Advanced Optimization of Ultrasonic Metal Welding Parameters with Thermal Validation through Finite Element Modeling

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Abstract

Ultrasonic metal welding (USMW) is a solid-state joining process whose weld quality depends on a small set of strongly interacting process parameters — welding pressure, weld time and vibration amplitude — making analytical parameter selection difficult without a validated predictive model. This paper develops second-order Response Surface Methodology (RSM) regression models, built on a Face-Centred Central Composite Design, to predict weld-bead density and weld resistance for ultrasonically welded aluminium foil and copper/copper–brass foil joints. Each RSM model is then embedded as the fitness function of a Genetic Algorithm (GA) to obtain globally optimized parameter combinations, following the RSM–GA coupling strategy validated for USMW by Elangovan, Anand and Prakasan (2012). The mechanical optimization results are cross-validated against an independent thermal-field model: interface temperature is measured using thermocouples and infrared thermography and compared against Finite Difference Method (FDM) and ANSYS-based Finite Element Analysis (FEA) predictions, following the FEA formulation of Elangovan, Semeer and Prakasan (2009). GA-optimized parameters closely reproduced experimentally measured weld-bead density/resistance for both material systems, and FDM/FEA-predicted interface temperatures agreed closely with thermocouple and thermal-imaging measurements. The results confirm that coupling RSM–GA optimization with independent thermal-field validation gives a more robust basis for USMW parameter specification than mechanical-strength optimization alone.

Keywords: Ultrasonic Metal Welding; Response Surface Methodology; Genetic Algorithm; Finite Element Analysis; Interface Temperature; Weld Strength Optimization

1. Introduction

Ultrasonic metal welding (USMW) joins similar or dissimilar metallic work-pieces through high-frequency, in-plane vibration applied under moderate clamping pressure, producing solid-state bonding through progressive shearing and localized plastic deformation without bulk melting (deVries, 2004; Graff, 2005). Because the process does not rely on fusion, it is well suited to joining thin foils and dissimilar-metal combinations such as aluminium-to-copper connections used in battery, electrical and automotive assemblies (Ganesh & Praba Rajathi, 2013). However, weld quality is highly sensitive to the combination of welding pressure, weld time and vibration amplitude, and these three factors interact non-linearly, making single-factor-at-a-time tuning inefficient and unreliable.

USMW has grown in industrial relevance alongside the transition toward lightweight electric-vehicle and consumer-electronics assemblies. In battery-pack manufacturing, USMW is routinely used to join copper and aluminium busbars, tabs and terminals because it avoids the intermetallic brittleness and thermal distortion associated with fusion-based joining of dissimilar metals. In these applications, joint electrical resistance and mechanical strength must both be tightly controlled, and process qualification timelines are typically short, leaving little room for extended trial-and-error parameter tuning. A validated, rapidly deployable optimization procedure is therefore of direct practical value, motivating the RSM–GA–FEA pipeline developed in this paper.

Response Surface Methodology (RSM) offers an efficient way to fit a predictive model of weld response across the factor space using a comparatively small number of experiments, and has been applied successfully to related processes including submerged-arc welding (Gunaraj & Murugan, 1999), CNC drilling (Onwubolu & Kumar, 2006) and electrical-discharge machining (Habib, 2009). Coupling the fitted RSM model with a Genetic Algorithm (GA) allows the global optimum of the response surface to be located reliably, since GA's population-based stochastic search is less prone than deterministic hill-climbing to becoming trapped in local optima on multi-modal surfaces (Canyurt, Kim, & Lee, 2008; Meran, 2006). This paper applies the RSM–GA pipeline to USMW of aluminium foil and copper/copper–brass foil joints, and — distinctively — validates the resulting optimized parameter sets against an independently developed thermal-field model, since interface temperature is itself a governing driver of bond formation.

The motivation for combining RSM–GA optimization with thermal-field validation, rather than relying on mechanical-strength optimization alone, stems from the underlying physics of USMW. Bond formation is driven by frictional heating and progressive oxide dispersal at the weld interface, so a parameter combination that appears mechanically optimal in a short-term strength test may still correspond to an interface-temperature regime that risks long-term joint degradation, localized annealing softening, or excessive tool wear. Conversely, a parameter set chosen purely to minimize interface temperature may under-develop the bond and leave weld strength below the level required for service. A validated optimization procedure therefore needs to reconcile both objectives simultaneously, which is the central aim of this paper: to fit and optimize RSM–GA mechanical response models for aluminium and copper/copper–brass USMW, and to check — rather than assume — that the resulting mechanically optimal parameter windows are also thermally sound.

The remainder of this paper is organized as follows. Section 2 reviews prior RSM, GA and FEA-based USMW studies. Section 3 presents the mathematical formulation of the RSM regression model. Section 4 details the GA-based optimization procedure. Section 5 describes the experimental framework used to fit and validate the models. Section 6 presents and discusses the RSM–GA results for aluminium and copper/copper–brass joints, the thermal-field validation, and the correlation between mechanical and thermal optima. Section 7 concludes the paper.

2. Related Work

2.1 RSM–GA Optimization of USMW

Elangovan, Anand and Prakasan (2012) developed an RSM model coupled with a GA to optimize USMW parameters for aluminium joints, reporting close agreement between GA-predicted and experimentally measured weld strength; the present study follows the same coupling strategy but extends it to Cu/Cu–brass joints and adds independent thermal validation. Elangovan, Prakasan and Jaiganesh (2010) applied a face-centred central composite RSM design to copper-to-brass ultrasonic joints, identifying pressure, weld time and amplitude as the dominant response drivers — the same three factors modelled here. Pradeep Kumar and Prakasan (2012) and Pop-Calimanu and Fleser (2012) used complementary factorial/Taguchi DOE approaches to confirm the primacy of pressure and weld time for copper and aluminium-composite USMW respectively, providing an independent cross-check on the RSM-derived sensitivities reported in Section 6.

2.2 Thermal and FEA-Based Modelling

On the thermal side, Elangovan, Semeer and Prakasan (2009) developed an FEA model predicting USMW interface temperature and stress as functions of material thickness, clamping force, weld time and friction coefficient, finding clamping force to be a dominant driver of interfacial deformation and hence heating — a relationship this paper re-examines through combined FDM/FEA modelling. Watanabe, Sakuyama and Yanagisawa (2009) reported comparable interface-temperature behaviour for dissimilar mild-steel-to-Al–Mg-alloy USMW joints, providing external benchmark data. Studies on horn design and vibration transmission (Li, Tan, Lei, & Jue, 2004; Kim, Sung, Kim, & Park, 2010) establish that the amplitude actually delivered to the interface — rather than the nominal generator setting — governs both the mechanical and thermal response, motivating the amplitude-focused RSM factor used here. Bloss and Graff (2009) and Annoni and Carboni (2011) further demonstrate that USMW process windows are alloy-specific, reinforcing the need for material-specific RSM models rather than a single universal parameter set. Jeng and Horng (2001) and Acarer, Demir and Findik (2004) provide micro-mechanical evidence that bonding proceeds through a temperature-dominated early stage followed by a roughness-dominated later stage, a mechanism used in Section 6 to interpret the observed weld-time optimum.

2.3 Complementary DOE and Process-Monitoring Studies

Complementary to RSM–GA studies, classical Taguchi/ANOVA screening (Ross, 2005; Tarng & Yang, 1998) has repeatedly identified the same three factors — pressure, weld time and amplitude — as dominant drivers of USMW strength, with weld time typically contributing the largest single share of response variation. This convergence across independent DOE methodologies (factorial, Taguchi and RSM) gives confidence that the factor set adopted in Section 3 captures the dominant physics of the process, even though the present paper does not repeat a full ANOVA decomposition and instead focuses on the continuous RSM–GA–FEA optimization pipeline. Process-monitoring literature (Ling, Wan, Wong, & Li, 2010) further shows that electrical/impedance signatures correlate with resistance-weld quality in allied processes, suggesting a possible future extension of the present framework toward in-process quality monitoring, discussed further in Section 7.

2.4 Positioning of the Present Study

Table-based comparisons in the literature (Sections 2.1–2.3) show that individual studies have separately validated RSM–GA mechanical optimization (Elangovan et al., 2010, 2012) and FEA thermal-field prediction (Elangovan, Semeer, & Prakasan, 2009) for USMW, but have generally treated the two as independent exercises rather than explicitly checking whether a mechanically optimal parameter set is also thermally sound. Genetic-algorithm-based optimization has likewise been validated for related joining processes — brass-plate welding (Meran, 2006) and laser hybrid welding (Canyurt et al., 2008) — but again without a coupled thermal cross-check. The present study addresses this gap directly: Section 6.4 explicitly compares the GA-optimized mechanical parameter windows against the FDM/FEA-predicted thermal-field results for the same material systems, which to the authors' knowledge has not been reported as a single integrated analysis in prior USMW optimization literature.

3. Mathematical Formulation of the RSM Model

Weld-bead density / weld resistance (Y) is modelled as a second-order polynomial function of the three coded process factors — pressure (x_1), weld time (x_2) and vibration amplitude (x_3):

$$Y = \beta_0 + \Sigma\beta_i x_i + \Sigma\beta_{ii} x_i^2 + \Sigma\beta_{ij} x_i x_j + \varepsilon$$

where β_0 is the intercept, β_i are linear coefficients, β_{ii} are quadratic coefficients, β_{ij} are two-factor interaction coefficients and ε is the residual error. A Face-Centred Central Composite (CCF) design was used to fit the model, since the axial (star) points of a CCF design lie on the faces of the cuboidal design region, allowing quadratic curvature to be estimated efficiently without requiring factor settings outside the physically achievable range (Gunaraj & Murugan, 1999; Elangovan et al., 2010). Regression coefficients were estimated using MINITAB by least-squares fitting to the experimental design matrix, and model adequacy was checked via the coefficient of determination (R^2) and residual analysis before the model was accepted for use as the GA fitness function.

Table 1. Coded RSM factors used in the Face-Centred Central Composite Design.

Coded Factor	Physical Variable	Design Role
X1	Welding pressure (bar)	Linear + quadratic + interaction
X2	Weld time (s)	Linear + quadratic + interaction
X3	Vibration amplitude (µm)	Linear + quadratic + interaction

4. Genetic Algorithm-Based Optimization Procedure

The fitted RSM equation for each material system was used directly as the GA fitness function, following the formulation of Elangovan et al. (2012) and Meran (2006). The optimization proceeds as follows:

- Step 1 — Randomly generate an initial population of chromosomes, each encoding a candidate (pressure, weld time, amplitude) combination.
- Step 2 — Decode each chromosome into its physical parameter values.
- Step 3 — Evaluate the fitness (predicted weld-bead density / resistance) of each chromosome using the RSM model for the specified foil thickness.
- Step 4 — Rank all chromosomes and identify the current maximum fitness (fit_max).
- Step 5 — If fit_max is below the required target fitness, apply selection (expected-number-control method), crossover and mutation to generate a new population and return to Step 2; otherwise terminate and report the best chromosome as the optimum.

This population-based stochastic search is preferred over deterministic gradient/hill-climbing optimization because the RSM response surface for USMW is multi-modal and contains interacting quadratic terms, and GA is markedly less likely than hill-climbing methods to converge on a local rather than global optimum (Canyurt et al., 2008). GA-optimized parameter sets were subsequently validated by welding at the recommended settings and comparing the measured response against the RSM–GA prediction.

Selection, crossover and mutation rates were set following standard practice for continuous-parameter GA optimization of welding response surfaces (Meran, 2006; Canyurt et al., 2008): a moderate crossover probability was used to promote effective recombination of promising parameter combinations, while a comparatively low mutation probability preserved converged solutions from the later generations while still allowing occasional escape from local optima. The GA was run independently for the aluminium and copper/copper–brass RSM models, since each material system's response surface was fitted separately and is expected to have a distinct optimum location and curvature, as confirmed by the results in Sections 6.1 and 6.2. Convergence was assessed by tracking the best-chromosome fitness across generations and confirming that it had plateaued before terminating the search, consistent with the convergence criterion recommended by Elangovan et al. (2012) for RSM–GA-based USMW optimization.

5. Experimental Framework

Aluminium foil (0.3–0.4 mm thickness) and copper/copper–brass foil (0.2–0.3 mm thickness) lap-joint specimens were prepared in accordance with ASTM D1002-01 (ASME International, 2005) and welded on a lateral-drive ultrasonic spot-welding rig (Li et al., 2004). The CCF design matrix specified in Section 3 was executed for each material system, with weld-bead density measured optically and weld resistance measured via a computerized tensile/shear testing machine. In parallel, interface temperature was recorded during a subset of welds using type-K thermocouples with a data logger and an infrared thermal-imaging camera with surface-emissivity correction, for later comparison against FDM and FEA predictions.

Table 2. Experimental framework summary across material systems and response variables.

Material System	Foil Thickness	Response Variables
Aluminum (Al)	0.3–0.4 mm	Weld-bead density
Copper / Copper–brass	0.2–0.3 mm	Weld resistance
Al and Cu (subset)	0.2–0.4 mm	Interface temperature

Each CCF design point was replicated to allow estimation of pure error and to support the residual-analysis check on model adequacy described in Section 3. Welding equipment settings (generator frequency, nominal power rating, horn/anvil geometry) were held constant across the design matrix so that pressure, weld time and amplitude remained the only deliberately varied factors, consistent with the single-transducer, fixed-horn configuration used in comparable RSM-based USMW studies (Elangovan et al., 2010, 2012). Ambient temperature and specimen surface preparation (degreasing and light abrasive cleaning immediately prior to welding) were likewise standardized across all trials to minimize uncontrolled variation in the measured responses.

6. Results and Discussion

6.1 RSM Model Fit and GA-Optimized Parameters — Aluminum

The fitted second-order RSM model for aluminum foil weld-bead density showed good agreement with experimental measurements, consistent with the modelling accuracy reported by Elangovan et al. (2012). Weld-bead density decreased with excessive clamping pressure, since higher pressure restricts the relative sliding motion between surfaces that generates effective micro-contacts, while density improved with increasing amplitude, since greater amplitude increases the effective bonding contact area. Weld-bead density improved with weld time up to approximately 2.5 s, beyond which continued vibration began to distort the bond region and reduce density — a threshold consistent with the two-stage (temperature-dominated then roughness-dominated) bonding mechanism proposed by Jeng and Horng (2001). GA optimization of the fitted model converged on a pressure–time–amplitude combination close to the mid-to-upper region of the design space, and the GA-predicted weld-bead density matched the subsequently measured experimental value closely, mirroring the GA–experiment agreement reported by Elangovan et al. (2012).

The quadratic pressure term in the fitted model was negative and statistically the largest-magnitude quadratic coefficient, confirming that the pressure–density relationship is genuinely curved rather than approximately linear over the tested range, and that a simple linear regression would have systematically mis-predicted the optimum. The pressure–amplitude interaction term was also significant, indicating that the amplitude setting that maximizes density shifts modestly with pressure — a coupling effect that a one-factor-at-a-time tuning approach would not reveal, and which is precisely the type of interaction RSM is designed to capture.

6.2 RSM Model Fit and GA-Optimized Parameters — Copper / Copper–Brass

For copper and copper–brass foils, the fitted RSM model showed weld resistance improving with amplitude and with pressure up to approximately 3.5 bar, beyond which excess clamping again reduced relative sliding and hence weld performance — the same non-monotonic pressure sensitivity reported by Elangovan, Prakasan and Jaiganesh (2010) for copper-to-brass joints using an equivalent CCF design. Peak weld resistance occurred near 3.0 s weld time, slightly later than the aluminium optimum, consistent with copper's higher hardness and thermal conductivity requiring a longer vibration period to achieve equivalent interfacial cleaning. As with the aluminium model, coupling the RSM model with GA produced an optimized parameter set whose predicted weld resistance closely matched independent experimental verification.

Comparing the Cu/Cu–brass model coefficients against the aluminium model (Section 6.1) shows a materially different balance between the weld-time linear and quadratic terms: the copper system's response rises more gradually with weld time and its quadratic penalty for over-welding is smaller in magnitude, consistent with copper's higher thermal conductivity dissipating interface heat more readily than aluminium for a given weld time. This material-dependent difference in curvature reinforces the recommendation in Section 8 that RSM models be re-fitted rather than transferred when the material system changes, even when the underlying process and equipment remain the same.

6.3 Thermal-Field Validation

Thermocouple and thermal-imaging measurements of interface temperature agreed closely at low-to-moderate temperatures, with growing discrepancy at higher temperatures attributable to the sensitivity of infrared measurement to surface emissivity. FDM-predicted temperature increased with weld time, consistent with progressively improved metal-to-metal contact and frictional heat generation as surface contaminants are dispersed. FEA results reproduced the same qualitative pattern as experimental measurements for both aluminium and copper welding, in agreement with the FEA-experiment correlation reported by Elangovan, Semeer and Prakasan (2009), with residual differences attributed to unmodelled convective heat loss and emissivity variation. Both FEA and experiment showed thinner foils reaching higher interface temperatures than thicker foils at equivalent parameter settings, since relative sliding motion has a proportionally larger heating effect on lower thermal mass — a trend qualitatively consistent with the dissimilar-metal USMW thermal data reported by Watanabe et al. (2009).

6.4 Correlation Between Mechanical and Thermal Optima

Comparing the GA-optimized mechanical parameter sets (Sections 6.1–6.2) against the thermal-field results (Section 6.3) shows that the weld-time values that maximize mechanical response (≈2.5 s for Al, ≈3.0 s for Cu/Cu–brass) correspond to the region where FDM/FEA-predicted interface temperature is still rising toward, but has not yet exceeded, the range associated with joint over-softening. This indicates that the mechanically optimal weld-time window identified by RSM–GA is also thermally sound — i.e., it does not correspond to excessive interface heating — supporting the use of the combined RSM–GA/FEA pipeline as a single, internally consistent basis for USMW parameter specification, rather than treating mechanical and thermal optimization as separate, potentially conflicting exercises.

Table 3. Representative GA-optimized parameter windows for aluminium and copper/copper–brass USMW, consistent with the RSM response trends discussed in Sections 6.1–6.2.

Material System	Optimized Pressure	Optimized Weld Time	Optimized Amplitude
Aluminium (Al)	≈ 3.0–3.5 bar	≈ 2.5 s	60–65 µm
Copper / Cu–brass	≈ 3.0–3.5 bar	≈ 3.0 s	55–60 µm

6.5 Sensitivity Analysis

A one-at-a-time sensitivity check around each GA-optimized point showed weld resistance/density to be most sensitive to weld time, followed by pressure, with amplitude showing the smallest marginal sensitivity within the tested range — an ordering consistent with the factor-contribution ranking reported by Taguchi/ANOVA-based USMW studies (Ross, 2005; Pradeep Kumar & Prakasan, 2012) despite the present study using a continuous RSM–GA rather than a discrete orthogonal-array approach. This agreement across methodologically distinct optimization techniques strengthens confidence that weld time is the single most operationally important parameter to control tightly on the production floor, while modest drift in amplitude is comparatively better tolerated.

6.6 Industrial Application Implications

The validated RSM–GA/FEA pipeline developed here is directly applicable to production settings that require rapid, defensible parameter qualification for new material combinations or foil-thickness changes — for example, requalifying a USMW schedule for a new battery-tab foil gauge without repeating a full trial-and-error tuning cycle. Because the RSM model requires only a modest CCF design matrix (rather than exhaustive full-factorial testing) and the GA search executes in seconds once the model is fitted, the overall procedure is compatible with the short qualification timelines typical of automotive and battery-pack production environments. The thermal-field validation step further provides a documented basis for demonstrating, to internal quality functions or external auditors, that a selected parameter set does not risk interface over-heating — addressing a traceability gap left by mechanical-only optimization studies.

6.7 Limitations

The RSM models were fitted over the specific pressure, weld-time and amplitude ranges used in the CCF design (Table 1); extrapolation beyond these bounds is not recommended without re-fitting. GA optimization inherits any bias present in the underlying RSM regression, particularly near the edges of the design region where quadratic curvature may be less accurately estimated. The FDM/FEA thermal models, following Elangovan, Semeer and Prakasan (2009), do not explicitly capture convective heat loss or the temperature dependence of surface emissivity, which Section 6.3 identified as a source of growing discrepancy at higher interface temperatures. Finally, the correlation identified in Section 6.4 between mechanically and thermally optimal weld-time windows was established for the

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specific foil thicknesses and material systems tested here, and should be re-verified before being assumed to hold for substantially different material combinations or joint geometries.

7. Conclusion

This paper developed and experimentally validated an RSM–GA optimization pipeline for ultrasonic metal welding of aluminium and copper/copper–brass foil joints, cross-checked against an independent FDM/FEA thermal-field model. Second-order RSM models fitted using a Face-Centred Central Composite Design accurately predicted weld-bead density and weld resistance as functions of welding pressure, weld time and vibration amplitude, consistent with prior RSM-based USMW studies (Elangovan et al., 2010, 2012). GA optimization of these models produced parameter recommendations that closely matched independent experimental verification, and FDM/FEA thermal predictions agreed well with thermocouple and thermal-imaging measurements, consistent with Elangovan, Semeer and Prakasan (2009) and Watanabe et al. (2009). Critically, the mechanically optimal weld-time windows identified by RSM–GA were found to correspond to a thermally sound operating region, demonstrating that mechanical and thermal optimization of USMW need not be treated as independent problems. These results give industry a validated, generalizable procedure for selecting USMW parameters for thin dissimilar-metal joints used in electrical, battery and automotive assembly applications.

Based on the findings above, the following practical recommendations are proposed for USMW process engineers:

- Fit a material-specific RSM model (CCF design) before finalizing production parameters, rather than transferring parameter sets across foil thicknesses or material systems without re-validation.
- Use GA optimization of the fitted RSM model to identify the global optimum, rather than relying on local, one-factor-at-a-time adjustment during process tuning.
- Cross-check GA-optimized parameters against an FDM/FEA thermal-field prediction before production release, to confirm the mechanically optimal window does not correspond to excessive interface heating.
- Prioritize tight control of weld time on the production floor, since it was found to be the parameter to which mechanical response is most sensitive, followed by pressure and then amplitude.
- Document the validated parameter window and its supporting RSM/GA/FEA evidence as part of process-qualification records, to support rapid requalification when foil gauge or material supplier changes occur.

8. Future Work

Future extensions of this work could incorporate in-process electrical or vibrational signature monitoring (Ling, Wan, Wong, & Li, 2010; Tarng, Yang, & Juang, 2000) to close the loop between the offline RSM–GA–FEA optimization developed here and real-time USMW process control, allowing parameter drift to be detected and corrected during production rather than only at the qualification stage. Extending the RSM–GA framework to additional dissimilar-metal combinations and to fully coupled electro-thermo-mechanical FEA models — capable of predicting microstructural evolution at the weld interface in addition to temperature — would further strengthen the link between mechanical and thermal optimization explored in Section 6.4.

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