

Numerical Modeling of Resistance Spot Brazing

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Abstract

This work describes two complementary numerical models developed using COMSOL Multiphysics® for the simulation of resistance spot brazing (RSB), a joining process used in high-volume manufacturing industries. The objective is to improve the understanding and prediction of the brazing process by capturing the coupled electrical, thermal, and mechanical phenomena involved during operation. Two complementary numerical models are proposed. The first one is a simplified three-dimensional electro-thermal model dedicated to investigating the influence of contact resistance on current distribution within the actual geometry of the assembly. This model is used to calibrate contact resistances through comparison with experimental results and to identify appropriate electrical contact conditions for the brazing process. The second one is a fully coupled 2D axisymmetric electro-thermo-mechanical model, using the calibrated contact resistance, and intended to provide a more detailed description of the local multi-physical phenomena occurring during brazing. Both models are based on a finite element formulation that describes Joule heating due to current flow, heat transfer within the components and electrodes, and, for the 2D axisymmetric model, the resulting thermo-mechanical response of the materials. Particular attention is given to the treatment of contact interfaces, where electrical and thermal resistances evolve as a function of pressure, temperature, and surface conditions. These interface effects strongly influence local heat generation and, consequently, the temperature distribution within the brazing foil and the surrounding materials. The results highlight significant temperature gradients within the brazing foil, demonstrating the potential for local regions to reach the melting temperature while others remain below it. The proposed framework provides a predictive tool for analyzing and optimizing resistance spot brazing operations. It can be used to reduce reliance on trial-and-error experimentation and to support process design and optimization in industrial contexts.

Keywords: Resistance Spot Brazing (RSB), Electro-thermo-mechanical coupling, Contact resistance, Joule heating.

Introduction

Resistance Spot Brazing (RSB) is a joining process used in high-volume manufacturing industries due to its high productivity and automation capabilities. The process relies on the generation of heat by the Joule effect when an electrical current passes through components clamped between two electrodes under mechanical pressure. In contrast to resistance spot welding, RSB is based on the localized melting of a brazing filler metal, while the base materials remain below their melting temperature. The molten brazing foil subsequently solidifies after the brazing cycle, forming the brazed joint. The quality and reliability of the joints are strongly influenced by the electrical, thermal, and mechanical interactions occurring throughout the process.

The numerical simulation of RSB remains challenging [1][2] because it involves strongly coupled electrical, thermal, and mechanical phenomena. In particular, the electrical and thermal contact resistances evolve during the brazing cycle as functions of pressure, temperature, and surface conditions, significantly affecting the current

distribution and local heat generation. These interface phenomena can therefore strongly influence the temperature reached within the brazing foil and the surrounding materials. Accurate modeling of the contact interfaces is consequently essential for reliably predicting the thermal conditions required to melt the brazing foil while preventing excessive heating of the base materials.

This work presents two complementary numerical models developed using COMSOL Multiphysics®. The first is a 3D electro-thermal model dedicated to analyzing the influence of contact resistance on the current distribution within the actual geometry of the assembly. This model is used to characterize the current paths and to identify an appropriate contact conductance through comparison with experimental observations. The second is a fully coupled 2D axisymmetric electro-thermo-mechanical model using the contact conditions identified from the 3D analysis. This model provides a more detailed description of the coupled electrical, thermal, and mechanical phenomena occurring during the brazing cycle, while explicitly accounting for the brazing foil.

The numerical results are compared with experimental measurements to assess the ability of the models to reproduce the thermal response of the assembly. In addition, the influence of contact conductance and the main process parameters on the resulting temperature distribution is investigated. Consideration is given to the temperature gradients within the brazing foil, which may result in different melting conditions. The proposed modeling framework provides complementary levels of description of the RSB process, combining the geometrical accuracy of the 3D approach with the computational efficiency and multi-physics capabilities of the 2D axisymmetric model. It therefore provides a suitable basis for improving the understanding and optimization of resistance spot brazing conditions while reducing reliance on trial-and-error experimental approaches.

Modeling

Geometries

The geometry, shown in Figure 1, consists of two electrodes mounted on their respective electrode holders, two copper sheets (the clad and the busbar) to be joined, and a brazing foil inserted between them. During the brazing cycle, the electrical current flows from the upper electrode to the lower electrode through the stack-up. The electrode holders are included in the computational domain to accurately represent the electrical and thermal boundary conditions, particularly the current distribution and heat extraction through the electrodes.

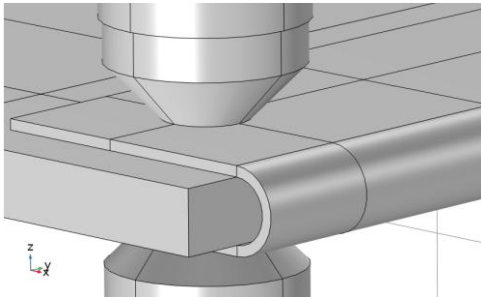


Figure 1. 3D Geometry

For the 2D axisymmetric simulations, the geometry is simplified by assuming rotational symmetry around the electrode axis, as illustrated in Figure 2. The busbar, brazing foil, electrodes, and electrode holders can all be represented within this axisymmetric framework. The clad is the only component whose actual three-dimensional geometry deviates from this assumption. Therefore, the 3D electro-thermal model is first used to assess the influence of the clad geometry on the current distribution and resulting thermal field. This analysis determines whether the three-dimensional features

of the clad have a significant influence on the brazing process and consequently whether the axisymmetric assumption is appropriate for the subsequent multi-physics simulations.

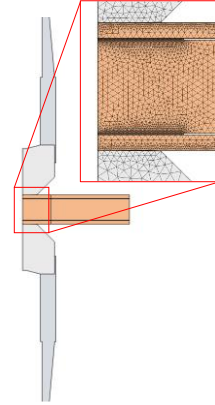


Figure 2. 2D axisymmetric geometry and mesh

Equations and boundary conditions

Electrical problem

To estimate the electrical potential and current in each element, the current conservation law is solved:

$$\nabla \cdot (\sigma \nabla V) = 0$$

where V is the electric potential and σ is the electrical conductivity of the material.

A prescribed normal current boundary condition is applied at the upper surface of the top electrode holder, representing the current supplied by the brazing machine. The lower surface of the bottom electrode holder is defined as an electrical ground, imposing a zero electric potential reference. The current therefore flows through the electrode-sheet assembly, generating heat due to Joule losses along the electrical path in the volume and at the interface through contact resistances as described in the next section.

Thermal problem

The thermal behavior of the brazing assembly is modeled using the Heat Transfer in Solids interface. The transient temperature distribution is obtained by solving the heat conduction equation with internal heat generation due to Joule heating:

$$\rho C_p \frac{\partial T}{\partial t} = \nabla \cdot (k \nabla T) + Q_{vol}$$

where ρ is the material density, C_p the heat capacity, T the temperature, k the thermal conductivity, and $Q_{vol} = \sigma (\nabla V)^2$ the volumetric Joule heat source generated by the electrical current.

At the contact interfaces, surface source terms are added through the Multiphysics coupling

“Electromagnetic Heating”. Concerning the other heat transfers, the cooling of the electrode holders is considered with an internal forced convective heat flux, and natural convection exchange is added for all the external surfaces.

Mechanical problem

The mechanical behavior of the brazing assembly is modeled in the 2D axisymmetric approach, by considering the busbar, the clad and the brazing foil as viscoplastic materials in order to accurately capture their deformation under the applied electrode force and the associated evolution of the contact conditions. A viscoplastic constitutive law, using Chaboche formulation [3], is therefore used for the components, allowing the deformation and contact pressure at the electrode–sheet interfaces to be properly estimated throughout the brazing cycle. The classical equations of motion are solved with:

$$\rho \frac{\partial^2 \mathbf{u}}{\partial t^2} = \nabla \cdot ((I + \nabla \mathbf{u})\mathbf{S})^T$$

where ρ is the density, $\mathbf{u}$ the displacement field, I the identity tensor and $\mathbf{S}$ the stress tensor.

The remaining components are assumed to behave elastically, while the electrodes are considered rigid. This assumption reduces the computational cost while preserving the main mechanical effects governing the contact between the electrodes and the sheets. A vertical force is applied at the top electrode holder. For the lateral boundaries fixed constraints conditions are used.

Contact Pairs are defined at the interface between electrodes and clad and between clad and busbar. A penalty-based contact formulation is employed to account for the evolution of contact pressure and deformation during the brazing process.

Contact Conditions

Contact resistances quantify the effects of thermal barriers and electrical barriers at the contact surfaces between two components. This barrier is mainly due to the different nature of the materials and/or the imperfections at surface level.

As studied in a previous work [4], the Mikic formulation can be used to evaluate these resistances across every part, in function of the contact pressure p (calculated in the 2D-axisymmetric approach or analytically estimated in the 3D approach), the local roughness, and the material properties. The roughness profile is described by the Root Mean Square (RMS) of the surface roughness height (σ_{asp}) and surface roughness slope (m_{asp}). The resulting

conductance expressions (inverse of the resistance) are written as:

$$h^{therm} = 1.54 \cdot k_c \frac{m_{asp}}{\sigma_{asp}} \left(\frac{p\sqrt{2}}{m_{asp}E_c} \right)^{0.94}$$

$$h^{elec} = 1.54 \cdot \sigma_c \frac{m_{asp}}{\sigma_{asp}} \left(\frac{p\sqrt{2}}{m_{asp}E_c} \right)^{0.94}$$

with k_c , the equivalent thermal conductivity $\frac{2}{k_c} = \frac{1}{k_1} + \frac{1}{k_2}$, $\frac{2}{\sigma_c} = \frac{1}{\sigma_1} + \frac{1}{\sigma_2}$, the equivalent electrical conductivity; E_c , the equivalent elastic modulus $\frac{1}{E_c} = \frac{1-\nu_1^2}{E_1} + \frac{1-\nu_2^2}{E_2}$, with E_i the Young modulus and ν_i the Poisson's ratio of each material i in contact.

To investigate the influence of the contact conductance magnitude, a dimensionless scaling factor, $k_{conductance}$, is introduced in the expressions of both the thermal and electrical contact resistances. This parameter is of particular importance in the following analysis, as an accurate estimation of the contact conditions is essential for the model to provide predictive capabilities.

Numerical Strategy

Both approaches are described in COMSOL Multiphysics® within a single component, combining the 3D geometry and the 2D axisymmetric representation. This setup facilitates the potential exchange of information between the two modeling approaches. A segregated solver is employed to handle the nonlinear problem, while a backward differentiation formula (BDF) scheme is used for the time-dependent solution. To assess the adequacy of the mesh and the time step, a power balance is evaluated for each model. The power balance obtained for the 2D axisymmetric model is presented here in Figure 3. It presents the temporal evolution of the individual power contributions to the global thermal balance of the process, plotted as a function of the normalized time t/τ . Four terms are considered: the surface source term (blue curve), the volume source term (green curve), the cooling flux (red curve), and the convective flux (cyan curve), together with the resulting enthalpy variation rate of the whole computational domain (magenta curve). The volume source term (green curve) is found to dominate the energy balance during the heating stage before decreasing progressively where the heat source is switched off, producing an abrupt drop in power. The surface source term (blue curve) contributes to a lesser extent, remaining below 0.1 (normalized units) throughout the simulation. The cooling flux (red curve) evolves as a negative counterpart to the volume source term, which

reflects the increasing heat extraction required to balance the energy input during heating. After the source is deactivated, this flux rapidly relaxes toward less negative values, consistent with the reduced thermal gradients during the cooling phase. The convective flux (cyan curve) remains comparatively small in magnitude over the entire cycle, indicating a minor but non-negligible contribution to the overall thermal exchange.

To assess the internal consistency of the numerical model, the sum of these four power contributions was compared, at each time step, with the enthalpy variation rate computed independently over all domains (magenta curve). The excellent agreement between the summed contributions (marked by black asterisks) and the magenta curve, observed over the entire simulated cycle, including across the sharp transient associated with the source cutoff at $t/\tau \approx 0.6$, confirms that the global energy balance is satisfied throughout the simulation.

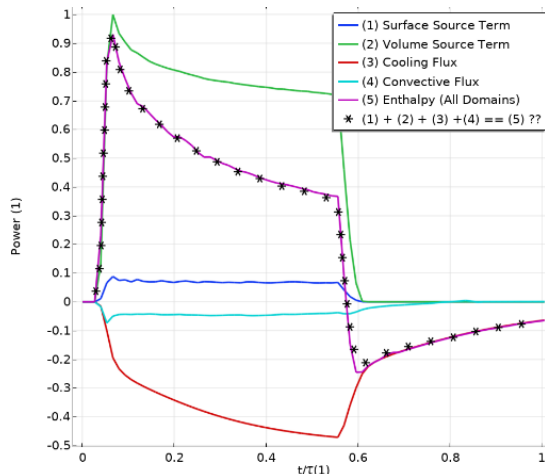


Figure 3. Power Balance as a function of time (normalized units)

This result validates the correct coupling between the heat source terms and the boundary flux conditions implemented in the model, thereby supporting the reliability of the numerical model used to simulate the brazing process.

Experimental Work

Figure 9 presents optical micrographs of the assembled joint. The low-magnification image indicates that the interlayer foil melted during the joining process, resulting in a continuous bond between the copper components within the electrode contact area. A higher-magnification view of the joint region is also provided. The copper busbar and clad material retain a microstructure that does not exhibit any obvious evidence of extensive melting at the resolution investigated. These observations

suggest that melting was predominantly confined to the interlayer foil, while the adjacent copper substrates were only limitedly affected by the thermal cycle. However, localized dissolution or partial melting of the copper substrates at the interface cannot be completely excluded based on optical microscopy alone. The micrographs were acquired using optical microscopy following chemical etching with a ferric chloride solution. The circular marks visible in the overview image are polishing and etching artifacts resulting from the circular motion applied during sample preparation.

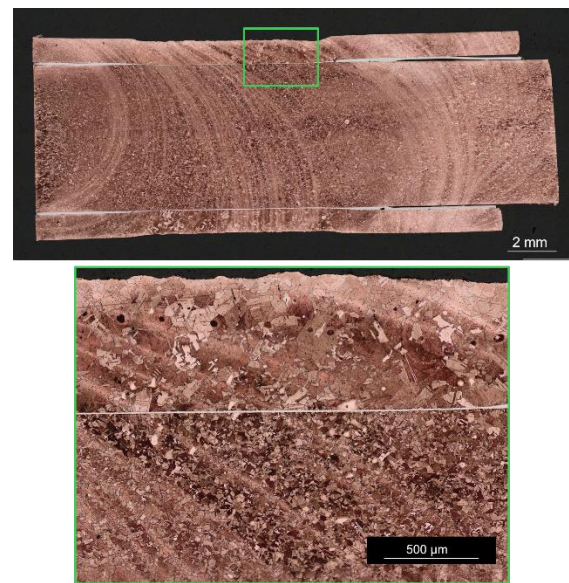


Figure 4. Micrograph of copper-to-copper assembly

Results and discussion

The results are first investigated using the 3D electro-thermal model in order to characterize the current distribution within the actual geometry of the assembly. This analysis provides insight into the current paths and the influence of the electrical contact conditions on the distribution of Joule heating, particularly at the clad and busbar interfaces. Based on these results and the available experimental observations, an appropriate value of contact conductance can then be identified. This value is subsequently used in the more refined 2D axisymmetric model, which additionally incorporates the complex mechanical behavior of the assembly. The 2D axisymmetric model therefore enables a more detailed description of the coupled electro-thermo-mechanical response of the resistance brazing process, while reducing the computational cost compared with the full 3D approach.

Current Paths (3D approach)

The first part of the numerical investigation focuses on the three-dimensional electro-thermal model. The objective is to determine an appropriate range of contact resistance values that promotes melting of the brazing foil while preventing melting of the busbar and clad materials. In the model, the electrical contact is characterized by the parameter $k_{conductance}$, which controls the conductance of the contact interface and therefore directly affects the current distribution within the assembly.

In Figure 5 the electrical potential distributions obtained for different values of $k_{conductance}$ are presented. A clear modification of the current path can be observed as the contact conductance is varied. For low values, corresponding to higher contact resistance, the current is preferentially redirected through the clad. Conversely, increasing $k_{conductance}$ reduces the electrical resistance of the contact and progressively promotes a direct current path through the busbar, thereby limiting the fraction of current flowing through the clad.

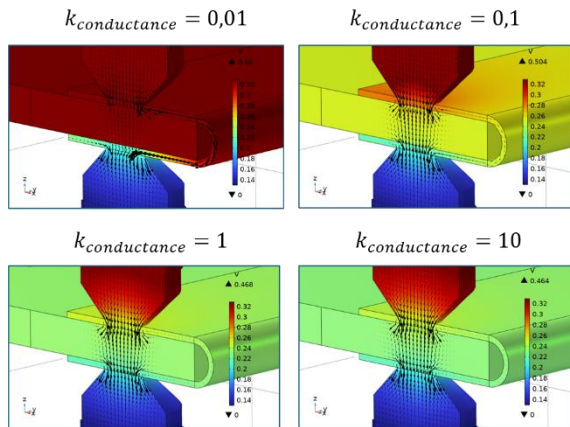


Figure 5. Electric potential for different contact conductance coefficients $k_{conductance}$

This behavior is quantified in Figure 6, which shows the proportion of the total current (in red) flowing through the clad (in cyan) and in the busbar (in green) as a function of the contact conductance parameter. The fraction of current carried by the clad increases significantly as $k_{conductance}$ decreases. This confirms that contact conductance is a key parameter controlling the current distribution between the clad and the busbar. For $k_{conductance}$ values above a certain range, the current distribution becomes relatively insensitive to further increases in conductance, whereas decreasing $k_{conductance}$ progressively favors current flow through the clad.

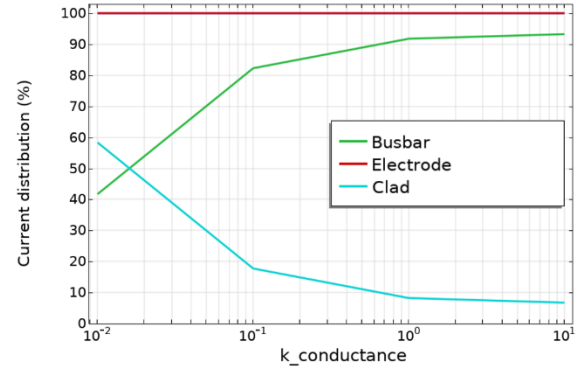


Figure 6. Current distribution as a function of the contact conductance $k_{conductance}$

The corresponding temperature fields are presented in Figure 7. These results demonstrate the direct impact of the current redistribution on the thermal response of the assembly. For high $k_{conductance}$ values, the temperature field shows limited sensitivity to further changes in conductance, consistent with the small fraction of current flowing through the clad. In contrast, for low $k_{conductance}$ values, a significant part of the current is forced through the clad, resulting in increased Joule heating in this region and unphysically high temperature values.

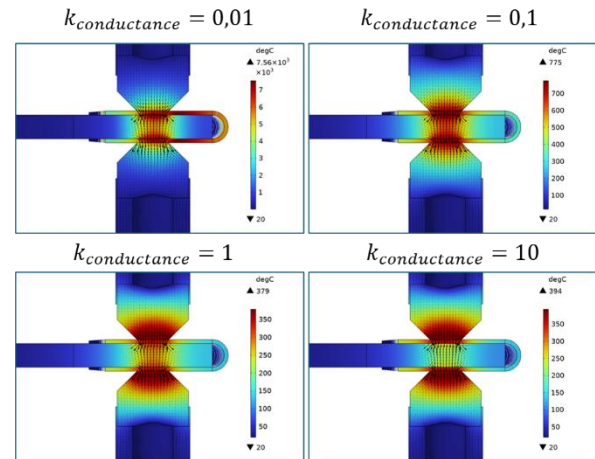


Figure 7. Resulting Temperature field for Contact Resistances coefficients from $k_{resistance}$

A $k_{conductance}$ value of 0.1 represents a relevant transition point for the present study. At this value, approximately 17% of the total current flows through the clad (see Figure 6), while the resulting temperature fields reach the required order of magnitude for the brazing process. The absolute temperature values are not reported here due to confidentiality constraints. Nevertheless, the simulations indicate that this range of contact conductance provides a suitable compromise between promoting sufficient heating of the brazing foil and limiting excessive heating of the clad and

busbar materials. The $k_{conductance}$ parameter can therefore be used to identify the electrical contact conditions required to achieve selective heating and melting of the brazing foil while maintaining the integrity of the surrounding materials.

Based on the results obtained with the 3D electro-thermal model, the relatively limited contribution of the clad to the overall current distribution, together with the resulting temperature fields, suggests that its influence on the global thermo-electrical response remains moderate. These observations indicate that a 2D axisymmetric model can provide an adequate representation of the brazing process while significantly reducing the computational cost. The contact resistance identified from the 3D simulations was therefore used as an input parameter for the 2D axisymmetric model. The latter additionally incorporates the mechanical behavior of the assembly, enabling the analysis of the coupled electro-thermo-mechanical response during the resistance brazing process. The following section focuses on these 2D axisymmetric simulations and investigates the resulting thermal and mechanical behavior of the assembly.

Thermo-Mechanical Results (2D-axisymmetric approach)

The second part of the study focuses on the 2D axisymmetric model, which incorporates the mechanical response of the assembly in addition to the electro-thermal phenomena. This approach highlights the multi-physical and highly coupled nature of the resistance brazing process, particularly when the brazing foil is explicitly considered in the model. The simultaneous evolution of the electrical, thermal, and mechanical fields makes the numerical description of the process particularly challenging, while providing valuable insight into the local conditions governing brazing and melting.

In Figure 8 the evolution of the coupled fields at four different times during the brazing cycle are presented. On the left, the white streamlines represent the electric field, together with the corresponding stress distribution. On the right, the temperature distribution is shown, with the black and grey lines representing the temperature contours. The results illustrate the strong spatial and temporal coupling between the electrical current distribution, Joule heating, temperature evolution, and mechanical response. As the process progresses, the localization of the current and the resulting heat generation lead to significant temperature gradients within the assembly, including within the brazing foil.

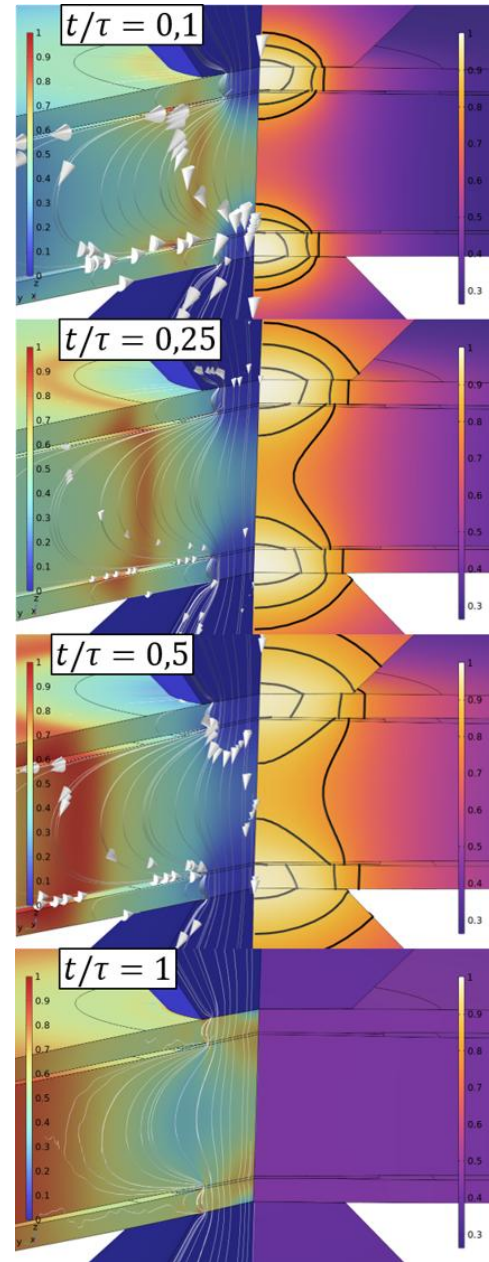


Figure 8. For four different instants, on the left : Electric field streamlines (white lines) and stress distribution, on the right: Temperature contours (black and grey lines) and temperature distribution

The time evolution of the temperature is further analyzed in Figure 9. The maximum temperature reached in the whole assembly is shown in blue, while the maximum and minimum temperatures within the brazing foil are represented in green and red, respectively. A significant difference can be observed between the maximum and minimum temperatures within the brazing foil throughout the brazing cycle. This temperature spread indicates that the brazing foil does not experience uniform thermal conditions. Consequently, depending on their local position, some regions of the foil may reach the

melting temperature while other regions remain below it. This result highlights the importance of accounting for the spatial distribution of the coupled physical fields rather than only relying on a global or average temperature to assess the brazing conditions.

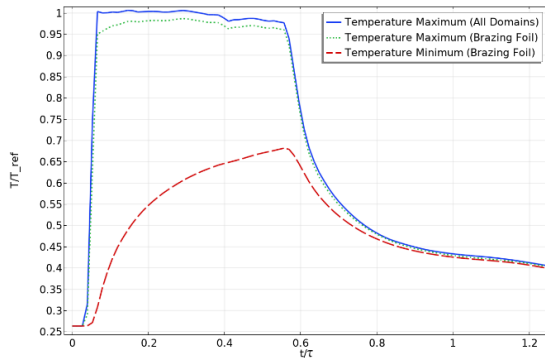


Figure 9. Time evolution of the maximum temperature in the brazed part and the brazing foil, and the minimum temperature in the brazing foil during the brazing cycle.

These results emphasize the value of the numerical approach for understanding and optimizing the resistance brazing process. The strong coupling between electrical conduction, heat generation, heat transfer, temperature-dependent material behavior, and mechanical response can lead to highly non-uniform local conditions that are difficult to characterize experimentally.

Conclusions

This study presents a two-step numerical strategy for investigating resistance spot brazing (RSB), combining a 3D electro-thermal model with a 2D axisymmetric electro-thermo-mechanical model. The 3D model was used to characterize current distribution within the actual assembly geometry and to calibrate an appropriate contact conductance, showing that the contribution of the clad to the overall current path remains limited for the selected operating range. This justified the use of a computationally efficient 2D axisymmetric representation for the more detailed multiphysics analysis.

The 2D axisymmetric model revealed the strongly coupled and spatially heterogeneous nature of the RSB process, particularly within the brazing foil, where significant temperature gradients were observed. This heterogeneity means some regions of the foil may reach the melting temperature while others remain below it — a result that could not be anticipated from a global thermal balance alone, and which underlines the value of a fully coupled, spatially resolved approach over simplified thermal models.

A full 3D electro-thermo-mechanical model is currently under development to overcome the limitations of the axisymmetric assumption. The 2D axisymmetric model will nonetheless remain a valuable tool for parametric studies, owing to its lower computational cost. Together, these complementary approaches form a progressive modeling strategy aimed at defining robust RSB operating conditions that ensure reliable, homogeneous joints while preserving the integrity of the surrounding materials.

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