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Induction brazing of thin-walled pipes from AISI 304 steel using copper-based solder

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Abstract. Pipes made of austenitic stainless steels are widely used in automotive industry. They are connected together or to other components by different joining technologies. The quality of produced joints is often critically important for passenger safety assurance. The joint lifetime is significantly influenced by their corrosion behaviour. The paper deals with induction brazing of thin-walled pipes from austenitic stainless steel using high corrosion-resistant Cu-Ni solder. To design appropriate parameters of induction heating, the effective method of numerical simulation of induction heating using the software ANSYS was applied. Simulation model for evaluation of electro-magnetic and temperature fields in the process of induction brazing of exhaust pipes from AISI 304 steel using copper-based solder was developed and verified by experimental temperature measurement during pipe induction heating. Based on performed numerical experiments and results of numerical simulations, appropriate parameters and operating diagram for the induction brazing of thin-walled pipes of the AISI 304 steel using copper-based solder were suggested.

1. Introduction

Induction brazing is used in various applications in the automotive, aviation, aerospace, electro-technical or medical industries. A number of materials can be joined using this method including aluminum, brass, copper, copper alloys, iron, steels or stainless steels. Induction brazing is very suitable also for production of dissimilar joints when materials to be joined have quite different material properties [1-3].

Induction brazing provides many benefits comparing with other joining technologies. Induction heating represents a fast, controllable, reproducible and clean method of material heating. Moreover, it is very efficient, energy saving, safe, adaptable for automated processes, and thus compatible with the growing demands of mass production [4-6]. Since the material is heated rapidly in a small localized area, the rest of the components being joined is thermally unaffected what is advantageous for eliminating distortion, stresses, undesirable metallurgical changes, surface corrosion, and oxidation of the components [9-13].

The oxidation and corrosion is one of key problems of butt weld joints in the exhaust system of cars, prepared by fusion welding technologies [14-16]. In some cases, the replacement of butt weld joints by lap brazed joints of exhaust pipes can provide an outstanding solution, mainly when joining the pipes of austenitic stainless steels using proper types of corrosion resistant solders. According to accomplished research [17], the copper-based solder containing from 3 to 10 wt.% of Ni can be a promising choice.
The main aim of this paper is to design the parameters of induction heating for induction brazing of thin-walled pipes from AISI 304 steel by copper-based solder using numerical simulation of the joining process in the ANSYS program code. For this purpose, methodology of numerical simulation of a pipe induction heating was suggested and verified by experiment. Afterwards, simulation model for induction brazing of pipes from AISI 304 steel was developed and applied to study the electromagnetic and temperature fields in brazed pipes and solder during the process.

2. Problem description

Two pipes made of AISI 304 steel with the outer diameters of \( D_1 = 31.8 \text{ mm} \) and \( D_2 = 33.6 \text{ mm} \), respectively and the same wall thickness of 0.9 mm should be brazed by B-Cu97Ni(B) solder using internal induction heating, i.e. with inductor coil placed inside tubes being brazed. The solder is supplied in the form of rings prepared from a wire of 1 mm in diameter. As inductor, a copper water cooled induction coil with two turns is suggested. The loop diameter is 28 mm, wire outer diameter is 4 mm and the wall thickness is 1 mm. The allowed maximum duration of induction heating applying the frequency of 20 kHz is 12 seconds.

Chemical composition of AISI 304 austenitic stainless steel is given in Table 1. The copper-based EN 1044 B-Cu97Ni(B) solder with the content of 87 wt.% of copper and 0.02 – 0.05 wt.% of boron is used for the high-temperature brazing of alloyed and unalloyed steel as well as hard metals, wolfram, molybdenum and tantalum [18-19]. The addition of nickel ensures a higher tensile strength compared to pure copper and better wetting properties of the solder.

| Element | C   | Cr  | Ni  | Mn  | Si   | P     | S    | Fe    |
|---------|-----|-----|-----|-----|------|-------|------|-------|
| wt. [%] | max. 0.08 | 18 - 20 | 8 - 10.5 | max. 2.0 | max. 1.0 | 0.045 | 0.03 | bal.  |

The solidus and liquidus temperatures of the AISI 304 steel are \( T_S = 1360 \text{ °C} \) and \( T_L = 1440 \text{ °C} \), respectively. The melting point of the applied B-Cu97Ni(B) solder is lower, the solidus temperature \( T_S = 1080 \text{ °C} \) and the liquidus temperature \( T_L = 1105 \text{ °C} \). The solder working temperature is from the range of 1115 °C to 1125 °C. The main issue is if the required solder working temperature may be achieved using induction heating without melting thin-walled pipes from AISI 304 steel, i.e. if the pipe temperature does not exceed the stainless steel solidus temperature of 1360 °C.

3. Mathematical model

In induction heating processes, an alternating voltage applied to an induction coil terminals produces an alternating electrical current flow in the coil circuit, generating a time-variable magnetic field in the coil surroundings. The workpiece placed into the magnetic field, eddy currents of the same frequency and the opposite direction are induced and the workpiece material is heated up due to resistive and hysteresis losses. The induced eddy currents and consequently the generated heat are not uniformly distributed throughout the workpiece. Approximately 63 % of induced current and 86 % of generated heat is concentrated in the surface layer of the heated workpiece called penetration or skin depth. At the distance of one penetration depth from the workpiece surface toward its core, the current density \( j \) decreases exponentially from the maximum value of \( j_0 \) at the surface to the value \( j = j_0/e \) [6]. The penetration (skin) depth \( \delta \) depends on electrical and magnetic properties of material heated and mainly on the frequency of current in the inductor coil according to the relationship [6]

\[
\delta = \sqrt{\pi \rho_{cl} \mu_0 \mu_r f}
\]

where \( \rho_{cl} \) is the electrical resistivity of a workpiece material, \( \mu_0 \) is the permeability of vacuum \((\mu_0 = 4\pi \times 10^{-7} \text{ H.m}^{-1})\), \( \mu_r \) is the relative permeability and \( f \) is the frequency of the source current.
Numerical simulation of induction heating processes requires to solve coupled electro-magnetic and transient thermal problem because of temperature dependent electrical and magnetic material properties, time, frequency and material dependent loading. The material properties in both, electro-magnetic and thermal analyses, vary very strongly with temperature. In addition, the boundary conditions may be temperature and/or time dependent as well.

3.1. Governing equations for the electro-magnetic field

The governing equations for the electro-magnetic analysis can be derived from the classical Maxwell’s equations [6, 21]

\[ \text{rot } H = j + \frac{\partial D}{\partial t} \quad (2) \]
\[ \text{rot } E = -\frac{\partial B}{\partial t} \quad (3) \]
\[ \text{div } D = \rho_c \quad (4) \]
\[ \text{div } B = 0 \quad (5) \]

where \( D \) is the vector of electric flux density, \( E \) is the electric field intensity, \( B \) is the magnetic flux density, \( H \) is the magnetic field intensity, \( \rho_c \) is the free charge density, \( j \) the current density and \( t \) is the time.

The field vectors \( D \) and \( E \) and also \( B \) and \( H \) are related by material properties through the functions referred as the constitutive equations

\[ D = \varepsilon E \quad (6) \]
\[ B = \mu H \quad (7) \]
\[ j = \sigma E \quad (8) \]

in which \( \sigma \) is the electrical conductivity, \( \varepsilon \) is the permittivity given by the product of the vacuum permittivity \( \varepsilon_0 \) and the relative permittivity \( \varepsilon_r (\varepsilon = \varepsilon_0 \varepsilon_r) \) and \( \mu \) is the magnetic permeability \( (\mu = \mu_0 \mu_r) \).

Since \( B \) satisfies a zero divergence condition, \( \text{div } B = 0 \), the magnetic vector potential \( A \) can be defined by the relationship

\[ B = \text{rot } A \quad (9) \]

Then the Maxwell’s equations (2)-(5) lead to following expressions of the diffusion equation for electrically conductive (10) and non-conductive materials (11), respectively

\[ \Delta A - \varepsilon \frac{\partial^2 A}{\partial t^2} - \mu \sigma \frac{\partial A}{\partial t} = 0 \quad (10) \]
\[ \Delta A - \mu \varepsilon \frac{\partial^2 A}{\partial t^2} = 0 \quad (11) \]

For time harmonic electro-magnetic fields, the current density and magnetic vector potential vary with time according to the relationships

\[ j = j_0 e^{i\omega t} \quad (12) \]
\[ A = A_0 e^{i\omega t} \quad (13) \]

where \( \omega \) is the angular frequency.

For axisymmetric condition, the magnetic field intensity \( H \) acts in the axial direction, the magnetic vector potential \( A \) and eddy current have only one component in peripheral direction.
Using Eqs. (12) - (13) and axisymmetric conditions, the Eqs. (10) and (11) can be rewritten to the form

\[ \frac{\partial^2 A}{\partial r^2} + \frac{1}{r} \frac{\partial A}{\partial r} - \omega \sigma \mu A = 0 \]  
\[ \frac{\partial^2 A}{\partial z^2} + \frac{1}{r} \frac{\partial A}{\partial r} + \omega^2 \rho \mu A = 0 \]  

### 3.2. Governing equations for the temperature field

The temperature fields are governed by the Fourier-Kirchhoff’s heat diffusion equation \[22\] representing the energy conservation law for heat conduction which can be written in the form

\[ \rho c_p \frac{\partial T}{\partial t} = \frac{\partial}{\partial x} \left[ \lambda_x(T) \frac{\partial T}{\partial x} \right] + \frac{\partial}{\partial y} \left[ \lambda_y(T) \frac{\partial T}{\partial y} \right] + \frac{\partial}{\partial z} \left[ \lambda_z(T) \frac{\partial T}{\partial z} \right] + q_v \]  

where \( T \) is the temperature, \( \rho \) is the density, \( c_p \) is the specific heat, \( \lambda_x \), \( \lambda_y \) and \( \lambda_z \) are the thermal conductivities in \( x \), \( y \) and \( z \) directions, respectively and \( q_v \) is the volumetric heat source density, i.e. the heat generated per unit time in a unit volume. In induction heating, this term depends on the Joule heat generation in a heated material due to the eddy currents.

For the heat conduction in an isotropic material \( (\lambda=\lambda_x=\lambda_y=\lambda_z) \) at axisymmetric conditions, Eq. (16) can be rewritten as follows

\[ \rho c_p \frac{\partial T}{\partial t} = \left( \frac{\partial^2 T}{\partial r^2} + \frac{1}{r} \frac{\partial T}{\partial r} + \frac{\partial^2 T}{\partial z^2} \right) + q_v \]  

Usually, three kinds of boundary conditions for heat diffusion equation (16) are used. The boundary condition of the first kind is determined by the defined surface temperature as a function of position, \( r \), and time, \( t \)

\[ T = f_1(r, t) \] at the surface \( S_1 \)

The boundary condition of the second kind expresses the surface conductive heat flux as a function of position and time

\[ q = -\lambda \frac{\partial T}{\partial n} = f_2(r, t) \] \( S_2 \)

where \( \partial T / \partial n \) denotes differentiation along the outward-drawn normal \( n \) at the boundary surface \( S_2 \). This condition is applied as well as at the adiabatic (insulated) surfaces or as a symmetry condition when the surface heat flux is zero.

The most frequently, a boundary condition of the third kind is used. According to this condition, the surface conduction heat flux is equal to the convection heat flux

\[ -\lambda \frac{\partial T}{\partial n} = h (T_w - T_f) \] \( S_3 \)

where \( h \) is the heat transfer coefficient, \( T_w \) is the workpiece surface temperature and \( T_f \) is the fluid (surrounding) temperature. Usually, the heat transfer coefficient includes the influence of convection and radiation, so it is given by the sum of convection heat transfer coefficient \( h_c \) and radiation heat transfer coefficient \( h_r \)

\[ h = h_c + h_r = h_c + \varepsilon_0 \sigma_0 (T_w^4 - T_f^4) \] \( T_w - T_f \)

where \( \varepsilon_0 \) is the emissivity and \( \sigma_0 \) is the Stefan-Boltzmann constant.
3.3. Solution procedure

To solve the problem of induction heating for the process of induction brazing of thin-walled pipes, the sequential field-coupling method \cite{21, 23} provided by the ANSYS program code was applied. A special user subroutine was developed to control the field coupling.

According to Figure 1, the harmonic electro-magnetic analysis was performed in the first step to compute the Joule heat generated owing to the eddy currents flowing in a heated workpiece at the initial workpiece temperature. In the next step, the computed Joule heat was applied as a loading for the transient thermal analysis in order to predict the time-dependent temperature distribution. As the temperature field influences the electro-magnetic field by means of the temperature dependent electro-magnetic properties, the computed temperatures were entered as a load for the electro-magnetic analysis. The procedure was repeated to the final time of induction heating.

![Figure 1. Scheme of solution procedure using the sequential field coupling in ANSYS code.](image)

4. Verification experiment

To verify the described methodology for numerical simulation of induction heating processes, a simple experiment was carried out. The temperatures measured during verification experiment were compared with the results of performed numerical simulation.

4.1. Description of verification experiment

A pipe with the outer diameter of 31.8 mm, the wall thickness of 0.9 mm and the length of 150 mm made of AISI 304 steel (Figure 2) was heated using the two-turn induction copper coil with the same dimensions as inductor proposed for induction brazing, i.e. with the loop diameter of 28 mm, the wire outer diameter of 4 mm and the wall thickness of 1 mm. The position of the induction coil is shown in Figure 3. The parameters of induction heating including applied frequency $f$, current density in induction coil $j$, and heating time $t_i$ are given in Table 2. During experiments, the temperature was measured by two thermocouples located at the outer pipe surface at the distances of $Y_1$ and $Y_2$ according to Figure 2 and Table 2.
Table 2. Parameters of induction heating during verification experiment.

| Experiment No. | $j_s$ [A.m$^{-2}$] | $f$ [kHz] | $t_i$ [s] | $T_f$ [$^\circ$C] | $Y_1$ [mm] | $Y_2$ [mm] |
|---------------|------------------|-----------|-----------|------------------|------------|------------|
| 1             | 1.86x10$^8$      | 20        | 12        | 24.0             | 37.5       | 45.5       |
| 2             | 1.78x10$^8$      | 20        | 14.5      | 25.5             | 36.5       | 44.0       |

Figure 2. Dimensions of a heated pipe, inductor location and thermocouple positions during verification experiment.

4.2. Simulation model of experimental induction heating

In compliance with Figure 2, geometrical model for numerical simulation of induction heating of a pipe of AISI 304 steel was prepared. The model for electro-magnetic analysis consists of a heated pipe, water cooled induction coil and surrounding air (Figure 3a). In thermal analysis, only the axisymmetric model of a pipe was taken into account. The finite element model (Figure 3b) was generated using the PLANE13 element with the axisymmetric element behaviour option considering the skin depth. The mesh density was higher near the heated pipe surface as well as in the whole computation domain near the induction coil. A detail of the finite element mesh in the region around the inductor is shown in Figure 3c. In the thermal analysis, the element type was switched to PLANE55.

Figure 3. Geometrical model (a) and finite element model (b) for experimental induction heating with a detail of generated mesh near the induction coil (c).
Thermal, electrical and magnetic properties of the AISI 304 austenitic steel in the dependence on temperature were computed using the JMatPro software [24] on the base of chemical composition of the steel presented in Table 1.

Computed values of the thermal conductivity, density, specific heat and electrical resistivity of the AISI 304 steel vs. temperature are plotted in Figure 4. The relative permeability and emissivity of the austenitic stainless steel were considered as constant with the values of 1.05 and 0.53, respectively. The solidus and liquidus temperatures of this steel were computed to be 1360 °C and 1440 °C, respectively. In the process of induction brazing, the heated pipe of AISI 304 steel must not be melted.

As the copper induction coil is water cooled, the material properties of copper for electro-magnetic analysis were entered only for the room temperature with the values: electrical resistivity $\rho_{el} = 1.68 \times 10^{-8} \, \Omega \cdot m$ and relative permeability $\mu_r = 1$. Water and dry air are similarly as copper non-magnetic, so their relative permeability is also equal to one.

![Figure 4](image1.png)

**Figure 4.** Thermal and electrical properties of the AISI 304 steel in the dependence on temperature.

For electro-magnetic axisymmetric harmonic analysis, the model was loaded by current density in induction coil and current frequency as summarized in Table 2. Moreover, the pipe initial temperature of 20 °C was up-dated based on the results of thermal analysis.

In thermal analysis, the Joule heat distribution computed using electro-magnetic analysis was considered as a loading in the form of the volumetric heat source density. The initial temperature of the heated pipe was supposed to be 20 °C. The pipe cooling by mechanisms of convection and radiation was taken into account and entered as the boundary condition of the 3rd type (Eq. 20). The surrounding temperature $T_f = 20$ °C was defined.

![Figure 5](image2.png)

**Figure 5.** Dependence of the combined heat transfer coefficient on the pipe surface temperature.
The heat transfer coefficient in the dependence on the pipe surface temperature was calculated according to Eq. 21 using classical criterial equations to determine the convection heat transfer coefficient. The obtained dependence of the combine heat transfer coefficient on the temperature is illustrated in Figure 5. In the $y$-axis, the symmetry conditions were applied for both, electro-magnetic and thermal, analyses by definition of zero $\mathbf{A}_z$ magnetic vector potential and zero heat flux.

4.3. **Comparison of computed and experimental results**

To verify the suggested methodology for numerical simulation of induction heating and developed simulation model, the temperatures measured during experiments were compared with the temperatures computed using numerical simulation in the nodes which location approximately corresponded to the thermocouple positions. In Figures 6 and 7, the time dependence of measured and computed temperatures are plotted exhibiting a good match of the obtained results.

![Figure 6. Comparison of measured and computed temperatures during the experiment 1.](image)

![Figure 7. Comparison of measured and computed temperatures during the experiment 2.](image)
Slight deviations of measured and computed temperatures result from the fact that according to generated mesh the positions of nodes do not exactly fit thermocouple locations. Moreover, some deflections could likely arise due to inaccuracies in the material properties and cooling conditions applied. The relative error of computed temperatures corresponding to that measured by thermocouple 1 and thermocouple 2 in the experiment 1 is 5.68 % and 3.35 %, respectively. In the experiment 2, these errors are less than 5 %.

Based on the results of verification experiment and comparison of measured and computed temperatures it can be concluded that the methodology of sequential field coupling applied for numerical simulation of a pipe induction heating using the ANSYS software is correct and can thus be exploited to design parameters of induction brazing of thin-walled pipes.

5. Simulation model for numerical analysis of induction brazing of thin-walled pipes

In the next step, the simulation model was developed in order to analyse the process of induction brazing of pipes made of AISI 304 steel using the copper-based solder. Geometrical model (Figure 8a) consists of two pipes with the outer diameters of 31.8 mm and 33.6 mm, respectively, the wall thickness of 0.9 mm and the length of 50 mm. The suggested length of the pipe overlap in the brazed joint is 2 mm. The solder has the form of a ring made of the wire 1 mm in diameter. For induction brazing, the same type of induction coil was suggested as applied in verification experiment. The problem was solved as axisymmetric. The generated finite element mesh (Figure 8b) takes into account the skin effect and the concentration of magnetic field in the area of induction coil as illustrated by a detail in Figure 8c.

Material model of the austenitic stainless AISI 304 steel was described in the previous section. The temperature dependence of thermal and electrical properties of the B-Cu97Ni(B) solder computed using JMatPro software is depicted in Figure 9. The melting point of the applied B-Cu97Ni(B) solder is lower. The solidus and liquidus temperatures of the solder were computed to be $T_s = 1080 \, ^\circ\text{C}$ and $T_l = 1105 \, ^\circ\text{C}$, respectively. The solder working temperature is ranging from 1115 °C to 1125 °C. The relative permeability of the solder was supposed to be 1.35.

![Figure 8](image_url)

**Figure 8.** Geometrical model (a) and finite element model (b) for induction brazing of pipes with a detail of generated mesh near the induction coil (c).
Similarly to the verification model, symmetry conditions were defined in the y-axis applying zero magnetic vector potential and zero heat flux density. The pipe cooling by convection and radiation to the surrounding air at the temperature of 20 °C was considered. It was supposed that the thermal and electrical contact between the pipes as well as between the pipe and solder were ideal. The initial temperature of pipes and the solder was 20 °C. The frequency of source current was constant (20 kHz). The current density was varied from the interval of $1.5 \times 10^8$ A.m$^{-2}$ to $2.1 \times 10^8$ A.m$^{-2}$.

6. Results and discussion

Using the developed simulation model of the induction brazing, numerical experiments were carried out applying the ANSYS 18.2 software to analyse the electro-magnetic and temperature fields in the thin-walled tubes during the joining process and to design suitable induction heating parameters for the production of a high quality brazed joints.

6.1. Analysis of electro-magnetic and temperature fields

To illustrate the mutual relationships of electro-magnetic variables, the distribution of current density, magnetic vector potential, the intensity of magnetic field, magnetic induction and generated Joule heat at the end of induction heating in the time of 12 seconds applying the current density of $1.7 \times 10^8$ A.m$^{-2}$ is shown in Figure 10. In Figure 10f, the temperature distribution at the end of induction heating is documented as well. The intensity of magnetic field is maximal near the induction coil. The highest induced eddy currents flowing through the solder result in the maximum generated Joule heat and the highest temperature increase in the solder. This results can be supported also by Figure 11 illustrating the details of temperature fields in the pipes and solder in the time of 11.96 s when the solder reached the working temperature. The maximum temperature differences in solder at this time are less than 6 °C.

6.2. Influence of current density on the solder temperatures

According to the required heating time of 12 seconds, the influence of current density in induction coil on the temperature fields in the copper-base solder was analysed. In Figure 12, the time histories of the temperatures in the centre of the solder cross-sectional area are depicted for chosen source current densities. The maximal solder temperature is reached at the end of the heating process in the time of 12 s. Consequently, the temperature of the solder decreases owing to the convection and radiation cooling.

In Figure 13, the solder temperature in the time of 12 s as a function of the current density in induction coil is plotted. The temperatures from the interval from 1115 °C to 1125 °C correspond to the recommended working temperatures of the B-Cu97Ni(B) solder.
Figure 10. Details from the distribution of electro-magnetic variables in the time of 12 seconds
a) current density,  b) vector potential,  c) intensity of magnetic field,  d) magnetic induction,
e) generated Joule heat and  f) temperature field (source current density of $1.7 \times 10^8$ A.m$^{-2}$).

Figure 11. Details of temperature fields in the pipes and solder in the time of 11.96 seconds.
Based on the results presented in a detail from Figure 13, the current density range from $1.67 \times 10^8$ A.m$^{-2}$ to $1.69 \times 10^8$ A.m$^{-2}$ can be proposed for induction brazing of thin-walled pipes.

### 6.3. Influence of the current density on the heating time of solder to the brazing temperature

In order to design the operating diagram, heating time vs. current density, for induction brazing of thin-walled pipes of the AISI 304 steel using copper-based solder, the effect of the current density on the duration of induction heating of the B-Cu97Ni(B) solder to its liquidus temperature and solder working temperature was investigated.

Figure 14 shows the time dependence of the solder temperature for considered values of the current density in inductor coil with a detail of the time history of temperatures in the region of recommended solder working temperatures. Based on the obtained graphs, the heating times of the B-Cu97Ni(B) solder to the temperature of 1080 °C and 1125 °C, corresponding to the liquidus temperature and maximal recommended solder working temperature, respectively, were determined and plotted to the

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**Figure 12.** Time histories of the temperatures in the centre of the solder cross-sectional area for chosen source current densities.

**Figure 13.** Solder temperature in the time of 12 seconds in the dependence on the current density in induction coil.

Based on the results presented in a detail from Figure 13, the current density range from $1.67 \times 10^8$ A.m$^{-2}$ to $1.69 \times 10^8$ A.m$^{-2}$ can be proposed for induction brazing of thin-walled pipes.
operating diagram in Figure 15. Using the operation diagram, the heating time needed to attain required solder temperature applying selected current density can be defined or vice versa for a desired heating time, the required current density can be determined.

![Operating diagram for induction brazing of stainless steel pipes.](image)

**Figure 15.** Operating diagram for induction brazing of stainless steel pipes.

7. **Conclusions**

The research was focused on the investigation of the process of induction brazing of thin-walled pipes made of AISI 304 steel using the B-Cu97Ni(B) solder with the aim to design appropriate parameters of induction brazing by means of numerical simulation of the process in the ANSYS software.

- For induction heating of pipes, a two-threaded copper water cooled induction coil was suggested.
- Simulation model for numerical analysis of pipe induction brazing was developed.
The process of induction brazing was considered as a coupled problem involved harmonic electro-magnetic analysis and transient thermal analysis.

To verify the developed simulation model of induction brazing, verification experiment was performed.

Subsequently, the simulation model was applied to design suitable parameters for the induction brazing of thin-walled AISI 304 steel pipes using a copper-based solder. 

Based on the obtained results, the operating diagram (current density vs. heating time) for the investigated induction brazing process was developed.

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