

Finite Element Modeling and Experimental Validation of Induction Heating for Efficient TLP Bonding with Cu-Sn Layers

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This study investigates high-frequency induction heating for transient liquid phase (TLP) bonding of Cu-Sn layers, offering a fast and localized approach for MEMS packaging. Finite element simulations are carried out in parallel with experiments to model the coupled electromagnetic and thermal behavior, with a focus on the frequency-dependent skin effect. Two modeling strategies are evaluated: one resolves the skin depth volumetrically while capturing all conductor losses, and the other uses a simplified boundary condition to reduce computational cost. Both approaches show less than 5 % deviation from experimental results. The findings identify 27.12 MHz as the minimum frequency needed to reach the Cu-Sn bonding temperature of 250 °C using just 12 A of current, with heating rates reaching up to 35 K/s at 55 MHz.

Index Terms—Electromagnetic induction, electronics packaging, finite element analysis (FEA), radio frequency, selective heating.

I. INTRODUCTION

Integrating chips, wafers, and components are essential for the development of intelligent systems, yet bonding of heterogeneous materials with distinct thermomechanical properties presents complex challenges. Achieving a hermetically sealed and mechanically stable interface is crucial. Conventional thermal bonding techniques risk damaging of the components, potentially compromising system integrity. Localized heating techniques such as reactive bonding [1] are gaining attention to mitigate this by reducing thermal impact and focusing heat precisely to bond interfaces. Alternatively, induction-based systems, particularly those using Cu-Sn frames for transient liquid phase (TLP) bonding, offer precise selective heating and minimized thermal stress.

Unlike earlier studies constrained to sub-2 MHz frequencies [2], this work addresses the ISM-band for induction-based TLP bonding, leveraging standard generators and components to enable efficient heating at reduced input power. A key contribution is the comparative application of two modeling strategies in COMSOL, one resolving skin depth explicitly, the other using computationally efficient boundary conditions, tailored for this high-frequency use case. Experimental validation confirms the accuracy of both models, supporting design optimization with minimal error while reducing the reliance on extensive experimental testing.

II. THEORY

The principle of inductive bonding for MEMS packaging relies on the use of electromagnetic (EM) fields to selectively heat intermediate metallic bond layers. According to the Ampère-Maxwell law, an alternating current in the primary conductor (here, a micro-coil) generates an oscillating EM field. When a secondary conductor (here, Cu-Sn bond frames) is exposed to this EM field, the induced voltage generates eddy currents within the frames, causing Joule heating.

Finite element analysis (FEA) with commercial software, such as COMSOL Multiphysics, enables the modeling of this phenomenon using the magnetic vector potential (A), from which the magnetic flux density (B) and the electric field (E) are calculated by solving (1) and (2). The current density (J_e) in (1) depends on the skin depth of the conductor, which decreases exponentially with distance from the surface, as described by (3). The inverse relationship between skin depth and frequency allows for localized, rapid heating of the secondary conductors while requiring lower input power. Consequently, resistive heating in the primary conductor is minimized, reducing energy losses and improving overall efficiency.

$$J_e = (j\omega - \omega^2 \epsilon_0 \epsilon_r) \mathbf{A} + \nabla \times (\mu_0^{-1} \mu_r^{-1} \nabla \times \mathbf{A}) \quad (1)$$

$$\mathbf{B} = \nabla \times \mathbf{A}; \mathbf{E} = -j\omega \mathbf{A} \quad (2)$$

$$J(x) = J_e \cdot e^{\left(-\frac{x}{\delta}\right)}; \delta = \left(\sqrt{\pi \cdot f \cdot \mu_r \cdot \sigma}\right)^{-1} \quad (3)$$

The multi-physics model considers all three modes of heat transfer: conduction, convection, and radiation. The primary heat source terms Q_{rh} and Q_{ml} , defined in (4b), are computed based on the solution of (1). To compensate for the Joule heating of the induction coil, an internal or external cooling mechanism is required. In this study, the coil was cooled using a constant water flow. The full heat transfer model, accounting for all heat transfer modes, is solved using (4) to compute the resulting temperature distribution. The multi-physics model integrates electromagnetism, heat transfer, and fluid flow to provide an accurate representation of induction-based heating.

$$\rho c_p \frac{\partial T}{\partial t} + \rho c_p \mathbf{u} \cdot \nabla T + \nabla \cdot \mathbf{q} = Q_{source} \quad (4)$$

$$\mathbf{q} = -k \nabla T; Q_{source} = Q_{rh} + Q_{ml} + Q_{conv} + Q_{rad} \quad (4a)$$

$$Q_{rh} = 0.5 \times \text{Re}(\mathbf{J} \cdot \mathbf{E}^*); Q_{ml} = 0.5 \times \text{Re}(i\omega \mathbf{B} \cdot \mathbf{H}^*) \quad (4b)$$

$$Q_{conv} = h(T_{amb} - T); Q_{rad} = \epsilon \sigma (T_s^4 - T_{amb}^4) \quad (4c)$$

III. EXPERIMENTAL AND SIMULATION SETUP

The experimental setup includes three main components: an inductive bonding module with an integrated copper coil, a water-cooling channel, and a glass substrate with thin Cu-Sn layers patterned in a frame structure, similar to [2]. Representing this configuration, the simulation domain is similarly divided into subdomains (Fig. 1a). Due to their high aspect ratio, the Cu-Sn bonding frames are modeled as boundaries to enhance simulation efficiency.

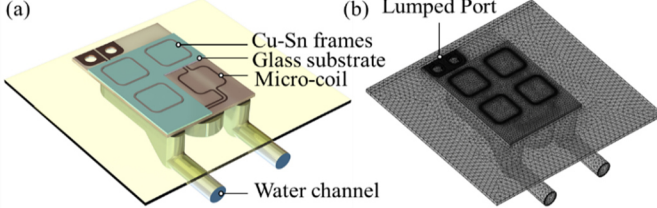


Fig. 1. Inductive bonding module: (a) CAD model; (b) Mesh model.

The bonding module (Fig. 1) enables inductive heating within the ISM radio frequency band of 13.56 MHz to 40.68 MHz. To analyze the effects of frequency variation, additional experiments and simulations were conducted at 1.84 MHz and 55 MHz for a constant current (I_0) of 12 A across all cases.

For the simulation model, accurately resolving the skin depth of the conductors is crucial. Since most of the current (63 %) is concentrated near the surface, a fine mesh is necessary to resolve the field concentration. Based on Equation (3), the skin depth of the coil is in the range of $1/10^{\text{th}}$ of the coil thickness at the lowest frequency (f_0) of 1.84 MHz; hence, meshing with only volumetric tetrahedral elements will lead to a computationally complex and expensive model.

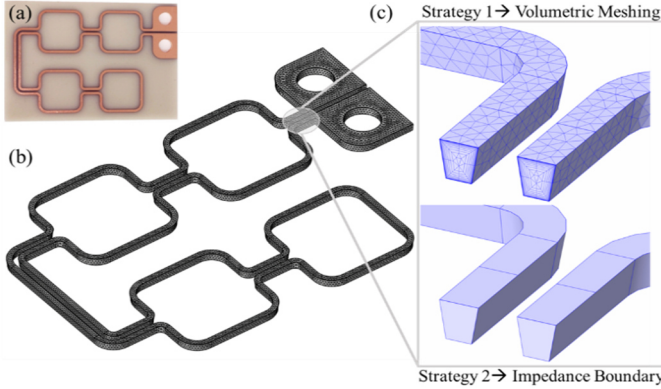


Fig. 2. Copper Coil: (a) As fabricated; (b) Mesh Model; (c) Strategy I and II.

Two strategies are implemented to address this issue as follows. Strategy I employs boundary layer meshing to explicitly resolve the skin depth and capture conduction losses from the surface to the interior of the coil. Strategy II models the coil as an impedance boundary with a defined thickness equivalent to its skin depth at the operating frequency, eliminating the need for volumetric meshing. While strategy I enables direct visualization of the skin effect, strategy II offers a computationally efficient alternative, reducing the mesh element count by 25 % with minimal loss in accuracy—making it suitable for faster simulation runs as substitutes for extensive experimental trials. Frequency-transient studies are conducted

for both approaches using time steps aligned with the experimental setup. Additionally, a lumped port is implemented to match the external impedance of the generator circuit.

IV. EXPERIMENTAL AND SIMULATION RESULTS

The temperature comparison between the experimental data and the FEA of strategy I, and strategy II at $f_0=27.12$ MHz and $I_0 \approx 12$ A for a heating time of $t_h = 10$ s is depicted in Fig. 3. The average deviation for both strategies, calculated relative to the experimental results, are less than 5 % at all frequencies.

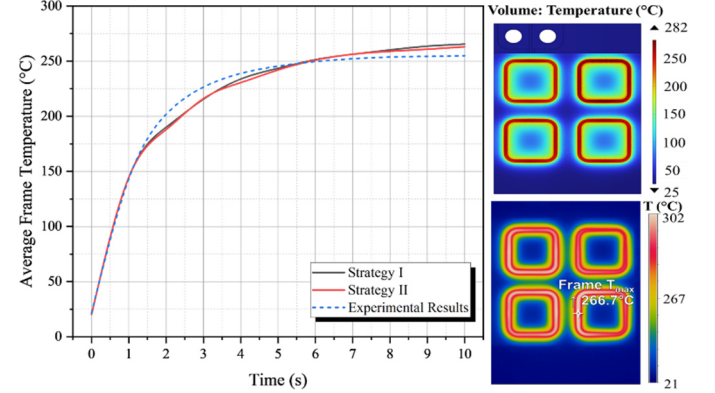


Fig. 3. Comparison of average frame temperatures for Strategy I, Strategy II, and experiments at $I_0 = 11.8$ A, $f_0 = 27.12$ MHz, and $t_h = 10$ s.

Fig. 4 illustrates the temperature rise after 10 s as the operating frequency of the micro-coil increases, ranging from 55 °C at 1.84 MHz to 375 °C at 55 MHz. A minimum frequency of 27.12 MHz is sufficient to achieve the required temperature of 250 °C for intermetallic compound (IMC) formation in the Cu-Sn binary system [3] at coil currents of 12 A. The maximum heating rate is calculated to be 35 K/s at 55 MHz.

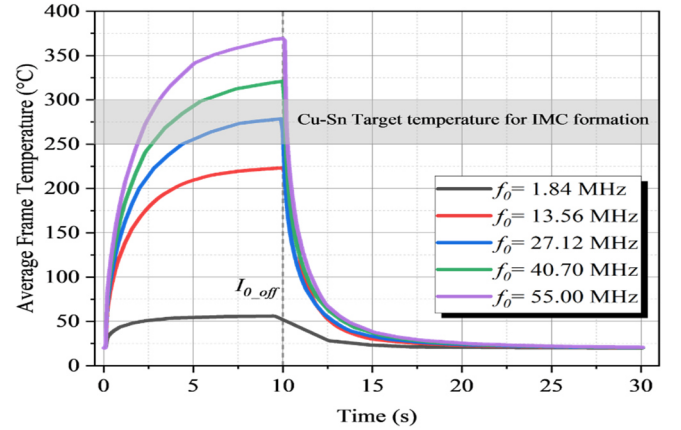


Fig. 4. Temperature-time curves showing the average frame temperature for different applied frequencies at a constant $I_0 = 12$ A, and $t_h = 30$ s (Strategy I).

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