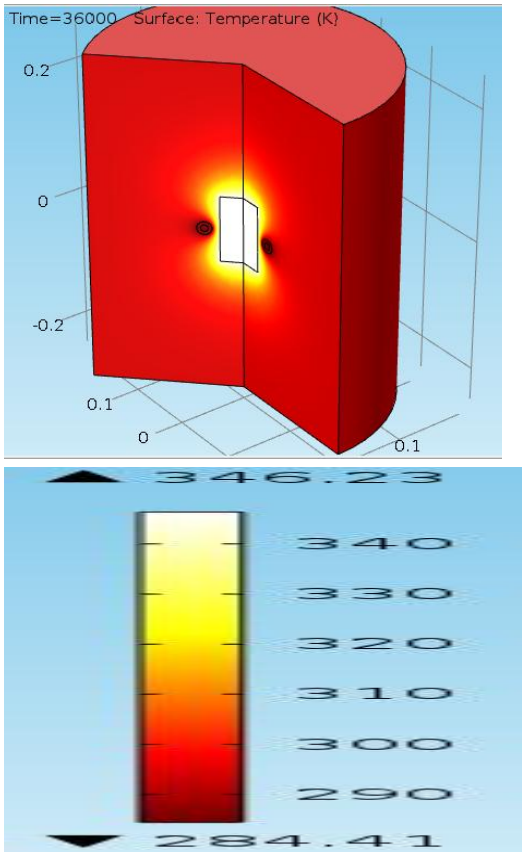

Fig: 6. Surface temperature of cylinder after 10 hrs.

Figure 6 shows the temperature distribution after 10 hours and the average temperature of the copper cylinder increased from 293 K to 346 K during this period. The current in the coil has amplitude of 2 kA. The temperature distribution in the workpiece depends primarily on parameters like, coil position, electrical current through the induction coil, frequency of the current, thermal properties of the workpiece etc.Figure 7 shows the temperature evolution in the center of the copper cylinder and in the cooling channel. Graph shows that temperature rises sharply initially from 0 sec to 9000 sec i.e slope of graph is very sharp but after that temperature rise rate is slower or steeper for rest of model working period upto 10 hrs.

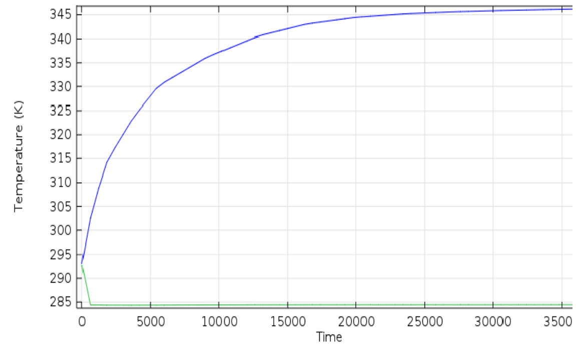

Fig: 8. Point graph Temperature (K)

5. Conclusions

The induced currents in a copper cylinder produce heat, and when the temperature rises, the electric conductivity of the copper changes. Therefore, solving the heat transfer simultaneously with the field propagation is hence crucial for an accurate description of this process. A challenge in induction heating is that the high current in the induction coils requires continuous cooling. We can vary anyone of the parameter and analyze the change in the heated copper cylinder temperature distribution or by varying the copper material itself with some other materials with different induced current. Simulation of electric field with heat transfer is presented in this model. Also further to increase the efficiency of the process, we can choose the induction coil material of low resistivity in comparison to workpiece having high resistivity.

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