

## Resistance Welding Simulation

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Resistance spot welding (RSW) is the predominant joining process in the automotive industry, with a single vehicle containing several thousand spot welds. The process relies on the simultaneous application of mechanical pressure and an electric current to generate localized *Joule* heating, forming a molten nugget that solidifies to create the joint. Numerical simulation of RSW has become indispensable for understanding the complex interplay between electrical, thermal, mechanical, and metallurgical phenomena, enabling process optimization, material selection, and weld quality control.

Current understanding emphasizes that a high-fidelity RSW model must capture the strongly coupled multi-physics: the electric current path, heat generation at faying interfaces (contact resistance), temperature-dependent material properties, phase transformations, and electrode deformation. The typical modeling approach employs coupled finite element (FE) analysis, often with an axisymmetric assumption to reduce computational cost, while advanced models incorporate thermoelectric coupling and mechanical contact.

### Governing Equations and Their Assumptions

The core of RSW simulation lies in the simultaneous solution of electrical potential, heat transfer, and mechanical equilibrium equations, with interaction terms representing Joule heating and contact phenomena.

#### *Electrical Potential (Current Flow)*

The distribution of electric potential  $\phi$  in the workpiece and electrodes is governed by the steady-state current continuity equation (quasi-static approximation, since the frequency is DC or 50/60 Hz AC with negligible inductive effects):

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

where  $\sigma$  is the electrical conductivity (temperature-dependent). The current density is  $\mathbf{J} = -\sigma \nabla \phi$ .

The skin depth at typical frequencies (e.g., 1000 Hz for medium-frequency DC) is large compared to workpiece thickness; thus inductive and capacitive effects are ignored. This simplifies the equation to a scalar Poisson-type problem, vastly reducing computational cost. Most RSW geometries (electrodes with rotational symmetry, flat sheets) are modeled as 2D axisymmetric. No azimuthal variation in current or temperature is assumed, which reduces mesh size by orders of magnitude, enabling parametric studies. However, this fails for non-axisymmetric features (e.g., misalignment, edge welds). The electrical conductivity is considered isotropic and a function only of temperature. This is acceptable for most metals; however, in the mushy zone, a mixture rule (e.g., linear interpolation between solid and liquid conductivity) is required to avoid unrealistic current concentrations.

#### *Heat Transfer (Thermal Equation)*

The temperature field  $T$  is obtained from the transient heat conduction equation with an internal heat generation term (Joule heating):

$$\rho c_p \frac{\partial T}{\partial t} = \nabla \cdot (k \nabla T) + \dot{q}_{Joule}$$

where  $\rho$  is the material density,  $c_p$  heat capacity,  $k$  thermal conductivity, and  $\dot{q}_{Joule} = \mathbf{J} \cdot \mathbf{E} = \sigma |\nabla \phi|^2$  is the volumetric heat generation rate.

The solid-liquid phase change is handled via an enthalpy method or effective heat capacity. The latent heat  $L_f$  is incorporated as:

$$c_p^{eff} = c_p + L_f \frac{\partial f_l}{\partial T}$$

where  $f_l$  is the liquid fraction. Accurate modeling of the mushy zone is critical for nugget size prediction and solidification behavior. In RSW, the melt pool is small (5–10 mm diameter) and the weld time is short (hundreds of milliseconds). Fluid flow (natural and Marangoni convection) is often neglected in traditional FE models due to the dominance of conduction and the complexity of coupling fluid dynamics. This simplification can lead to underestimation of heat transfer to the periphery, affecting the predicted nugget shape. Advanced models include Marangoni flow (via a coupled CFD or effective thermal conductivity multiplier) and show better agreement with experiments, especially for high-current regimes. Temperature-dependent thermal properties,  $k(T)$ ,  $\rho(T)$ , and  $c_p(T)$ , are essential. They are assumed to be isotropic and measured for each material. Ignoring the drop in thermal conductivity in the liquid state or the increase in specific heat near the melting point leads to errors in cooling rate predictions.

#### *Mechanical Contact and Electrode Force*

The mechanical deformation of electrodes and sheets, as well as the contact pressures at interfaces, directly influence the electrical and thermal contact resistances. The mechanical analysis is usually quasi-static, solving:

$$\nabla \cdot \boldsymbol{\sigma} = 0$$

with an appropriate elastic-plastic constitutive model (e.g., *von Mises* with isotropic hardening).

The electrodes and sheets undergo large plastic strains (especially the electrode tips, which mushroom over life). Small-strain theory is often used for simplicity, but large-strain formulations are more accurate for predicting indentation and contact area evolution. The contact area between electrodes and work piece directly determines current density; underestimating plastic deformation leads to overestimated current densities and premature nugget growth. The contact pressure at the electrode–sheet and sheet–sheet interfaces is computed from the mechanical solution and is used to evaluate contact resistances. The contact interfaces are assumed to have no relative sliding (stick condition).

#### *Contact Resistance Modeling*

The most critical and challenging aspect of RSW simulation is the representation of electrical and thermal contact resistances at the interfaces (electrode/sheet and sheet/sheet). These resistances dominate the heat generation. They are typically modeled as:

Electrical contact resistance is defined as  $R_{ec} = R_{ec}(T, P, \text{surface condition})$  and thermal contact resistance is  $R_{tc} = R_{tc}(T, P, \text{surface condition})$ . A common phenomenological model is:

$$R_{ec} = \frac{R_{ec0}}{(P/P_0)^m} \cdot f(T)$$

where  $P$  is the contact pressure,  $m$  an exponent (typically 0.5–1.0), and  $f(T)$  accounts for the softening and melting of surface asperities.

Often, the thermal contact resistance is related to the electrical contact resistance via the Lorenz number  $L_0$ :  $R_{tc} = R_{ec} \cdot L_0 T$ , where  $L_0 = 2.44 \times 10^{-8} \text{ W}\Omega/\text{K}^2$ . This relationship holds for clean metal contacts. This allows coupling of electrical and thermal contact models without separate calibrations, but may introduce errors for heavily oxidized surfaces. A constant contact resistance value may be used; however, modern models incorporate the transient evolution of contact area due to softening and plastic deformation. The contact resistance decreases rapidly as the temperature rises and the material yields, which is responsible for the “self-regulating” nature of RSW.

### *Coupling Strategies and Solution Approaches*

The multi-physics nature of RSW requires a coupled solution strategy. Two common approaches are:

1. Staggered (sequential) coupling: The electrical-thermal problem is solved first, then the mechanical problem is updated with the temperature, and iterations are performed within each time step. If the multi-physics coupling is weak this method is computationally efficient but may suffer from convergence issues if the coupling is strong (e.g., large plastic deformation).

2. Fully coupled (monolithic) approach: All three physics are solved simultaneously using a monolithic matrix. This requires specialized solvers and is computationally expensive which is more robust for highly nonlinear problems, particularly when contact conditions change drastically during the weld.

### *Metallurgical and Phase Transformation Models*

After the welding current ceases, the nugget solidifies and subsequent cooling induces phase transformations in the heat-affected zone (HAZ). For automotive steels (e.g., dual-phase, martensitic, press-hardened), predicting the final microstructure is essential for joint strength assessment.

Thermal cycles from the coupled thermal-mechanical simulation are fed into \*\*kinetic phase transformation models. Johnson–Mehl–Avrami–Kolmogorov (JMAK) equations are used for ferrite, pearlite, bainite formation. Koistinen–Marburger equation is used for martensite formation:

$$f_M = 1 - \exp(-\alpha(M_s - T))$$

where  $f_M$  is the volume fraction of the martensite,  $M_s$  the martensite start temperature and  $\alpha$  a material constant. The phase transformations are decoupled from the thermal and mechanical fields (no transformation-induced plasticity considered). \*Significance:\* Simplifies the model; however, for high-strength steels, transformation strains can affect residual stresses and distortion, which may require more advanced coupled metallurgical-mechanical models.

### Applications in the Automotive Industry

Numerical simulation of RSW has become a standard engineering tool in automotive manufacturing, addressing challenges from new materials to electrode lifetime optimization.

### *Weldability of Advanced High-Strength Steels (AHSS)*

The automotive industry increasingly uses AHSS (e.g., DP800, 22MnB5) to reduce weight while maintaining crashworthiness. These materials present challenges due to their high hardenability and susceptibility to weld nugget cracking or HAZ softening.

Simulation selects optimal welding schedules (current, time, electrode force) to achieve an acceptable nugget size (e.g.,  $4\sqrt{t}$ , where  $t$  is the sheet thickness) without expelling molten metal. Axisymmetric FE models with temperature-dependent properties and phase transformation kinetics also predict the HAZ width and the fraction of martensite. The model assumes homogeneous material properties for each sheet, ignoring the effect of galvanized coatings on the contact resistance. Coating effects could be incorporated through additional interface resistance layers, but this requires extensive calibration. The simulation helps avoid the “expulsion window” by limiting the peak temperature and nugget growth rate.

#### *Electrode Life Prediction and Design*

Electrode wear is a major cost factor in automotive assembly lines. Cu–Cr–Zr electrodes degrade due to thermal cycling, plastic deformation (mushrooming), and alloying with the sheet coating (e.g., Zn from galvanized steel). Simulation predicts the evolution of electrode tip diameter and contact area over thousands of welds to schedule electrode dressing operations. Coupled thermo-mechanical models simulate successive welds, tracking accumulated plastic strain and temperature cycles. A damage criterion (e.g., based on the number of cycles to crack initiation) is applied. The electrode geometry is updated periodically based on a wear model (e.g., Archard’s law), which allows optimization of electrode cooling (water flow rate) and tip geometry to maximize electrode life, reducing downtime.

#### *Dissimilar Material Joining (Steel to Aluminum)*

With the rise of multi-material lightweight vehicles, RSW is also used to join aluminum alloys to steel, although this is challenging due to the formation of brittle intermetallic compounds (IMCs) and the large difference in electrical and thermal properties.

Simulation optimizes the weld schedule to control the IMC layer thickness ( $Fe_2Al_5$ ,  $FeAl_3$ ) and achieve acceptable joint strength. 3D models are often required because the current path is asymmetric. The simulation includes temperature-dependent contact resistances at the Al/steel interface and considers the influence of an interlayer (e.g., Al–Si coating). Species transport or phase field models can be coupled to predict IMC growth. The IMC growth is diffusion-controlled and follows a parabolic rate law with temperature and time; the simulation provides the thermal history at the interface to estimate IMC thickness, which enables the identification of process windows that keep IMC thickness below critical values (typically 1–5  $\mu\text{m}$ ).

#### *Weld Splash (Expulsion) Prediction*

Expulsion of molten metal is a major defect that compromises weld quality and can damage electrodes or surrounding components.

Simulation predicts the onset of expulsion based on melt pool pressure exceeding the electrode force. Advanced models couple the thermal-mechanical solution with a melt pool dynamics (CFD) or use a simple criterion: when the liquid pressure at the interface exceeds the contact pressure, expulsion is assumed. Expulsion occurs when  $P_{hydrostatic} + P_{dynamic} > P_{electrode}$ . This allows process engineers to design current profiles (e.g., upslope, pulsing) that avoid expulsion while maximizing nugget size.

#### *Residual Stress and Distortion in Assemblies*

For large automotive body assemblies (e.g., side frames, floor pans), the cumulative distortion from hundreds of spot welds affects final fit-up and dimensional quality.

Simulation predicts welding-induced distortion and optimize welding sequence. The thermal cycle from a single spot weld model is simplified into a heat input history and applied to a coarse mesh of the entire assembly. An inherent strain method or thermo-elastic-plastic FE analysis is used. The effect of each weld is additive and independent; interactions are neglected except for the accumulated temperature field. This enables simulation of full body-in-white (BIW) structures, guiding robot path planning and clamping strategies to minimize rework.

### Concluding Remarks

The current understanding of resistance spot welding numerical simulation has matured into a robust discipline that integrates electrical, thermal, mechanical, and metallurgical phenomena. Key assumptions—such as axisymmetry, quasi-static electromagnetic fields, and phenomenological contact resistance models—are essential for balancing accuracy and computational feasibility. The significance of each assumption lies in its impact on the prediction of critical outputs: nugget size, HAZ properties, electrode deformation, and defect formation.

For the automotive industry, simulation is no longer a research luxury but a necessity for rapid development of welding schedules for new materials, extending electrode life, and ensuring the structural integrity of lightweight multi-material vehicles. Future trends point toward the integration of machine learning for real-time process control, high-fidelity 3D models for complex geometries, and coupled microstructure evolution models to predict long-term joint performance under fatigue loading.