



## ELECTROMAGNETIC-THERMAL COUPLED ANALYSIS OF A BRAZING PROCESS BY INDUCTION FURNACE USING FINITE ELEMENT METHOD

Dr. Mohammad Hameed Khazaal<sup>1</sup>, \*Dr. Isam Mahmood Abdulbaqi<sup>2</sup>, Dr. Rabee' Hashim Thejel<sup>3</sup>

- 1) Ministry of Industry and Minerals/ Alkarama Company, Baghdad, Iraq.
- 2) Prof., Faculty of Engineering/ Al-Mustansiriyah University, Baghdad, Iraq.
- 3) Prof., College of Engineering/ University of Basrah, Basrah, Iraq.

**Abstract:** In this research the induction heating (IH) furnace is simulated and analyzed to implement brazing process using two programs to couple the electromagnetic and thermal analyses, Ansoft Maxwell and ANSYS packages. The simulation by Ansoft Maxwell package is used to determine the electromagnetic field distribution inside the work coil and calculate the Ohmic loss for three different excitation currents (100A, 200A and 300A) and different frequencies (50 kHz, 75 kHz and 100 kHz). The simulation by ANSYS package is used to determine the temperature distribution inside the workpiece and the required work coil current and its frequency to raise the temperature of the two Copper workpieces up to 1000°C (below melting point (1083°C)) within two minutes only. The simulation results are well matched with the practical brazing process done in the lab.

**Keywords:** Brazing, Ansoft Maxwell, ANSYS.

### تحليلات المجال الكهرومغناطيسي المقترنة بالتحليلات الحرارية لعمليات اللحام بالنحاس الاصفر بواسطة الفرن الحثي باستخدام طريقة العنصر المحدد

**الخلاصة:** في هذا البحث أستخدم برنامجين هما Ansoft Maxwell و ANSYS في محاكاة وتحليل فرن حثي لتنفيذ عملية لحام بالنحاس الاصفر. تم استخدام برنامج Ansoft Maxwell لمحاكاة الحمل من ناحية حساب المجال المغناطيسي والخسائر الناتجة عنه بسبب المقاومة باستخدام ثلاثة تيارات تغذية مختلفة (100A, 200A, 300A) بثلاثة ترددات مختلفة (50kHz, 75kHz, 100kHz)، فيما تم استخدام برنامج ANSYS لمحاكاة الحمل لغرض تحديد توزيع درجات الحرارة داخل القطعة النحاسية. من خلال عملية الإقران بين البرنامجين تم إيجاد قيمة التيار الأمثل المطلوب وتردده لرفع درجة حرارة قطعتي النحاس الى 1000 درجة مئوية ( اقل من درجة الانصهار البالغة (1038 درجة مئوية)) خلال دقيقتين. إن نتائج التطبيق المختبري لعملية لحام النحاس جاءت متطابقة مع نتائج المحاكاة.

## 1. Introduction

Induction heating (IH) is a technique used for heating the metals (workpiece) by eddy currents induced directly inside the workpiece using a strong and variable magnetic field produced by a high-intensity alternating current through an inductor<sup>[1]</sup>. Brazing is an induction joining application. It requires four components to complete the process, these are: 1) work coil, 2) high frequency inverter, 3) the parts to be joined

\* Corresponding Author [embaki56@yahoo.com](mailto:embaki56@yahoo.com)

(workpieces) and 4) filler material and flux if required. In brazing process, two pieces of metal (workpieces) are held very close together, putting in between a filling material and the joint area is heated to a temperature lower than the melting point of the workpieces, but higher than the melting point of the filling material; a flux is applied to the joint to enhance the flow of the brazed material into the joint by capillary action<sup>[2]</sup>. The filler material is an alloy provides high strength joints that can resist reasonably raised temperatures without failure.

In order to design a power supply (inverter) used for induction heating to braze two Copper workpieces, it is necessary to know the required current and frequency used to rise up the temperature of the Copper workpiece to a specified degree and time. The distribution of the temperature of the workpiece is the approximate form of the distribution of induced currents. Computing the eddy current losses and converting these losses to heat within a certain time is a complex problem. Such problem is called Multiphysics problem because it contains electromagnetic and thermal analysis. Computer simulation is becoming more popular in the study, analysis, and development in numerous fields.

A computer simulation technique is required to get the desired current, frequency and time to rise up the temperature of the workpiece to the required limits. Many numerical techniques are used to analyze the electromagnetic problems. One of these techniques is the finite element method (FEM)<sup>[3]</sup>.

A coupling field analysis is a recombination of simulations between two or more different software programs that connected together to solve a Multiphysics problem such that the output of one program simulation depends on the solutions from another program simulation, then simulations are coupled.

The Multiphysics problems are solved using Ansoft Maxwell program<sup>[4, 5]</sup> by solving Maxwell's equations<sup>[6-8]</sup> within a bounded region and suitable initial conditions to get a guaranteed result.

## 2. Induction Heating Analysis Using Ansoft Maxwell

The IH usually consists of three major parts: high-frequency source (Generator), workpiece, and work coil. The modeled IH system using Ansoft Maxwell program has dimensions listed in Table-1<sup>[9]</sup>.

Table -1- IH load dimensions.

Descriptions	Dimensions (cm)
Height of the induction coil	11.00
Diameter of the induction coil	6.00
Outer diameter of the pipe of the induction coil	0.6
Inner diameter of the pipe of the induction coil	0.4
Height of the workpiece	4.0
Diameter of the workpiece	1.68

The Induction heating work coil is shown in Fig.1. For high power induction heaters, the work coils are composed of hollow tubes to permit a flow of a cooling liquid through it. The resistivities of the conducting materials as well as length and cross-section area are responsible for the Ohmic losses. These losses can be simulated within an Ansoft Maxwell program.

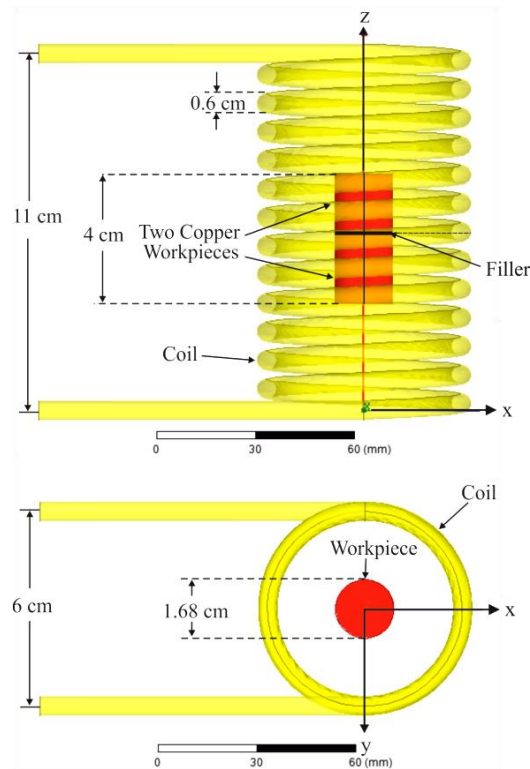


Fig.1 IH coil with workpiece dimensions.

### 3. Thermal Coupling Between Ansoft Maxwell Ih Design And Ansys

Induction heating applications depend on the characteristics of IH power supply (inverter) which depends on its frequency and power rating. The power rating of the inverter proportional directly with inverter output current. The frequency and current of the inverter effect on the uniformity of temperature distribution inside the workpiece and the required heating time for each application.

The induction work coil is operated at high frequency currents and a workpiece which has conductive material property is placed inside the work coil to induce currents and create heat. The kilohertz band (the frequency of excitation current) includes time scale which is measured in parts of a millisecond, while for thermal responses, the time scale is measured in seconds or minutes. Therefore, there are a difficulty and complexity in simulation and analysis of IH in these two regions (milliseconds and minutes) that need a lot of time and huge computer. A.K.M. AL-Shaikhli et al. state that there are three ways to couple the electromagnetic and heat transfer problems<sup>[10]</sup>. They use an indirect coupling method for analyzing induction furnaces with magnetic

workpiece. This method was valid and very effective. Therefore, this problem will be solved using this approach by using two programs Ansoft Maxwell and ANSYS.

The Ansoft Maxwell program is used to simulate the induction heating process with the kilohertz region in terms of field distributions and Ohmic losses. While the ANSYS program will be used for thermal simulation to convert the Ohmic loss to heat with respect to time.

This process helps to meet efficiency and high accuracy AC simulation of the electromagnetic system with updated temperatures for transient and steady state thermal analysis.

Coupling of Ansoft Maxwell 3D design with ANSYS v.14.5 is supported via the Workbench interface. There are many types of coupling with Workbench interface. One of these types is thermal feedback, which is supported for Maxwell 3D eddy current solver type.

The flow chart of coupling Ansoft Maxwell 3D IH design with ANSYS v.14.5 using ANSYS Workbench interface is shown in Fig.2. The ANSYS thermal solver is used for transient thermal analysis. The Ohmic losses from Ansoft Maxwell program are mapped directly to the transient thermal solver.

The thermal simulation provides a solution for the heat flow response based on the Ohmic loss and boundary conditions.

### **3.1 Three Dimension (3D) Electromagnetic Fields Analysis Of IH**

The realistic 3D model of IH furnace using Ansoft Maxwell program is shown in Fig.3. This figure is too complex for Maxwell to mesh and solve within a reasonable time, therefore a simplified IH model is made with rectangular helix coil as shown in Fig.4.

The eddy current solver is used in Ansoft Maxwell for the AC simulation in the kHz band (75 kHz excitation current frequency) to resolve skin depths and Ohmic losses within the workpiece.

The electromagnetic property of the workpiece in Ansoft Maxwell program is defined as a function of temperature, for which the temperature can be mapped directly after that to ANSYS thermal tools.

To set temperature dependent material properties of the workpiece, the conductivity of the Copper workpiece is set as a function of temperature according to the following formula:

$$\text{If } (Temp > 1000, C_m = 0.2), \text{ But if } (Temp < 0, C_m = 1), \text{ otherwise, } \\ (C_m = 1 / (1 + 0.004 * (Temp - 22))).$$

Since  $Temp$  : is the temperature of the workpiece at a certain point

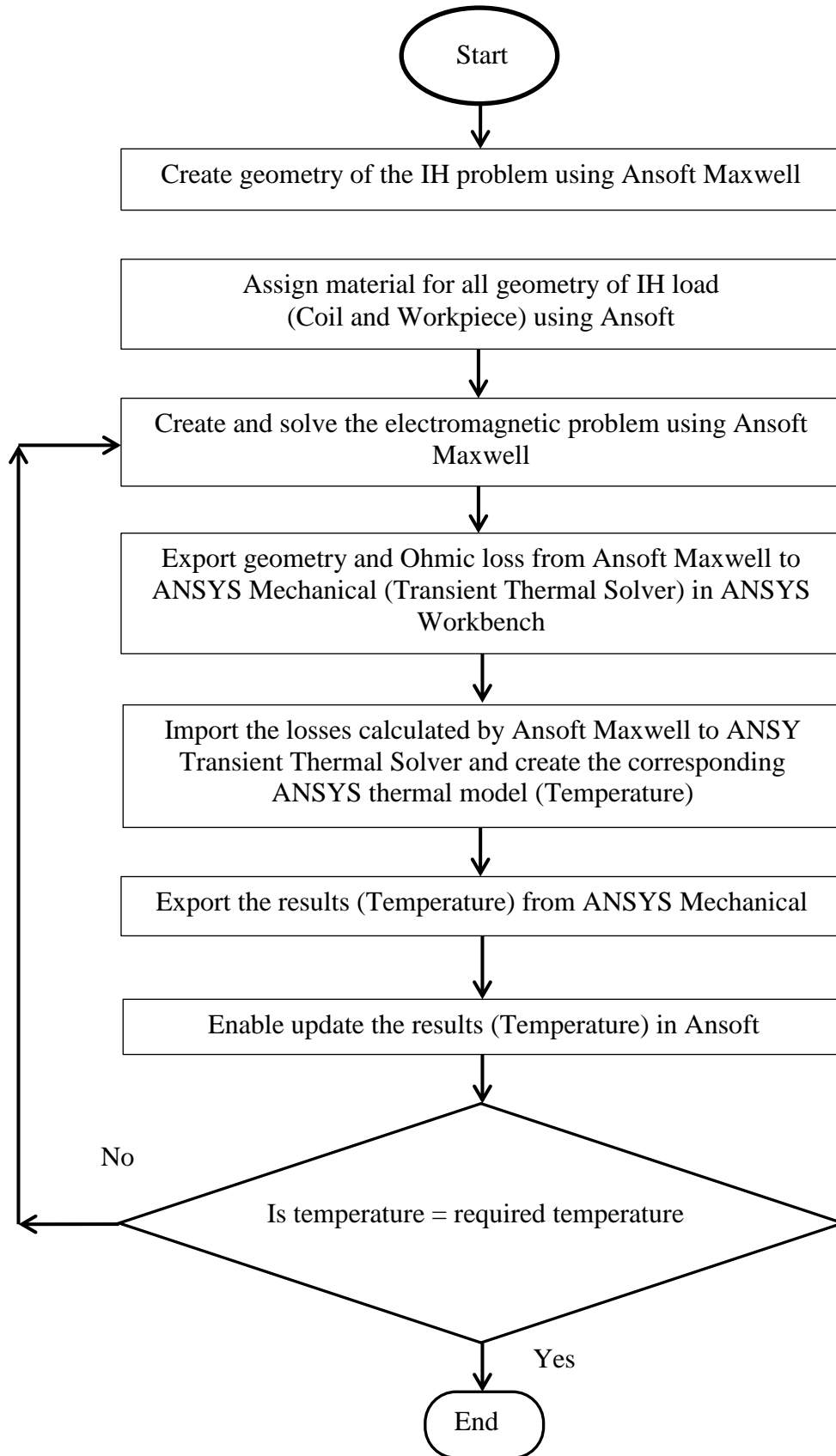


Fig.2 Flow chart of coupling Ansoft Maxwell 3D IH design with ANSYS using the ANSYS Workbench interface

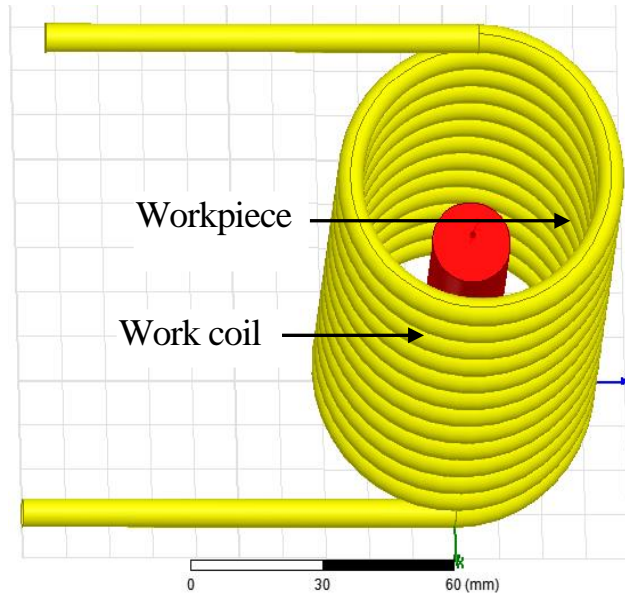


Fig.3 Real 3D simulation model for IH with cylindrical Copper hollow pipe

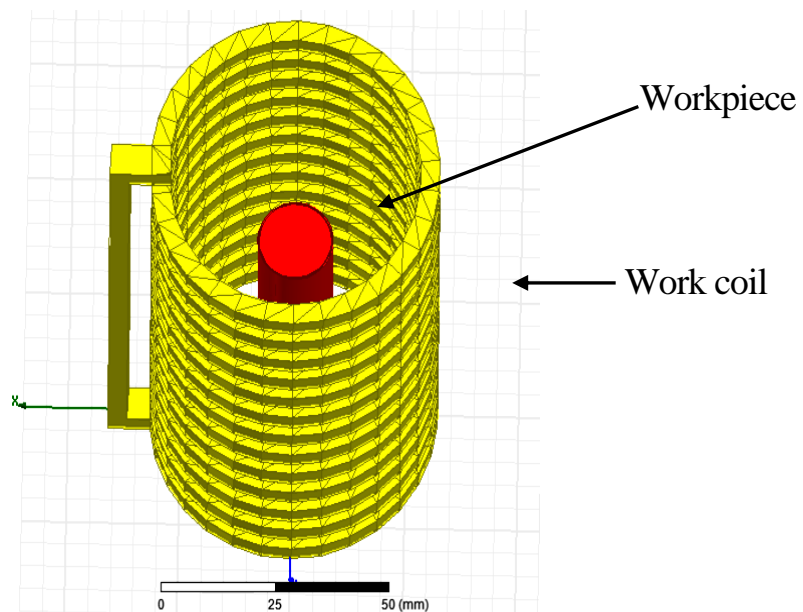


Fig.4 Simplified 3D simulation model for IH with rectangular helix coil.

At the starting of heating process, the temperature of the Copper workpiece is considered to be at 22°C. After solving the eddy current, data is transferred to the Ohmic loss in Ansoft Maxwell program after that the Ohmic loss will be transferred to temperature in ANSYS Mechanical transient thermal analysis.

Then temperature data is transferred back to Ansoft Maxwell. The new solution is recalculated with new temperatures applied through ANSYS Mechanical.

### 3.2 Meshing Operation In 3D

In 3D, Ansoft Maxwell program needs to mesh operation for efficient and accurate solution of Ohmic losses due to induced currents in the workpiece. Solving an electromagnetic field problem is always based on solving Maxwell's equations. The desired level of the accuracy of the solution depends on the size of each of the individual elements (tetrahedral).

The solutions based on meshes using thousands of elements are more accurate than solutions based on coarse meshes using relatively few elements. This requires a significant amount of computing power and memory.

Using fine mesh is a tradeoff between the accuracy of the solution and not confusing the available computer memory and processing power.

To assist the meshing, the Copper workpiece was created of multi layers depending on the skin depth. Because of this effect, 86% of the current density is concentrated at the outer surface of the workpiece<sup>[1, 2]</sup>. This depth is well known with the penetration depth ( $\delta$ ). The penetration depth ( $\delta$ ) depends on the following complicated parameters:

- 1- The source current frequency.
- 2- The resistivity of the workpiece.
- 3- The permeability of the workpiece.

The thickness ( $\delta$ ) is given by<sup>[1, 2]</sup>:

$$\delta = 503 \sqrt{\frac{\rho_w}{\mu_r \times f}} \quad (1)$$

Where,  $\delta$  is the penetration depth, in m,  $\rho_w$  is the resistivity of the workpiece, in  $\Omega\text{m}$ ,  $\mu_r$  is the relative permeability of the workpiece (unitless) and  $f$  is the frequency of the AC field of the work coil, in Hz.

The skin depth of 0.24 is solved using Eq. (1) at a frequency 75 kHz. To resolve the skin depth effectively without the need of too many elements, the surface of the workpiece is created at a depth of 0.125. This will ensure that there are at least two elements in skin region. Figure 5 shows how to create three layers while Fig.6 shows the workpiece after meshing operations.

Ansoft Maxwell program simulation tools are linked within the ANSYS Workbench interface by definition of the project schematic as shown in Fig.7. The geometry and solutions are transferred through this link. The geometry is shared in such a way that only the necessary pieces are used by suppressing the induction coil in the thermal simulations, but all the geometry is transferred and updated.

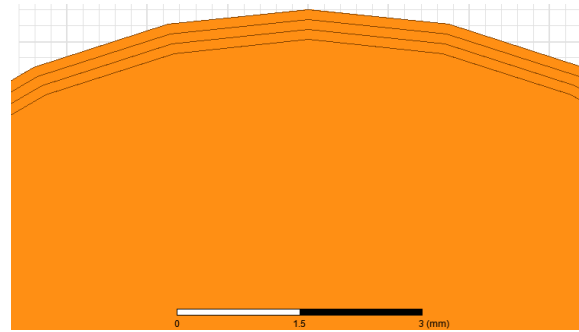
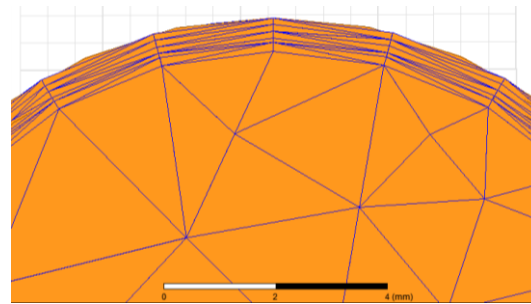
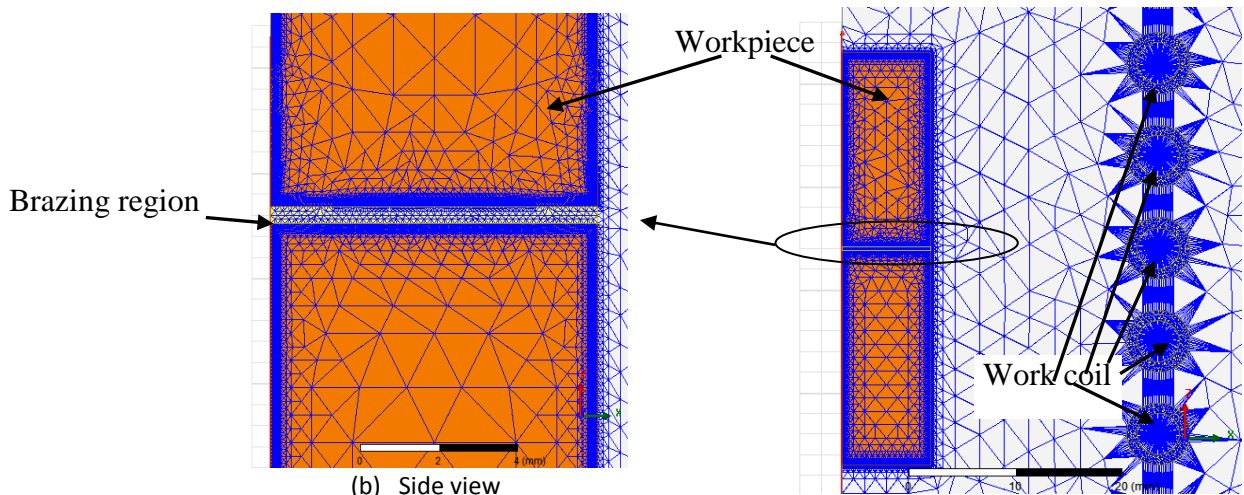


Fig.5 Workpiece is built from three layers to assist meshing operation.



(a) Top view



(b) Side view

Fig.6 Workpiece after meshing operations

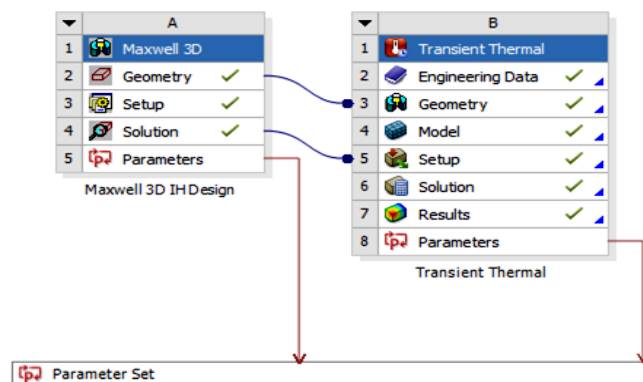


Fig.7 Coupling between Ansoft Maxwell 3D IH design and transient thermal using ANSYS Workbench interface



#### 4. Results Of ANSYS Workbench Interface

The ANSYS Workbench interface enables coupling of solution data between Ansoft Maxwell programs and ANSYS with highly accurate simulations. The thermal problem is solved step by step using a time step of 1s, 10s, 20s up to when the workpiece reaches the desired temperature 1000°C. The IH furnace is tested for three different peak excitation current (100A, 200A and 300A). The distribution temperatures on the workpiece are shown in Fig.8. One can note that the temperature distribution is not homogeneous due to non-homogeneous current density. To measure the temperature at the middle of the workpiece (brazing region), a line segment in the center of the workpiece is used (line-X3 from point (-8.4, 0, 54) to point (8.4, 0, 54)).

Figures 9-11 show the temperature at the middle of the workpiece along the line-X3 for three different peak excitation current through one second using 75kHz (after fitting). These figures show that the temperature distributions are non-uniform, but the difference in temperature at the surface and the core of the workpiece are not large due to the high thermal conductivity of Copper material.

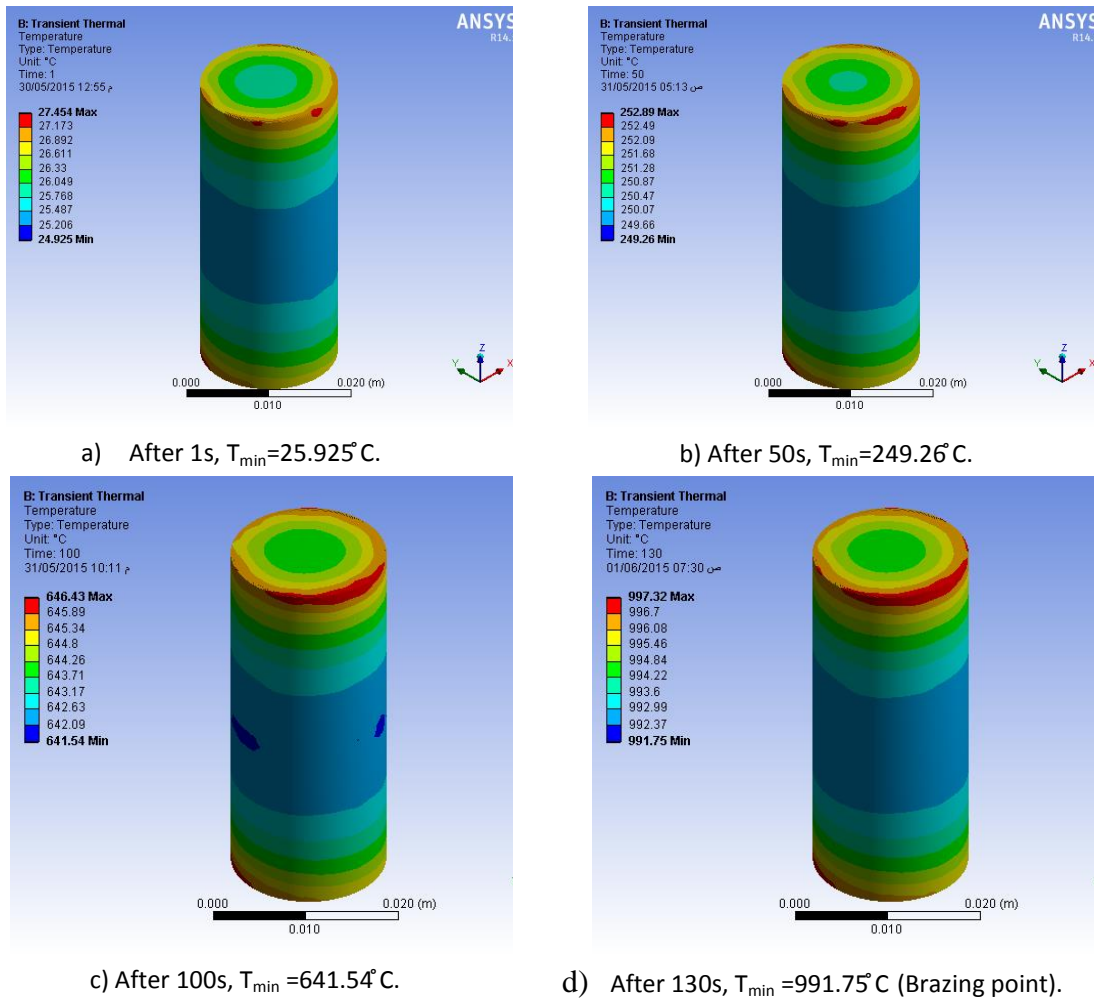


Fig.8 Temperature distribution at the workpiece for four different times and 300A peak excitation current with 75 kHz

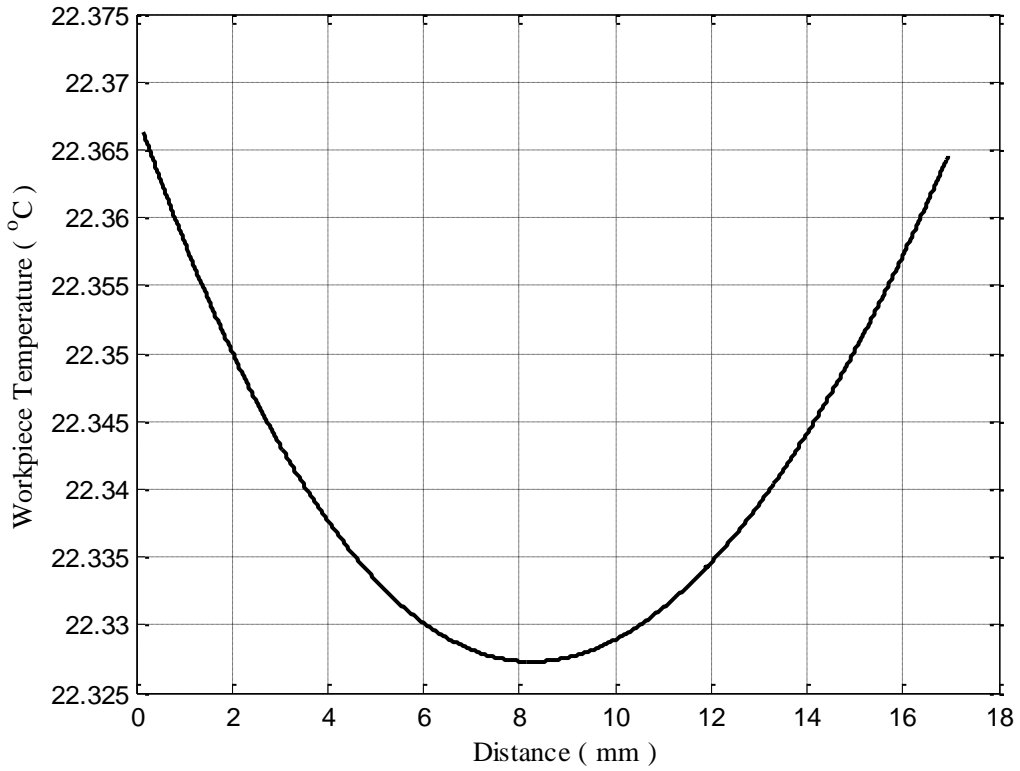


Fig.9 Temperature inside the workpiece along the line-X3 for 100A peak excitation current with 75 kHz after one second

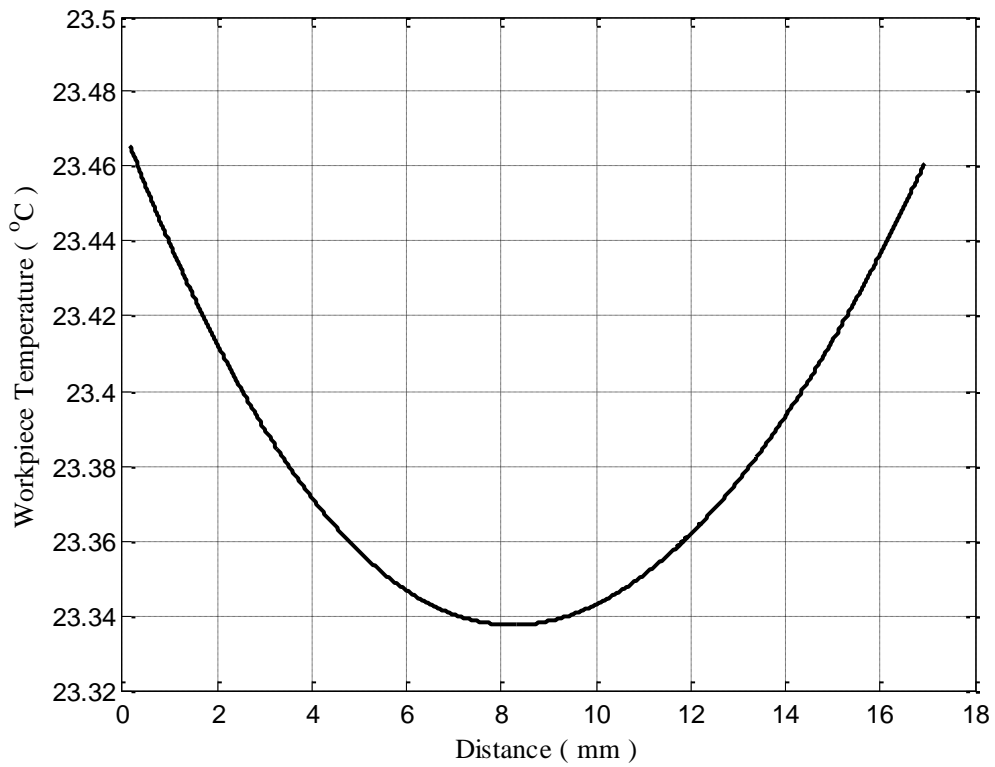


Fig.10 Temperature inside the workpiece along the line-X3 for 200A peak excitation current with 75 kHz after one second

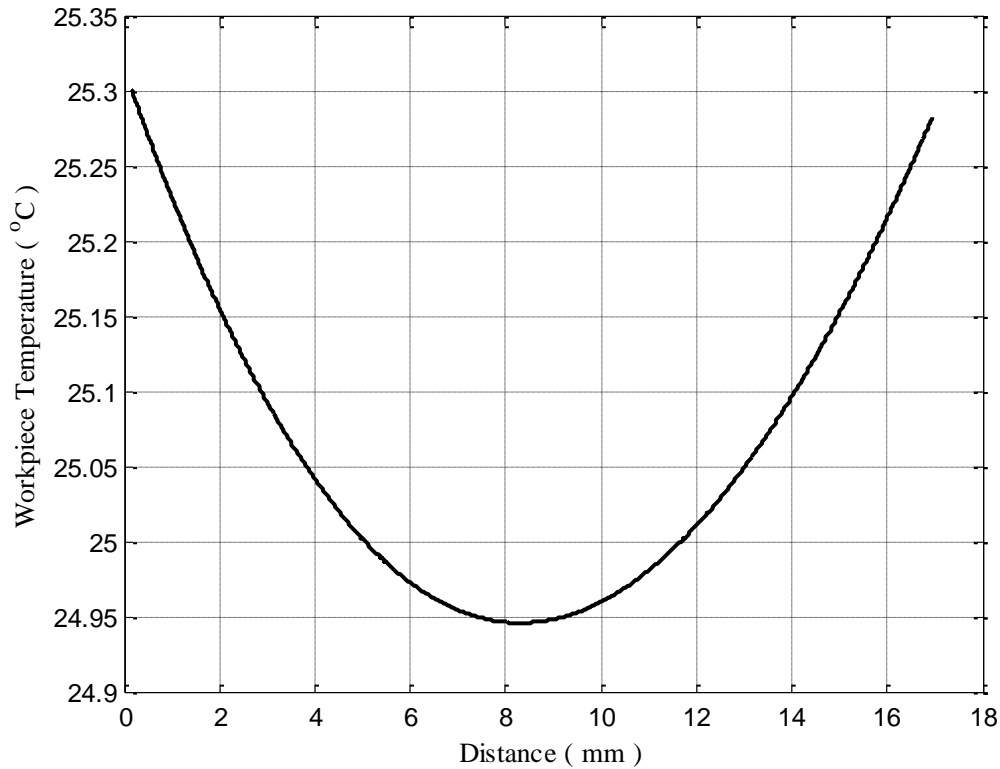


Fig.11. The temperature inside the workpiece along the line-X3 for 300A peak excitation current with (75 kHz) after one second.

Figure 12 shows the temperature rising at the workpiece versus time for three different excitation currents (100A, 200A and 300A) at 75 kHz. It is clear that using 100A peak excitation current is not suitable to raise the temperature of the workpiece up to 1000°C.

While using 200A peak excitation current, the workpiece requires greater than 300s to raise the temperature up to 1000°C, which is a very long time. The reasonable time to raise the temperature of the workpiece up to 1000°C is by using 300A peak excitation current which needs only 120s.

Figure 13 shows the temperature rise at the workpiece versus time for three different frequencies (50 kHz, 75 kHz and 100 kHz) using 300A peak excitation current. This figure states that in spite of the workpiece is non-magnetic material, the workpiece temperature increases as frequency increases.

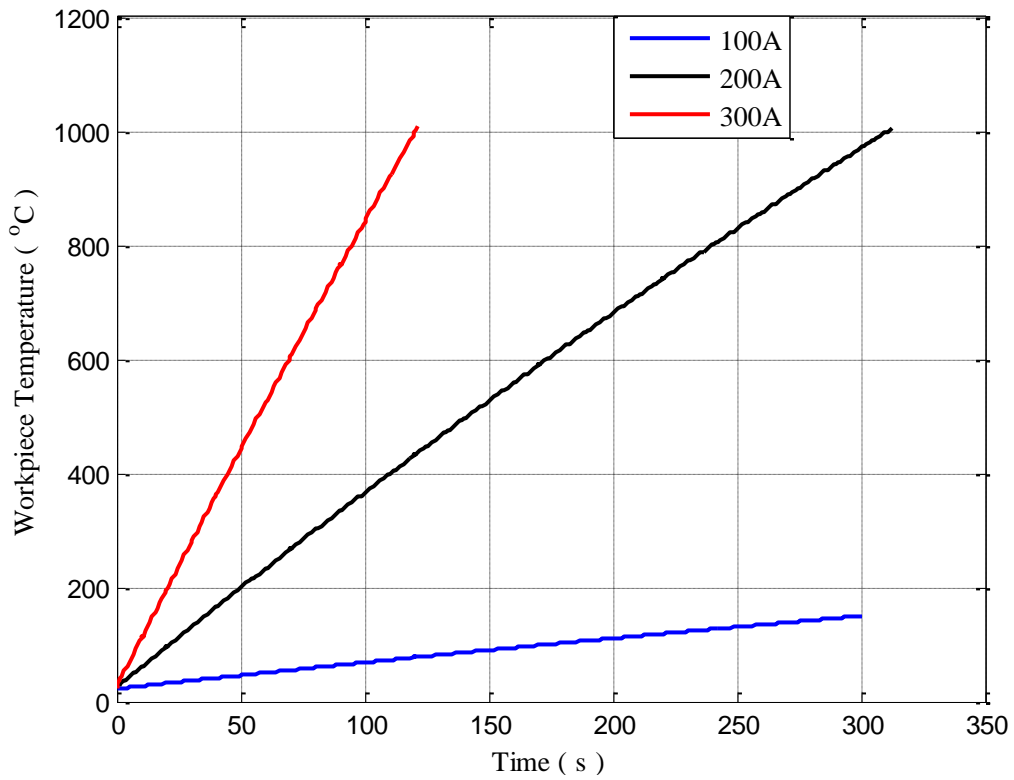


Fig.12 Temperature rise at the workpiece versus time for three different excitation currents (100A, 200A and 300A) at 75 kHz.

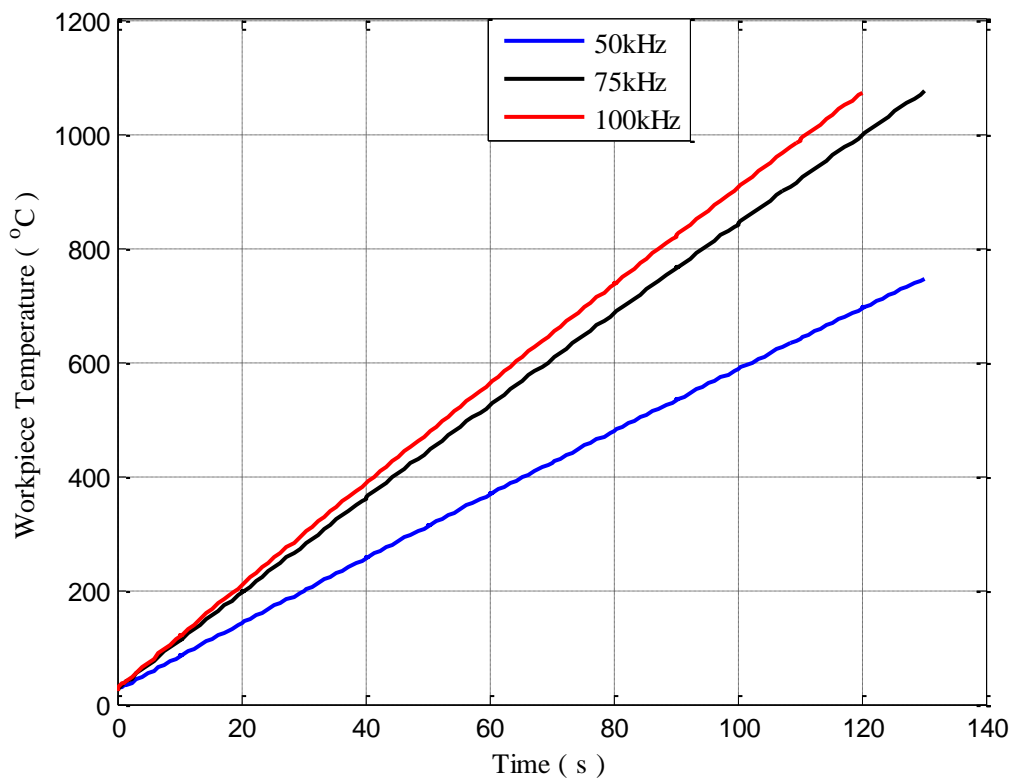


Fig.13 Temperature rise at the workpiece versus time for three different frequencies using 300A peak excitation current.

## 5. Conclusions

The analysis shows that the temperature inside the workpiece is not uniform. The main reason for the temperature differences in the core of a cylindrical workpiece is the skin effect. This effect depends upon the metal properties and the frequency of excitation current. Where the current is constrained at the surface of the workpiece and decreases to zero toward the core.

The IH inverter requires high current to increase the workpiece temperature to a limit less than 1083°C (melting point of the Copper workpiece) to braze two pieces of Copper. Therefore, a 300A peak excitation current with 75 kHz must be considered in designing the IH inverter. This will approximately take reasonable time (120s) to raise the temperature of the workpiece up to 1000°C for melting the filler.

## 6. References

1. S. Zinn and S. L. Semiatin, "Elements of Induction Heating: Design, Control, and Applications", ASM International and (EPRI) Electronic Power Research Institute, 1988.
2. Valery Rudnev, Don Loveless and Raymond Cook, "Handbook of Induction Heating", Marcel Dekker, Inc. New York, USA, 2003.
3. Isam Mahmood Abdulbaqi, "Analysis of Induction Furnace using FEM Electromagnetic-Thermal Coupled Approach", Ph.D. Thesis, Al-Rasheed College of Engineering and Science, January 2006.
4. Mark Christini, "Coupled Electromagnetic and Thermal Analysis of Ferrite Core Electronic Planar Transformer", ANSYS, Inc., 2012.
5. Vladimir L. Lanin, Ivan I. Sergachou, Vitaly T. Khotskin, "BGA Solder Balls Formation by Induction Heating", International Journal of Scientific Research on Knowledge, 2 (1), pp. 22-27, 2014.
6. Daniel Fleisch, "A Student's Guide to Maxwell's Equations", Cambridge University Press, pp. 57, pp. 101, pp. 29, pp. 53, 2008.
7. James J. Allen, "Micro Electro Mechanical System Design", Taylor & Francis Group, pp. 143, 2005.
8. Graham Woan, "The Cambridge Handbook of Physics Formulas", Cambridge University PRESS, pp. 135-140, 2000.
9. Mohammad H. Khazaal, Isam M. Abdulbaqi, Rabee H. Thejel, " Modeling, Design and Analysis of an Induction Heating Coil for Brazing Process Using FEM", Al-Sadeq International Conference on Multidisciplinary in IT and Communication Science and Applications (AIC-MITCSA) – IRAQ (9-10) May 2016.
10. A.K.M. AL-Shaikhli, Hanan A. R. Akkar and Mohammed Moanes Ezzaldeen Ali, "FEM-Simulation of Single and Multi Layered Induction Heating Systems", Eng. & Tech. Journal, Vol.27, No.13, 2009.