Simulation and Experimental Validation of Induction Heating of MS Tube for Elevated Temperature NDT Application.

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Abstract: Induction heating is multiphysics process, which includes electromagnetic induction and heat transfer. Both the physics are nonlinearly coupled with each other. In this paper, Mathematical modeling of induction heating of MS tube for elevated temperature NDT application is presented. Mathematical modeling of electromagnetic field is done by using magnetic vector potential formulation. Heat transfer is represented by using Fourier equation. Temperature dependent material properties like electrical conductivity, magnetic permeability, specific heat, thermal conductivity are considered. Finite element method is used to solve the electromagnetic field and heat transfer equations. Numerical results are compared with experimental results and found that they are in good agreement. This analysis can be applied for design and optimization of induction coil for forging and melting applications also.

Keywords: Induction heating, FEM, coil design, COMSOL

1. Introduction

Induction heating is non contact type heating techniques. It is widely utilized in industries in various applications such as heating, forging, melting, welding, crystal growth etc, because of high efficiency, cleanness and easy control[1] [2]. Therefore, induction heating is preferred to heat the different size of specimens for conducting elevated temperature non destructive testing (NDT). This paper only includes heating part of specimen.

Induction heating is coupled field phenomena, i.e combination of electromagnetism and heat transfer [3]. Both the physics are nonlinearly coupled with each other due to temperature dependent material properties. Mathematical modeling of electromagnetism and heat transfer is done by using maxwell equations and fourier equation respectively [3] [4]. Finite element method (FEM) based multiphysics software is used to solve the field equations. Numerically calculated temperature is validated with experimental results.

2. System description

Figure (1) shows the schematic diagram of induction heating system. As size and material of the specimens are different, therefore, a special fixture made from MS tube, Copper ring and aluminium disc were prepared. This fixture is cylindrical and placed inside the induction coil as shown in the figure (1). Induction coil produce high frequency magnetic field that coupled with MS tube and induce eddy current. Eddy current heat up MS tube by Joules effect. Copper ring and aluminium disc transferred the heat from MS tube to specimen at faster rate.

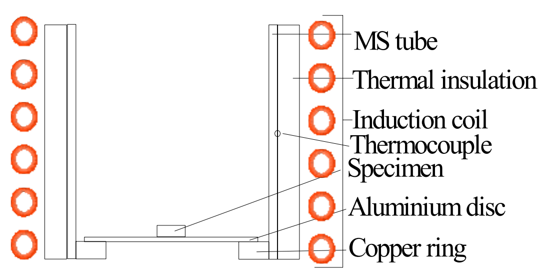

Figure 1:- Schematic of Induction heating system

3. Mathematical Model

Mathematical modeling of electromagnetism is done by using magnetic vector potential formulation [3] [4]. It requires less computation compared to field formulation [5]. Magnetic

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vector potential formulation is derived from maxwell equations,

$$\nabla . B = 0 \qquad (1)$$

$$\nabla . D = \rho_c \qquad (2)$$

$$\nabla \times E = -\frac{\partial B}{\partial t} \qquad (3)$$

$$\nabla \times H = J + \frac{\partial D}{\partial t} \qquad (4)$$

Here, H:- Magnetic field strength (A/m)
E: - Electric field strength (V/m)
σ: - Electrical conductivity (S/m)
J= Current density (A/m^2)
D= Electric flux density(C/m^2)
ρ_c=Electric charge density(C/m^3)
B= Magnetic flux density (Wb/m^2)

Constitutional equations for linear isotropic medium,

$$J = \sigma(T)E \qquad (5)$$

$$B = \mu_0 \mu_r(T)H \qquad (6)$$

$$D = \varepsilon_0 \varepsilon_r E \qquad (7)$$

Here,
μ_0= Free space magnetic permeability (H/m)
μ_r= Relative magnetic permeability
ε_0= Free space electric permittivity (F/m)
ε_r= Relative electric permittivity

Following assumption are made to simplify the computation,

1. The system is rotationally symmetric about Z-Axis.
2. All the materials are isotropic.
3. Displacement current is neglected.
4. Electromagnetic field quantities contents only single frequency component.

From eq (1), magnetic vector potential (A) is defined as,

$$B = \nabla \times A \qquad (8)$$

From eq (3), (4) and (8), Magnetic vector potential equation in frequency domain can be written as,

$$\frac{1}{\mu_0 \mu_{r(T)}} \nabla^2 A + J_s - j\omega\sigma(T)A = \qquad (9)$$

Here,
J_s= source current density (A/m2)
ω=Angular frequency (rad/sec)

For different domain of figure (2), eq (9) can be written as,

$$\frac{1}{\mu_0 \mu_{r(T)}} \nabla^2 A - j\omega\sigma(T)A = 0$$

$$\text{in } \Omega1, \Omega4, \Omega5, \Omega6 \qquad (10.1)$$

$$\frac{1}{\mu_0 \mu_{r(T)}} \nabla^2 A + J_s - j\omega\sigma(T)A = 0 \text{ in } \Omega2 \qquad (10.2)$$

$$\frac{1}{\mu_0 \mu_{r(T)}} \nabla^2 A = 0 \text{ in } \Omega3 \qquad (10.3)$$

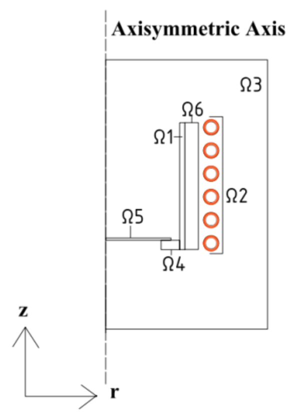


Figure 2:- 2-D Axisymmetric geometry of induction heating system

Heat generated in fixture is calculated by using magnetic vector potential and can be written as,

$$Q = \frac{{J_e}^2}{\sigma(T)} = \sigma(T)(j\omega A)^2 \qquad (11)$$

Here, Je= induce eddy current density (A/m^2)
Eq (11) coupled electromagnetism field and heat transfer, and it is used as heat input in fourier equation as shown below,

$$K(T).(\nabla^2 T) + Q = \rho c_p(T)\frac{\partial T}{\partial t} \qquad (12)$$

Here, T= Temperature (DegK)
ρ= Density (Kg/m^3)
c_p= Specific heat ((J/(Kg.K))
K=Thermal conductivity (W/(m.K))
Qconv= convection heat loss
Qrad= radiation heat loss
t =Time (Sec)

Boundary conditions in heat transfer fields are convection and radiation loss. Convection heat loss can be represent as,

$$Q_{conv} = h.(T - T_{amb}) \text{ W/m}^2 \qquad (14)$$

Radiation heat loss can be represent as,

$$Q_{rad} = \epsilon\sigma_b.\left(T^4 - {T_{amb}}^4\right) \text{ W/m}^2 \qquad (15)$$

Here,

h=convection coefficient (W/m^{2}K)

ϵ=Emissivity

σ_b= Boltzmann constant(5.67X10^{-8} W/m^{2}K^4)

T_{amp}= Ambient temperature (DegK)

Finite element method (FEM) is used to solve the eq (10) and eq (12), by applying initial condition, boundary conditions and forcing function as given in table-III and IV.

4. Simulation

Simulation is carried out by using FEM based multiphysics software (COMSOL).Programming and simulation is done in three steps i.e. preprocessing, procession and post processing as shown in figure (3) [6].

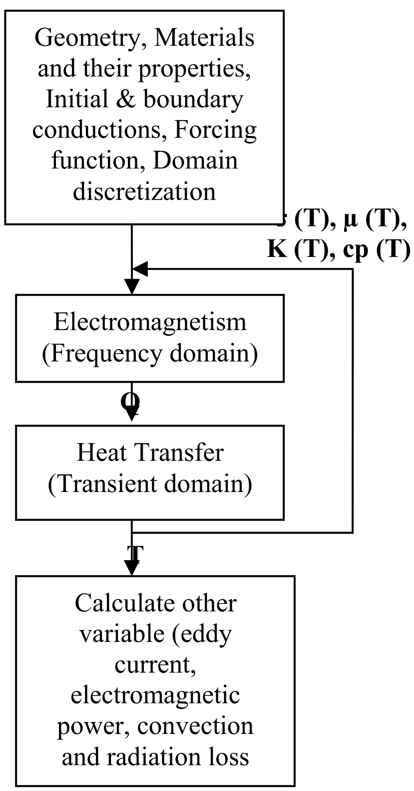


Figure (3). Programming steps for simulation

2-D axisymmetric geometry shown in figure (4) is used for simulation. Dimension details and material properties of copper ring, aluminum disc and induction coil are given in table-I and table-II. MS tube of size (200mm (OD) x100mm (h) x3mm (th)) is used for simulation. MS tube physical properties are given in figure 4. External domain size shall be more than 10 times of induction coil because Small External domain creates more reluctance to the magnetic flux path and creates error in numerical results.

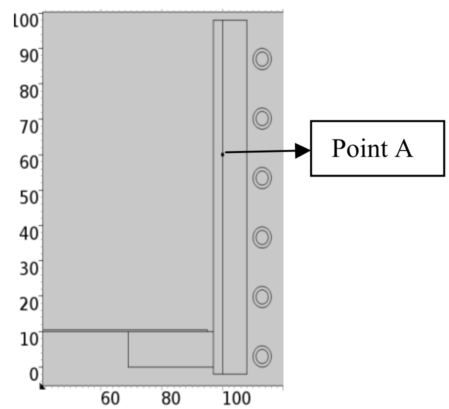
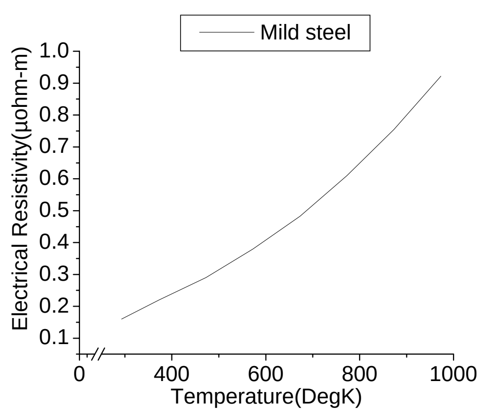
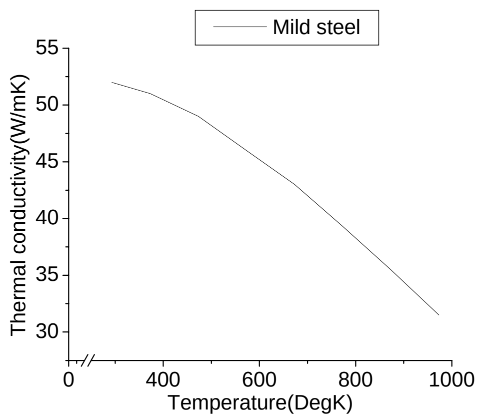


Figure 4. 2-D axisymmetric geometry

Temperature dependent material properties such as electrical conductivity, magnetic permeability, thermal conductivity, specific heat, are used for simulation as shown in figure (4).



(a)



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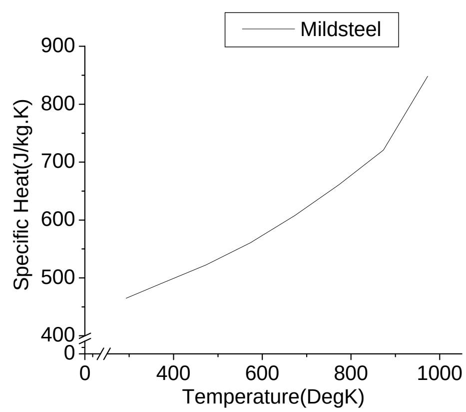
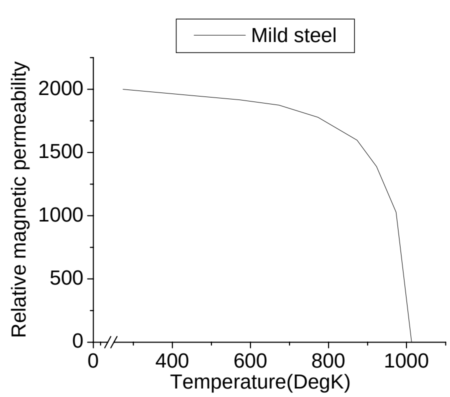


(c)



(d)

Figure 5:- Temperature dependent material properties of Mild steel [2]

Table-I. Copper ring and Aluminium disc dimensions & physical properties [2]

	Description	
Material	Copper ring	Aluminium disc
Dimension	194mm(OD) 138mm(ID) 10mm(th)	190(D) 5mm(th)
Electrical Conductivity (S/m)	$5.8X10^7$	$3.703X10^7$
Relative electric permittivity	1	1
Relative magnetic permeability	1	1
Density(kg/m3)	8760	2700
Thermal conductivity (W/(m.K))	395	211
Specific heat(J/(Kg.K))	378.34	933.33

Table-II Induction coil dimensions and properties

Induction coil	Description
Material	Copper
Inside diameter	220mm
Outside diameter	232mm
Height	90mm
Coil tube diameter	6mm
Coil tube thickness	1mm
No. of turn	6

Initial conditions, boundary conditions and forcing function for electromagnetism and heat transfer are given in table-III and table-IV respectively. Electromagnetism equations are solved in complete solution domain (induction coil, Fixture, air). Heat transfer analysis is done only in fixture, because induction coil is water cooled, and always at room temperature.

Table-III Boundary condition and forcing function for electromagnetism

Boundary condition	Description
Outer boundary	A=0
Asymmetry axis	$\frac{\partial A}{\partial n} = 0$
Induction coil current	0 to 270 sec=49.93 A 270 to 1110 Sec=94.31 A

Table-IV Initial and boundary condition for Heat transfer

Boundary condition	Description
Initial temperature	312 DegK
Convection coefficient(h)	10 (W/m^{2}K)
Emissivity(MS surface)	0.32
Emissivity(copper and Al)	0.04

Solution domain is discretized using trigular elements. Surface of MS tube and induction coil has dense meshing due to skin effect as shown in the figure 6.

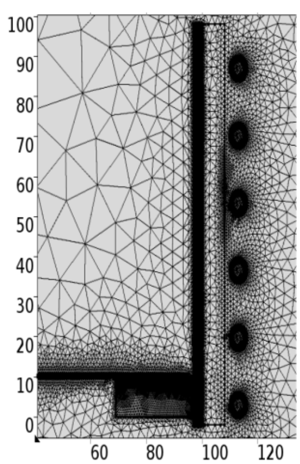


Figure 6. Domain discretization (Meshing)

As induction coil carries single frequency current (because of series resonance configuration), electromagnetic analysis is done in frequency domain. Heat transfer equation is solved in transient domain. COMSOL multiphysics software display results in terms of temperature profile in solution domain as shown in the figure 7. Temperature at thermocouple point (A) as shown in figure 4 is computed in post processing step.

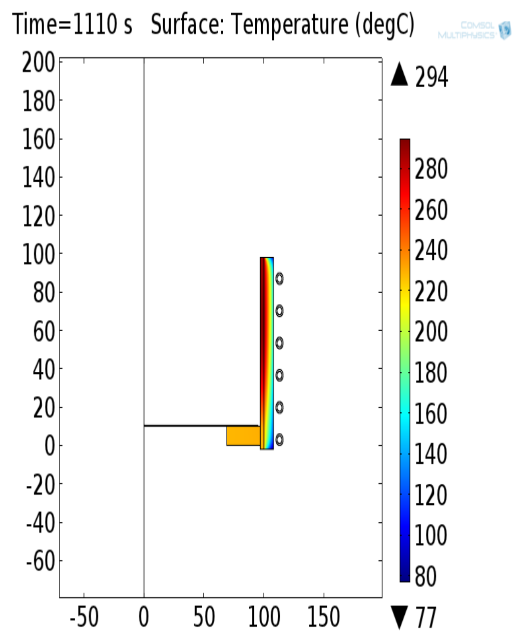


Figure 7. Temperature profile

5. Experiment

Figure 7 shows the set up used for conducting the heating experiments. 15 kW, 9 kHz solid state induction power source was connected to the water cooled induction coil. During experiments, Coil current and MS tube temperature were measured by rogowaski coil [7] and K type thermocouple respectively. K type thermocouple was connected at the centre of the MS tube and temperature is recorded through graphical user interface software.

Figure 8. Experimental set up

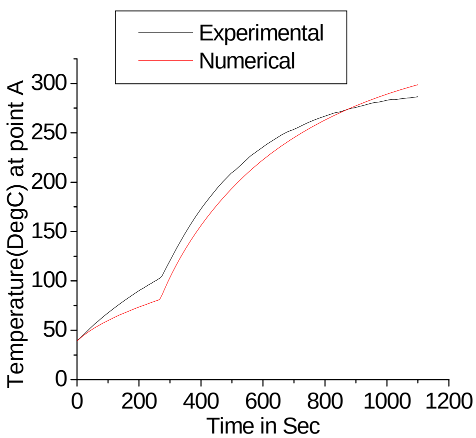


Figure 9. Comparison of numerical and experimental results

6. Conclusion

Numerical and experimental validation of induction heating of MS tube for elevated temperature NDT application was successfully carried out. Temperature dependent material properties are used for simulation that makes mathematical modeling close to the experiment. Numerical and experimental results are in good agreement. This analysis can be applied for design and optimization of induction heating process.

7. References

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