Thermal Analysis for the Solar Concentrating Energy and Induction Heating for Metals

A. Rojas-Morín*[1], Y. Flores-Salgado[2], A. Barba-Pingarrón[1], R. Valdez-Navarro[1], F. Mendez[1], O. Álvarez-Brito[3], M. Salgado-Baltazar[1].
[1]Facultad de Ingeniería, Universidad Nacional Autónoma de México.
[2]DGTIC, Universidad Nacional Autónoma de México.
[3]Programa de Posgrado en Ingeniería, Universidad Nacional Autónoma de México.
*Corresponding author: Edificio de Posgrado, 2° piso, Departamento de Mecánica, Ciudad Universitaria, D.F. México, 04510. armando_rm@unam.mx

Abstract In this paper, we simulated the heating of a work piece by coupling two heat sources. Concentrated solar energy was applied at the bottom of the work piece, which generated a heat flux from the parabolic solar dish concentrator. Subsequently, induction heating was applied, which generated Eddy currents that circulated through the work piece and heated the surface of the material. A numerical simulation for solving Maxwell's equations and coupled (DC-AC Module) and transient heat transfer conditions (Heat Transfer Module) was developed using COMSOL MULTIPHYSICS. In this case, the magnetic field and temperature distribution of a cylindrical magnetic metal was obtained for two dimensions, and the heating time of the work piece was also determined.

Keywords: Induction heating, solar concentration, Maxwell´s equations, temperature distributions.

1. Introduction

One of the most efficient technologies for the heating of metals is inductive heating, which can achieve thermal efficiencies up to 90%. In comparison, methods that use gas as a heat source afford thermal efficiencies of 60%. Inductive heating is a clean process, does not involve combustion, and does not oxidize the work piece surface [1]. Although the thermal efficiency of induction heating is high, the demand for electricity in these processes is also high. In order to reduce the consumption of electric power supplied to induction furnaces, concentrated solar energy, which preheats metal using a parabolic solar dish concentrator, can be employed. In the first part of the heating process, only concentrated solar energy is supplied. However, once the preheating temperature of the metal is achieved, induction heating is applied. The present paper is outlined as follows: the physical model of the proposed process is described in section 2, the governing equations, boundary conditions, procedure used to solve Maxwell's equations, and the coupled (DC-AC Module) and transient heat transfer conditions (Heat Transfer Module) used by COMSOL MULTIPHYSICS are provided in section 3. Finally, in section 4, changes in the temperature of the work piece and the surface of the metal over time are evaluated, and the magnetic field distributions are described. The distribution of the magnetic field and the temperature of the work piece in the presence and absence of concentrated solar energy and induction heating were compared to determine the optimal heating method. The results showed that preheating the material with concentrated solar energy provided considerable electric energy savings compared to induction heating alone. The proposed combined system may be used to melt metals in a controlled manner. In contrast, metal samples undergo surface oxidation when concentrated solar energy is employed exclusively.

2. Physical model

Figure 2.1 shows the proposed model. In this case, the iron work piece possessed a cylindrical axisymmetrical geometry. On the bottom of the work piece, a heat flux (q_0'') was generated from the solar concentrator. One cooper coil was placed at L/2, separate from the outer diameter of the work piece. In this case, electromagnetic heat transfer occurred from the coil (q_e), and only air was present between the coil and the work piece. The parameters of the model are shown in Table 2.1.

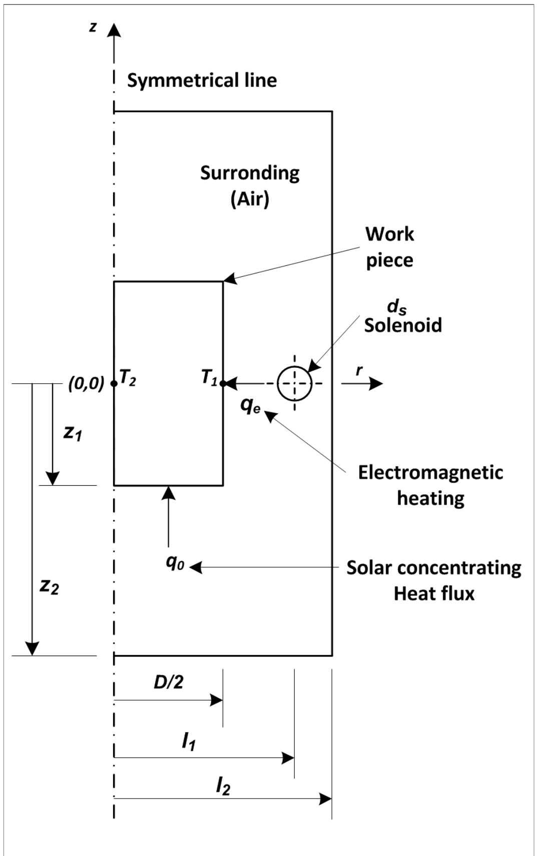

Figure 2.1 Model geometry and boundary conditions.

3. Use of COMSOL MULTIPHYSICS

3.1 Mathematical model

To construct an adequate mathematical model in accordance with Figure 2.1, Maxwell's equations were coupled to the heat transfer equation [2, 3]. The differential form of Ampere's law can be written as follows:

$$\nabla \times H = J + \frac{\partial D}{\partial t}$$

where H is the magnetic field intensity, J is the current density, and D is the electric flux density.

The constitutive relation to the magnetic flux density is given as:

$$B = \mu H$$

where μ is the permeability of the material. In terms of the vector potential A:

$$B = \nabla \times A$$

In Maxwell-Ampere's law:

$$\nabla \times \left(\mu^{-1} \nabla \times A\right) = J + \frac{\partial D}{\partial t}$$

In a time-harmonic quasi-static state, the reduced potential formulation is applicable:

$$\left(j\omega\sigma - \omega^2 \varepsilon\right) A + \nabla \times \left(\mu^{-1} \nabla \times A\right) = J_e$$

where ω is the angular frequency, and ε is the permittivity of the material.

For the heat transfer analysis, the equation takes on the following form:

$$\rho C_p \frac{\partial T}{\partial t} + \nabla \cdot \left(-k_{th} \nabla T\right) = Q$$

where ρ is the density of the material, C_p is the specific heat capacity, k_{th} is the thermal conductivity and Q is the heat source.

The boundary conditions for the heat transfer equation can be expressed as follows:

At the work piece surface, a surface-to-ambient radiation boundary condition occurs:

$$q = \varepsilon_{th} \sigma_{th} \left(T_{amb}^4 - T^4\right)$$

where ε_{th} is the surface emissivity, σ_{th} is the Stefan-Boltzmann constant, and T_{amb} is ambient temperature.

At the bottom of the work piece, a heat flux boundary condition is applicable:

$$q_0 = -k_{th} \nabla T$$

where q_0 is the heat flux.

3.2 Model Parameters

To resolve the mathematical model, the following parameters were employed in COMSOL: frequency transient = 10 *kHz*, coil current = 500 *A*, heat flux = 200 kW/m^2, and ambient temperature = 293.15 *K*.

With these parameters, COMSOL was used to resolve the mathematical model for induction heating only. Subsequently, a second analysis was performed to resolve the model under heat flux boundary conditions. The analyses provided the corresponding temperature changes of the work piece surface, the temperature profile of the two points and the magnetic fields of the work piece.

4. Results and Discussion

Figure 4.1 shows the temperature distribution of the work piece in the presence of induction heating. The interval simulation for the analysis was 0-4000 *s*. At 4000 *s*, a maximum temperature of 534°C was observed in the middle section of the work piece. At the bottom or top of the work piece, the temperature was 515°C.

Figure 4.2 shows the temperature distribution of the work piece due to induction heating and the introduction of concentrated solar energy at the bottom of the work piece (heat flux). In this case, the interval simulation was 0-2000 *s*. In the middle of the work piece, a maximum temperature of 730°C was observed. However, the temperature reached nearly 790°C at the bottom of the work piece. At the top of the work piece, the temperature was 670°C.

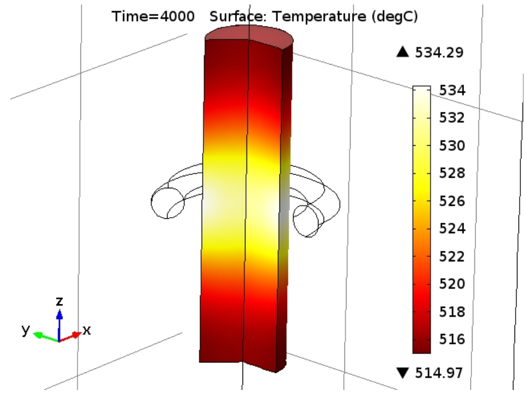

Figure 4.1 The surface temperature of the work piece in the presence of induction heating.

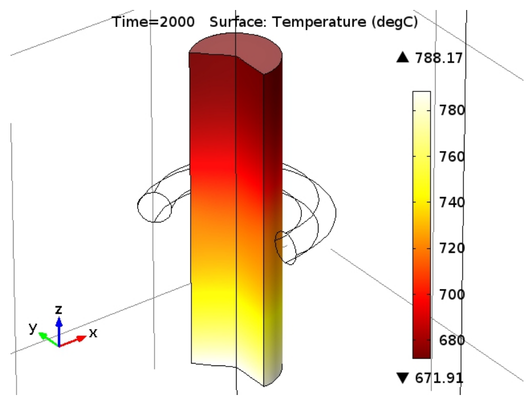

Figure 4.2 The surface temperature of the work piece due to induction heating and concentrated solar energy.

Figure 4.3 shows the temperature change of the work piece at T_1 and T_2, due to induction heating. The transient state ended at 3000 *s*, and the maximum temperature was 534°C, as shown in Figure 4.1

Figure 4.4 shows the temperature change of the work piece at T_1 and T_2. The transient state ended after 1600 *s*, and the maximum temperature was 790°C.

The maximum temperature at T_1 or T_2 was significantly higher when induction heating was coupled with concentrated solar energy. At 1600 *s*, a stationary state was observed. In contrast, when only induction heating was employed, a stationary state occurred at 3000 *s*. Clearly, energy was conserved when the work piece was heated using concentrated solar energy.

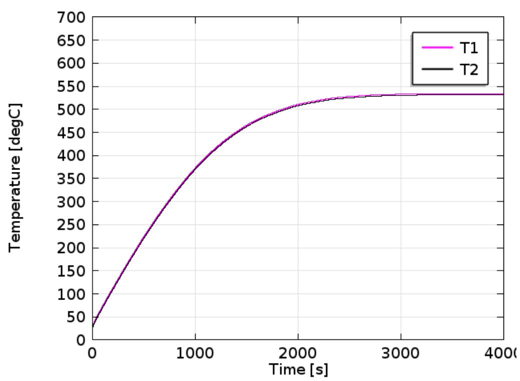

Figure 4.3 Temperature changes at T_1 and T_2 due to induction heating.

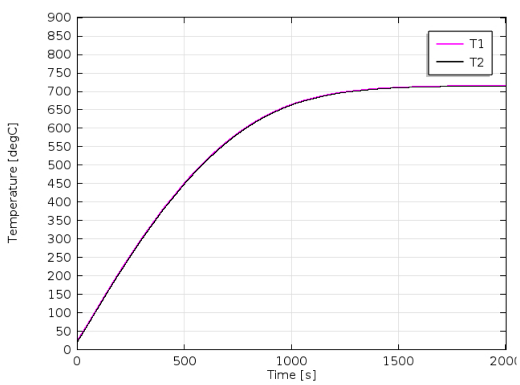

Figure 4.4 Temperature changes at T_1 and T_2 in the presence of induction heating and concentrated solar energy.

Figure 4.5 shows the magnetic field between the coil and the work piece, which reached a maximum of 3.11 x 10^4 *A/m* at a coil excitation of 500 *A*. In both cases, differences in the magnetic field were not observed because the magnetic field was only dependent on the coil excitation.

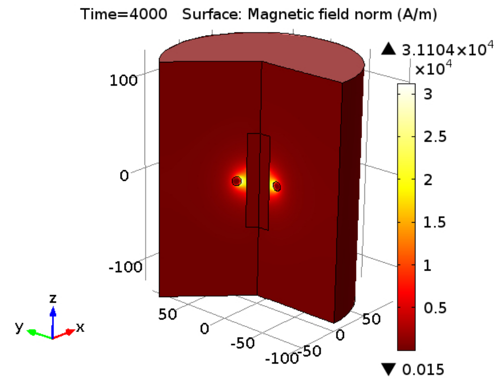

Figure 4.5 Magnetic field between the coil and the work piece

5. Conclusions

Induction heating is one of the most efficient methods of heating materials but is expensive because a significant amount of energy is required. When concentrated solar energy is combined with induction heating, a considerable amount of energy can be saved. The present paper showed that the maximum surface temperature of the work piece increased to 534°C *at 3000 s* in the presence of induction heating only. In contrast, when concentrated solar energy was supplied at the bottom of the work piece, a maximum temperature of 790°C was observed after 1300 *s*.

6. References

1. Y., Deshmukh, Industrial Heating, pp. 425-428. Taylor and Francis (2005).
2. AC/DC Module, *User´s Guide*, COMSOL.
3.Heat Transfer Module, *User´s Guide*, COMSOL.

7. Acknowledgments

The authors thank the PAPITT project (IN112613), DGAPA, and UNAM for their support.

8. Appendix

Table 2.1: Model Parameters

Diameter of the work piece, D	25.4 mm
One-half of the work piece height, z_1	50 mm
Distance from the origin to the solenoid center, l_1	22.7 mm
Half air mass width, l_2	100 mm
Half air mass height, z_2	125 mm