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ANALYSIS OF INDUCTION HEATING SYSTEM FOR HIGH FREQUENCY WELDING

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Abstract. *The aim of the work is the investigation of induction heating system used for longitudinal, high frequency pipe welding.Coupled electromagnetic and temperature field distribution has been studied in order to estimate system efficiency and factors influencing the quality of the welding process and required energy. The problem was considered as three dimensional. Time harmonic electromagnetic and transient thermal field has been solved using finite element method and COMSOL 4.2 software package.*

Key words: *induction heating, high frequency welding, 3D analysis, finite element method, coupled field problem*

1. INTRODUCTION

Technologies based on induction heating are widely used in industry due to their advantages: high energy efficiency, excellent product quality, very good accuracy in heating of certain zones in a short time, clean operating conditions [1]-[3]. Induction heating has a great variety of industrial applications [4]: induction hardening, induction tempering, induction brazing, induction bonding, induction welding, induction annealing, induction pre and post-heating, induction forging, induction melting, induction straightening, induction plasma production, etc.

The object of the study in this investigation is an induction heating system, used for high frequency longitudinal pipe welding. The aim of the research and motivation for carrying out the work is the necessity of development, analyzing and estimating of the system. The main task is to define and then to determine optimal factors and parameters influencing the welding process quality and required energy. The detailed determination and understanding of the processes in the device gives good possibilities for efficient control, management of the welding process and energy consumption monitoring.

The analysis of such systems, both theoretical [5]-[8] and experimental [9,10] is focused on frequency, welding speed, "heat affected zone", ‘vee’ angle, ferrite impeder presence and its position. Although there are a number of publications devoted to this topic, the processes in high frequency welding are still not studied well enough and many interactions and dependencies are not clear. This is not only because the processes are

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very complicated, but also because of specific differences of different systems, concerning dimensions, material properties and the purpose of the welded pipes.

2. Description of the Investigated Induction Heating System

The principal geometry of the investigated system is shown in Fig. 1. The system consists of high frequency spiral inductor, which induces voltage across the edges of the open steel pipe. The induced voltage causes high frequency currents, concentrated on the surface layer due to the skin and proximity effects. The currents flow along the edges to the point where they meet (point of closure), causing rapid heating of the metal. The weld squeeze rolls are used to apply pressure, which forces the heated metal into contact and forms welding bond.

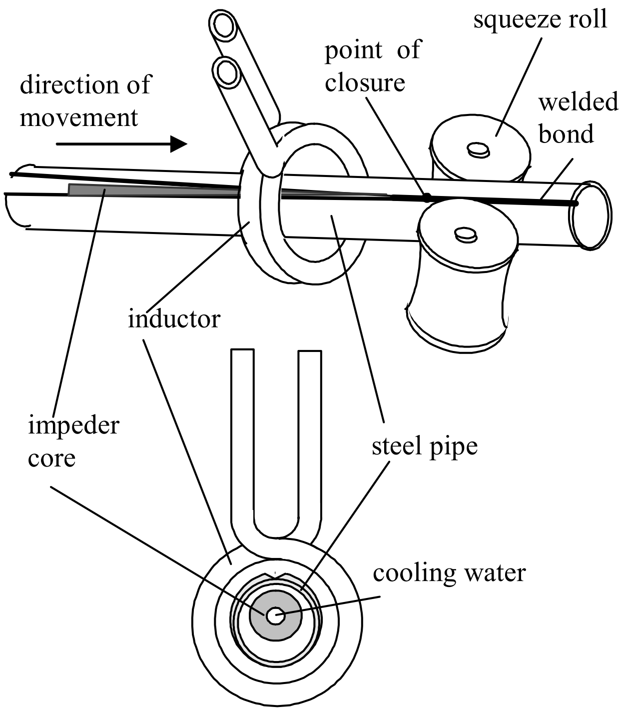

Fig. 1 Geometry of the investigated induction system

Special attention has to be paid to the "heat affected region" (Fig.2). In the so called "V"-zone, due to the skin effect and proximity effect, high frequency currents flow at high densities along surfaces in opposite directions and seek adjacent parallel surfaces for its return path.

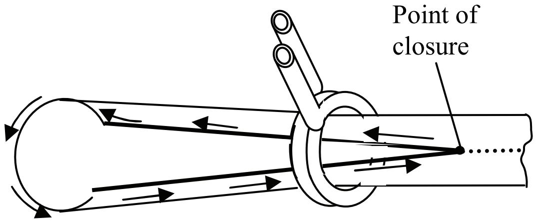

Fig. 2 In the "V"-zone HF currents flow along the two edges in opposite directions

The system includes also inner ferrite impeder, which concentrates magnetic flux and improves the welding efficiency. As it can be seen from geometry in Fig.1, the impeder is located not along the pipe axis, but moved closer to the welded region - i.e. the system is not axisymmetric and field distribution problem has to be analysed as three dimensional.

The cooling water flows inside the inductor and impeder for system cooling.

The investigation of the system is carried out for the inductor parameters shown in Table 1:

Table 1 Parameters of the induction heating system

Parameter	*Value*
Applied current *I*	1000 A
Voltage *U*	500 V
cos φ	0.1
Frequency *f*	200kHz ÷500kHz

The pipe material is steel with about 10% carbon. The end heating temperature must be about 1300÷1450^{0}C. The cooling water flowing inside the conductors is with temperature 40^{0}C. The temperature of ambient air and the initial temperature of the heated pipe is T_0=20^{0}C.

2. Mathematical Model of the Coupled Field Problem

As it has been already described the geometry of the investigated system is very complex, and nonsymmetric, so the mathematical model of the object has to be considered as three-dimensional. The study of the processes in the system includes determination of the electromagnetic and thermal field distribution – the task is coupled field problem. Thus the present work deals with modeling of the 3D time harmonic electromagnetic field. The electromagnetic field problem has been studied not only in the system elements, but also in the wide buffer zone around the device. It helps to define correct boundary conditions in field modeling. The eddy current losses, obtained in electromagnetic field analysis are field sources in modeling of the transient thermal field.

2.1. Investigated regions and domains

The investigated region used in electromagnetic field modeling is shown in Fig.3. It includes domains: Ω1- inductor; Ω2- impeder; Ω3- welded pipe; Ω4- cooling water; Ω5- buffer zone with air.

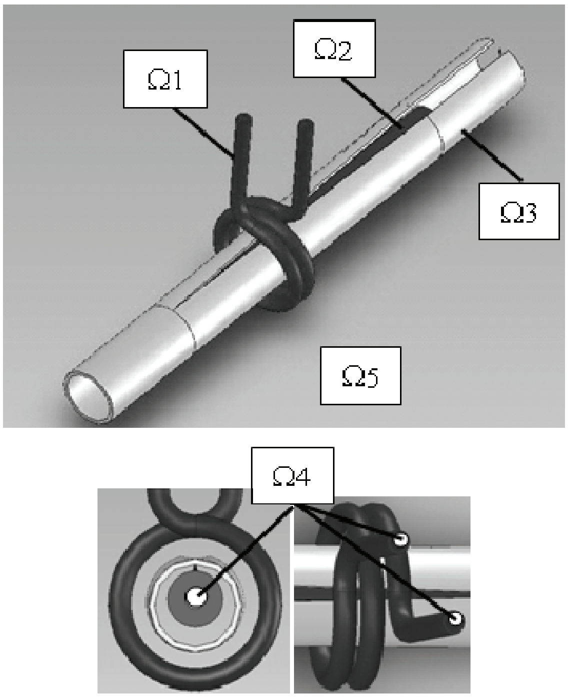

Fig. 3 Investigated region and domains

2.2. Basic equations

Electromagnetic field distribution can be described with equations (1) and (2):

$$\nabla \times (\mu^{-1}\nabla \vec{A}) = \vec{J}_e - \sigma\frac{\partial \vec{A}}{\partial t} \quad (1)$$

$$\vec{E} = -j\omega\vec{A} - \nabla V \quad (2)$$

where $\vec{A}$ is magnetic vector potential , $\vec{J}$ is current density, $\vec{E}$ is electrical strength , V is scalar electric potential, σ is electric conductivity and μ is magnetic permeability.

The boundary conditions are taken to be flux-parallel for the buffer zone boundaries. The time varying electromagnetic field produces eddy currents (3) and corresponding Joule losses (4) – source of heating in the region:

$$\vec{J} = j\omega\sigma\vec{A} \tag{3}$$

$$Q = \frac{[\sigma]^{-1}\vec{J}\vec{J}^{*}}{2} \tag{4}$$

The transient thermal field is modelled by the equation:

$$\rho C\frac{\partial T}{\partial t} + \nabla(-k\nabla T) = Q \tag{5}$$

where k is thermal conductivity , T is temperature, ρ is density, C is specific heat and Q is heat source, obtained in electromagnetic field analysis. The convection boundary conditions are posed both for outer boundaries of the inductor and the pipe and water cooling of the inner inductor boundaries:

$$-k\frac{\partial T}{\partial n} = h(T - T_{\text{inf}}) \tag{6}$$

where h is the heat transfer coefficient, T_{inf} is the external bulk temperature, $\vec{n}$ is the normal vector of the boundary.

3. FEM Analysis – Numerical Simulations and Results

Numerical simulation of the 3D coupled - electromagnetic and thermal fields was carried out using FEM and COMSOL 4.2 package [11]. In Fig.4 is shown the investigated system with the buffer zone around it and Fig. 5 presents the finite element mesh, used in solving the problem.

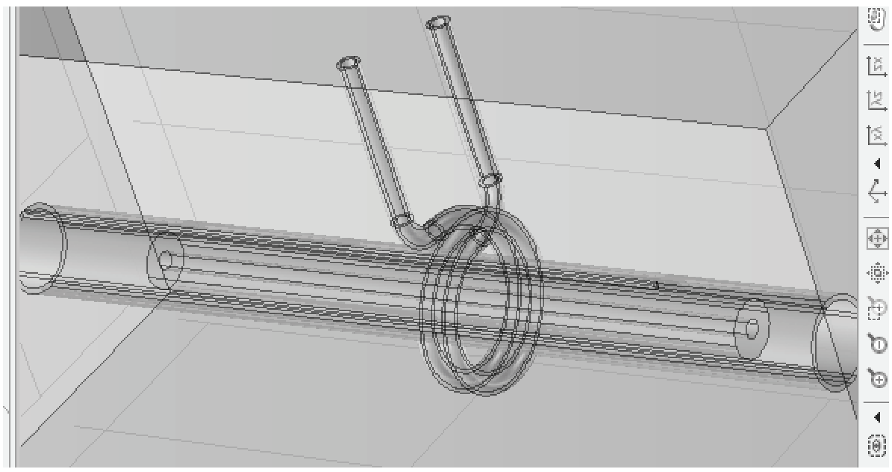

Fig. 4 Investigated system with the buffer zone around it.

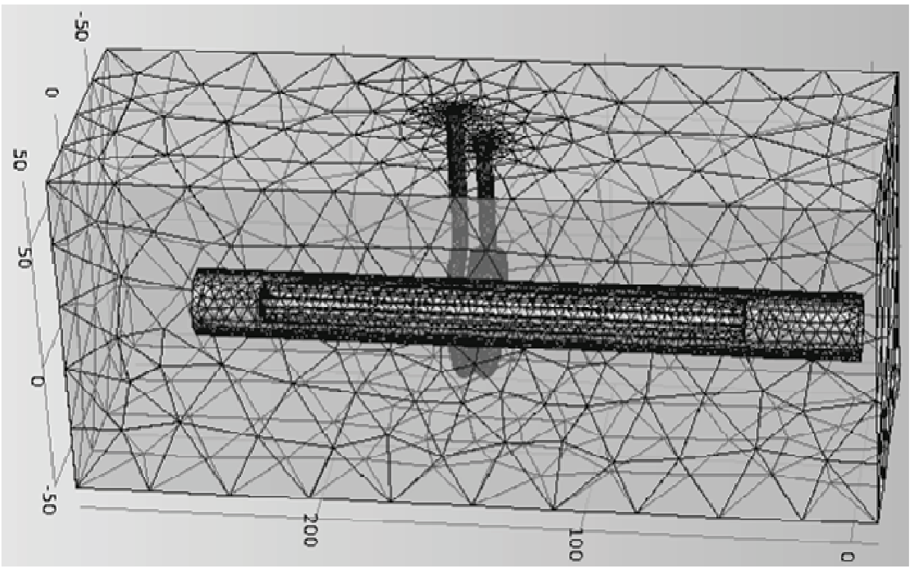

Fig. 5 Finite element mesh, used in solving the problem

Some results, obtained in solving the problem for frequency 300 KHz are shown in Fig. 6, Fig. 7, Fig. 8, Fig. 9 and Fig. 10. The analysis of electromagnetic field distribution indicates that maximal value of the magnetic flux density is about 0.19T. These values are reached in the "V" zone and around the inductor. Two different cross sections illustrate distribution of the magnetic flux density in the system in Fig.6 and Fig.7.

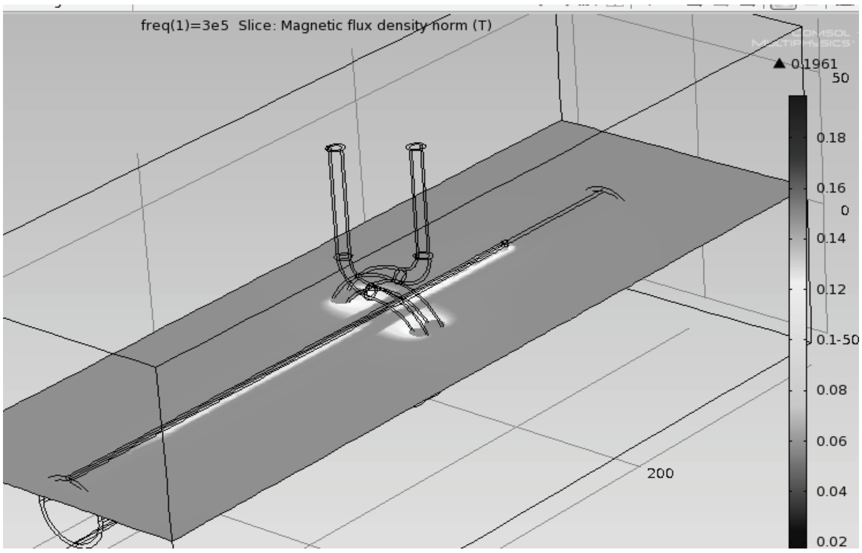

Fig. 6 Distribution of magnetic flux density in the investigated region, *f*= 300 KHz

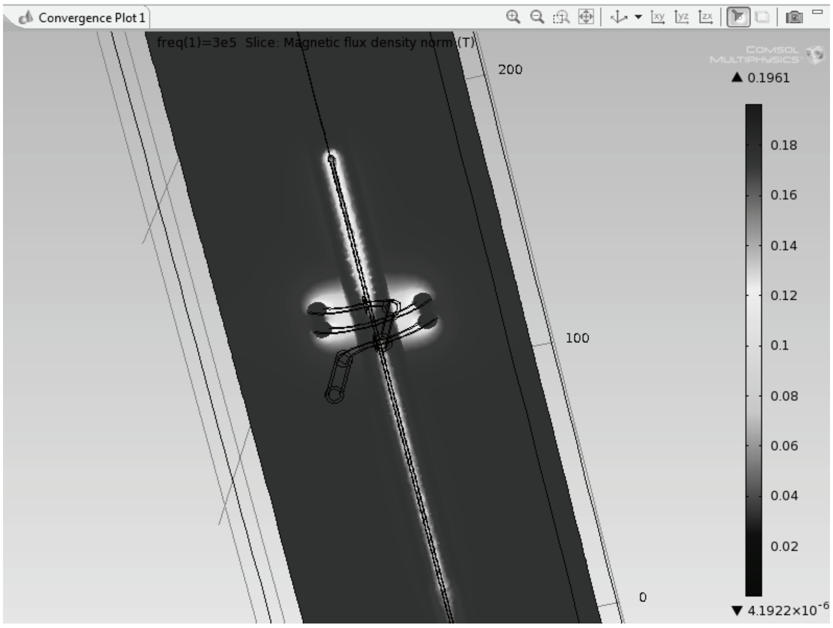

Fig. 7 Distribution of magnetic flux density along the "V" zone, $f = 300$ KHz

The results obtained for current density distribution in the region are shown in Fig.8.

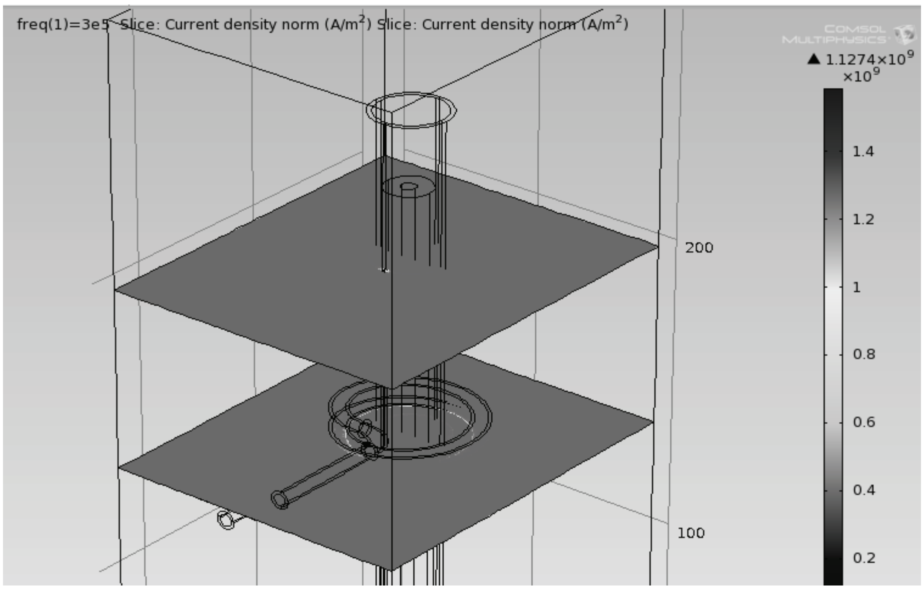

Fig. 8 Current density distribution

Two specifics for the problem cross sections - around "point of closure" and spiral inductors are picking out. The maximal value is 1.13×10^9 A/m2. Current density distribution around the "point of closure" is shown in Fig. 9 and in Fig. 10 around the spiral inductor.

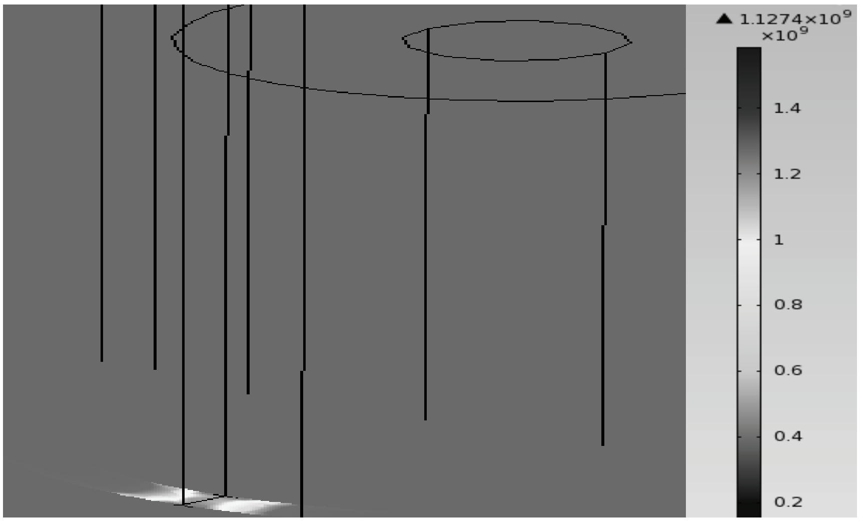

Fig. 9 Current density distribution around "point of closure"

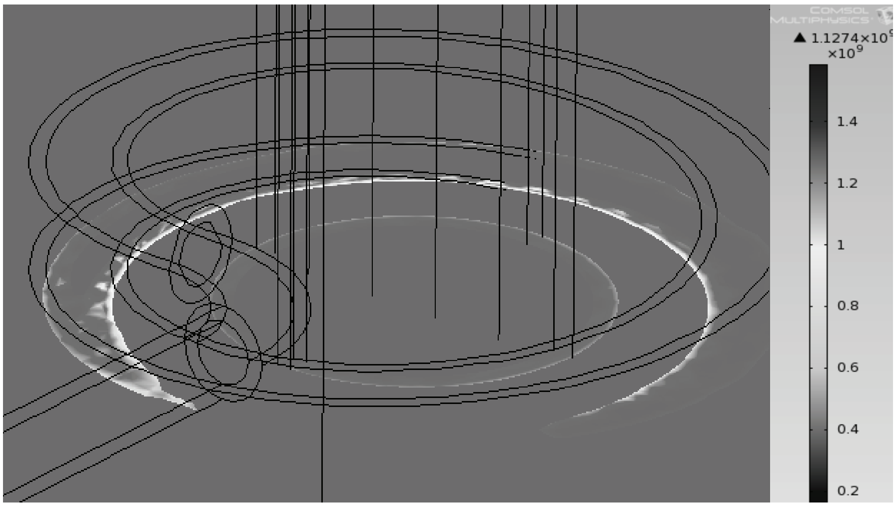

Fig. 10 Current density distribution around the spiral inductor

The results for temperature distribution in the zone of edges contact - around the "point of closure" are shown in Fig.11. In this zone, the temperature value increased to 1400 °C.

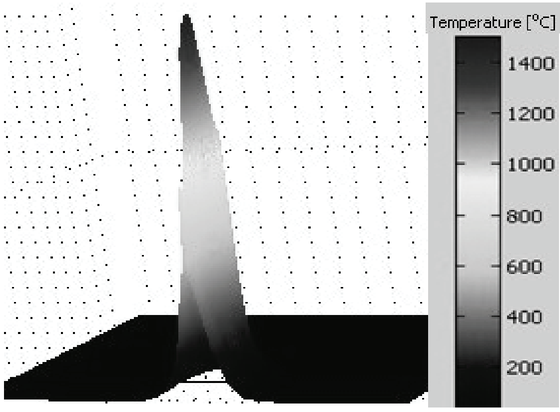

Fig. 11 Temperature distribution in the zone of edges contact - "point of closure"

3. CONCLUSION

Determination of electromagnetic and temperature field distribution of induction heating system used for longitudinal pipe welding has been obtained. The problem was considered as 3D, coupled – time harmonic electromagnetic and transient thermal field. It has been solved using finite element method and COMSOL 4.2 software.

The detailed determination of field distribution in the studied device is a tool for subsequent efficient control, management of the welding process and energy consumption monitoring.

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