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Research Paper

Exploring the Hidden Benefits and Dual Nature of Electrode Misalignment in Resistance Spot Welding: Unveiling Drawbacks and Advantages Through Isolated Thermal-Induced Stress and Nugget Formation Analysis

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Abstract
This study examines the effects of electrode misalignment on key parameters in Resistance Spot Welding (RSW), specifically nugget formation, temperature distribution, and thermal-induced residual stresses. Employing a detailed finite element model in ABAQUS, the research isolates the thermal impacts of misalignment, offering insights into how this often-overlooked factor affects weld quality. Traditionally, electrode misalignment has been regarded as a flaw that compromises weld integrity, resulting in uneven heat distribution, asymmetrical nugget formation, and elevated residual stresses. This study, however, reconsiders this view by investigating both the challenges and potential advantages of misalignment, particularly regarding future RSW machine design. The findings indicate that misalignment in RSW can expand nugget size and bonding area. However, it also introduces risks such as reduced nugget depth and increased residual stresses, which could impact weld durability. These trade-offs, however, can be effectively managed through precise adjustments to welding parameters. This research proposes that misalignment, rather than being purely detrimental, could be strategically utilized in specific applications, guiding the design of future RSW machines to optimize weld quality by harnessing the controlled advantages of misalignment.

Keywords
Resistance Spot Welding, Electrode Misalignment, Nugget Formation, Temperature Distribution, Thermal-Induced Residual Stress

1. Introduction

Welding is an indispensable process in modern industry, providing the strength and durability required to join materials across diverse applications. In the automotive sector, for example, welding forms the backbone of the "body-in-white" phase, where the structural frame of a vehicle is assembled to ensure safety and integrity. Beyond automotive, welding is fundamental in aerospace, construction, and heavy manufacturing, where reliable, high-quality joints are essential for components that endure substantial stresses. With its versatility, speed, and cost-effectiveness, welding remains a cornerstone of industrial production, driving advancements in how materials are combined to build everything from skyscrapers to aircraft [1-4]. Resistance Spot Welding (RSW) is a fundamental process in various manufacturing industries, particularly in automotive production, where it is widely employed to join sheet metals. The efficiency, speed, and relatively low cost of RSW make it an ideal choice for assembling body panels and other components in mass production. In the automotive sector, RSW is crucial during the "body-in-white" (BIW) phase, where the metal parts of a vehicle are joined before painting. These welds' quality directly influences the final product's structural integrity, durability, and safety. Given its significance, extensive research and development have optimized the RSW process, focusing on electrode design, welding current, pressure, and time [5-10]. Traditionally, electrode misalignment in RSW has been viewed as a critical defect that undermines weld quality. Misalignment refers to the improper positioning of electrodes relative to the workpieces, resulting in uneven current distribution, asymmetrical heat generation, and non-uniform nugget formation. This misalignment can lead to issues such as incomplete fusion, voids, cracks, and diminished mechanical strength. As a result, maintaining precise electrode alignment has been considered essential for producing high-quality welds. However, despite the focus on alignment, misalignment remains a common issue in industrial settings, often due to wear and tear of the equipment, operator error, or workpiece variations [11-13]. Extensive investigation has been conducted in numerous industrial procedures, such as forming [5-14], cutting [15-17], welding, etc., utilizing finite element simulations, which allow engineers and designers to examine these intricate physical occurrences. Numerical simulations offer valuable insights into stress, strain, temperature, and deformation patterns, supporting manufacturers in material selection, design adjustments, and the management of welding process complexities [4, 18. 19]. By utilizing finite element method simulations, researchers can analyze the welding process, study the effects of different parameters on weld quality, and predict outcomes accurately [20-22]. These RSW simulations help optimize process parameters, such as welding current, time, and electrode force, to enhance joint strength and durability [21]. Additionally, using explainable boosting machine algorithms in simulation models allows for high accuracy in predicting joint quality while maintaining interpretability, aiding process control and optimization [23].

Yashmetov et al. [24] introduced a novel hybrid mathematical framework for analyzing thermal deformation phenomena in resistance spot welding. Kumar et al. [25] developed a numerical simulation model that accurately represents the weld nugget formation during the resistance spot welding process. Lee et al. [26] created a simulation model for the 3D DC RSW process to anticipate the shape and size of the nugget accurately. This model has proven reliable and may be used to improve quality control in the automobile industry. The computational work conducted by Raoelison et al. [27] focused on resistance spot welding of zinc-coated steel sheets. They employed a sequential Electrical-Thermal-Metallurgical and Mechanical finite element analysis to expand the calculation to two-sheet assemblies, achieving successful results. The novel modeling environment for three-dimensional resistance welding has been developed by Nielsen et al. [28], integrating electro-thermo-mechanical connections and electrical, thermal, mechanical, and metallurgical properties. Wang et al. [29] created a comprehensive simulation model that encompasses multiple physical phenomena to analyze the resistance spot welding of Al-Steel. The integrity of welds produced in RSW can be significantly compromised by misalignment during the welding process. Misalignment refers to the improper positioning of the components to be welded, affecting the electrode contact's accuracy and the joint's overall quality [13]. Misalignment in welding causes uneven heat distribution, weak welds, and inconsistent weld nugget size, affecting mechanical strength and toughness, especially at the positive polarity electrode side [30]. Jun et al. [31] showed that the distance of misalignment influenced tensile shear strength, cross tension strength, ductility ratio, and failure mode in resistance element welding (REW), with abnormal current paths causing asymmetrical nugget shapes and stress concentration due to gaps between materials. Moreover, misalignment can adversely affect electrode wear and consumption [32]. Uneven electrode positioning leads to uneven pressure and thermal cycling, accelerating electrode wear, necessitating frequent replacements, increasing operational costs, and reducing production efficiency. Residual stress plays a crucial role in RSW, substantially impacting welded structures' mechanical properties and long-term durability, especially in the automotive sector. The residual stresses trapped in the material after welding can negatively impact the joints' strength, fatigue life, and resistance to cracking. As a result, this can affect vehicles' overall safety and integrity. The utilization of Advanced High Strength Steels (AHSS) and aluminum alloys in automotive applications poses distinct difficulties due to their specific material properties, which complicate the handling of residual stresses [33-35].

This study examines the potential benefits and challenges of electrode misalignment in RSW, focusing on thermal-induced residual stresses and their impact on weld integrity. By isolating thermal effects within a controlled simulation environment using ABAQUS, this research provides a nuanced understanding of how misalignment affects critical welding parameters such as nugget formation, temperature distribution, and stress patterns. The study's scope is intentionally specific, centering on a case of mild steel workpieces and copper electrodes with a 2.5 mm misalignment. This targeted approach allows in-depth analysis while recognizing limitations, primarily excluding mechanical stresses and material heterogeneity. The findings aim to contribute to the ongoing discussion on the role of misalignment in RSW, offering insights that may guide future research and support the design of RSW machines capable of harnessing controlled misalignment for improved weld quality.

Although this study is conducted within a specific context, it challenges the traditional view of electrode misalignment as purely detrimental. By examining the risks and potential advantages, this research seeks to open new pathways for understanding and optimizing the RSW process, potentially driving innovations in welding technology that enhance the quality and efficiency of industrial welding operations.

2. Simulation Framework and Numerical Approach

2.1 Finite Element Modeling in ABAQUS

Model Setup

A detailed finite element model was developed to investigate the effects of electrode misalignment in RSW using ABAQUS, a powerful simulation software well-suited for capturing the complex thermo-mechanical interactions inherent in welding processes. The schematic in Figure 1 represents the RSW process, widely used in the automotive and manufacturing industries for joining sheet metals. In this process, an alternating current (AC) passes through the upper and lower electrodes, generating heat at the contact points due to electrical resistance. This heat melts the metal, forming a localized weld nugget, while the electrodes apply force to ensure a strong bond. The upper electrode is movable to apply pressure, while the lower one remains fixed.

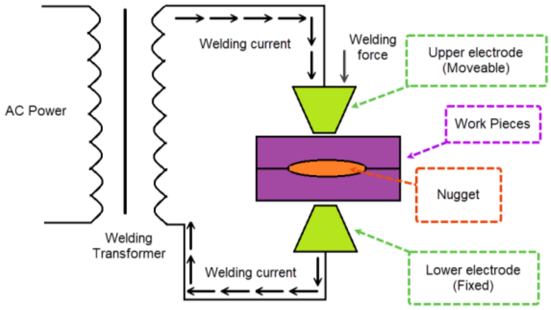

Figure 1. Schematic diagram of the Resistance Spot Welding (RSW)

Simulation Steps

This study's simulation was structured to ensure continuous contact between the workpieces and electrodes, effectively isolating thermal interactions and minimizing the impact of mechanical stresses. In achieving the simulation, appropriate interaction properties were defined in the ABAQUS model, ensuring the surfaces remained in contact without needing an initial squeeze phase typically used in physical RSW processes. The simulation included a brief squeeze time as a precautionary step, though the modeling choices minimized its influence on the overall process. This approach allowed for a more focused analysis of the thermal effects of electrode misalignment, reducing the potential confounding effects of mechanical stresses on the results. The RSW process was simulated through the following key steps:

- Welding Step: During this phase, an electrical current was applied through the electrodes, generating heat at the interface of the workpieces due to electrical resistance. The localized heating resulted in the formation of a molten nugget at the weld site. The welding current and duration were carefully controlled to replicate typical RSW conditions. The simulation monitored the temperature distribution and nugget formation, with particular attention to the impact of the electrode misalignment on these factors. Figure 2 illustrates the applied current in each step of the simulation.

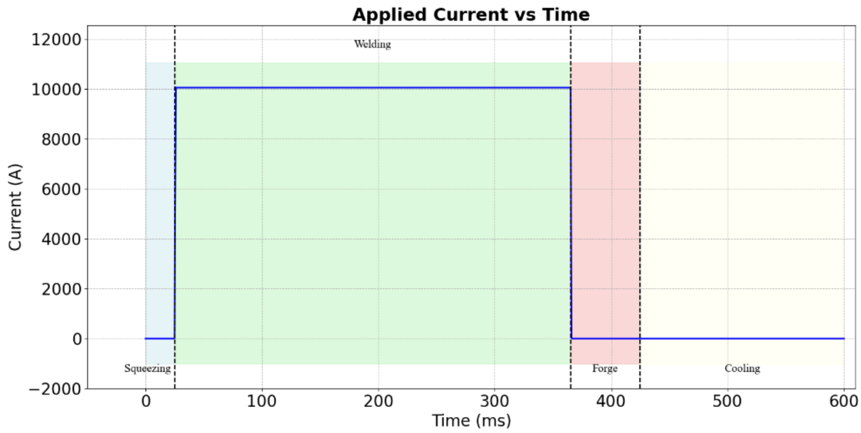

Figure 2. Applied electrical current in each step of the simulation

- Forging Step: Following the welding phase, additional pressure was theoretically applied in the model to forge the molten metal and ensure proper solidification. However, in the simulation, this was done by holding the electrodes in their place and continuing contact without additional forces.

- Cooling Step: In the final phase, the welded joint was allowed to cool to ambient temperature. This cooling process was critical for analyzing the development of thermal-induced residual stresses.

2.2 Material properties

Electrode

Copper is widely regarded as an optimal electrode material for RSW due to its high electrical and thermal conductivity, facilitating efficient heat generation and dissipation. In RSW, the performance of copper electrodes is significantly influenced by their temperature-dependent material properties, which vary under the high thermal loads typical of the welding process. Figure 3 provides a comprehensive overview of these temperature-dependent variations: Figure 3(a) illustrates the yield stress, which affects the electrode's ability to maintain structural integrity under pressure; Figure 3(b) displays the density, a factor influencing the thermal mass and heat transfer properties of the electrode; Figure 3(c) shows the specific heat, which determines the amount of heat required to raise the temperature of the copper, thereby affecting thermal regulation; and Figure 3(d) depicts the thermal conductivity across various temperatures, highlighting copper's capacity to conduct heat away from the weld site. These temperature-dependent variations are critical to accurately simulate and predict copper's behavior in RSW, as they directly impact heat flow, stress distribution, and electrode wear, all of which are essential for ensuring weld quality and process efficiency [36-37].

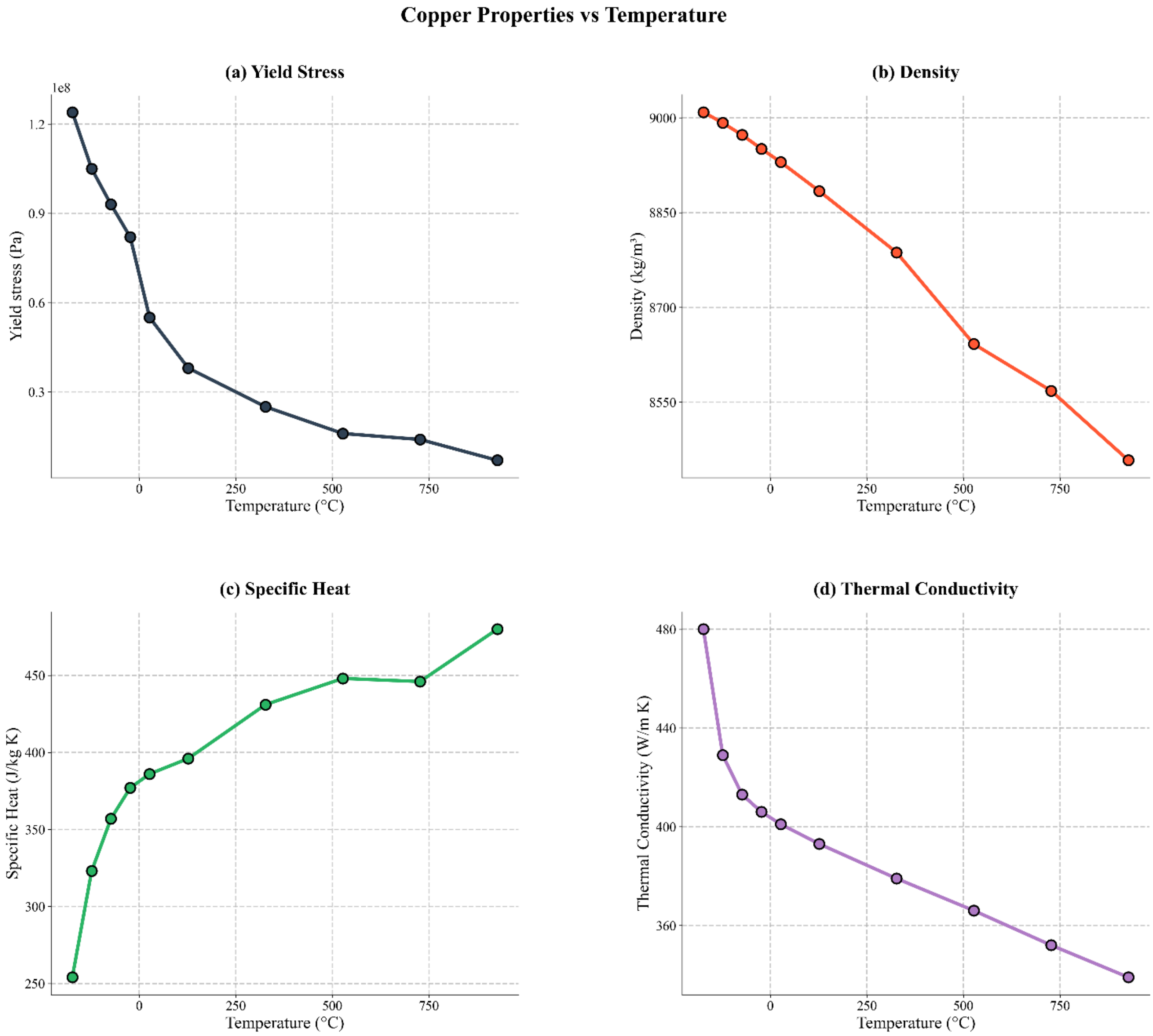

Figure 3. Temperature-dependent material properties of copper used as the electrode in the simulation. (a) yield stress, (b) density, (c) specific heat, and (d) thermal conductivity, each as a function of temperature ranging from -150°C to 900°C

Workpieces

Mild steel has temperature-dependent material properties that make it well-suited for RSW, as illustrated in Figure 4. The modulus of elasticity decreases with temperature (Figure 4a), allowing mild steel to deform slightly under welding forces. In contrast, the rising Poisson ratio (Figure 4b) enhances its ability to accommodate welding-induced stresses. Additionally, the thermal expansion coefficient increases with temperature (Figure 4c), facilitating intense fusion of the weld nugget. In contrast, thermal conductivity decreases (Figure 4d), concentrating heat within the weld zone to support structural integrity. These characteristics and a melting point near 1350°C make mild steel an optimal material for achieving robust, reliable spot welds in RSW applications [36-38].

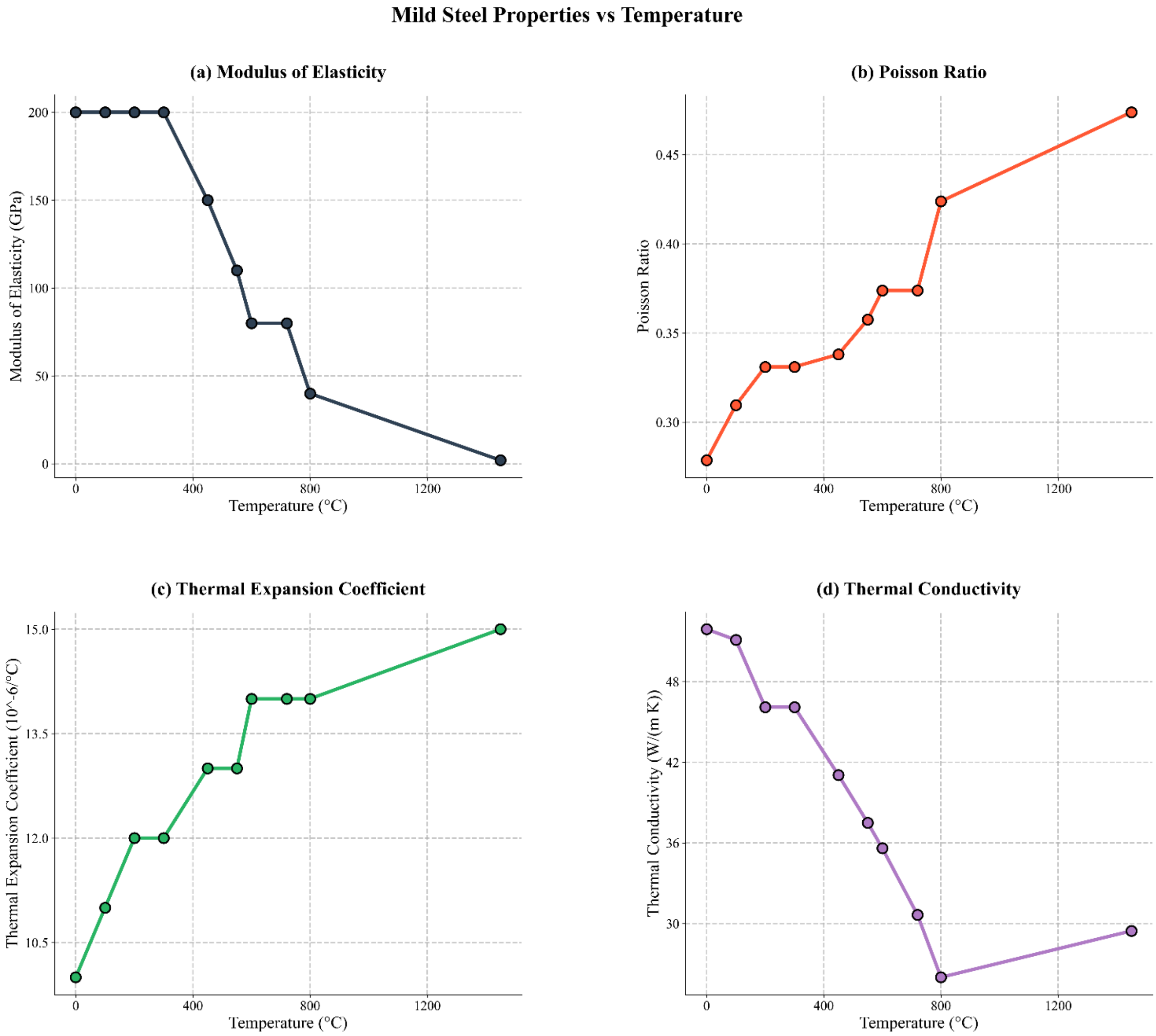

Figure 4. Temperature-dependent material properties of mild steel used in RSW. (a) modulus of elasticity, (b) Poisson ratio, (c) thermal expansion coefficient, and (d) thermal conductivity as a function of temperature

The misalignment modeling

In this work, the electrode is positioned with a misalignment along the longitudinal axis of the plate, namely at a distance of roughly 2.5 mm. This misalignment is depicted in Figure 5.

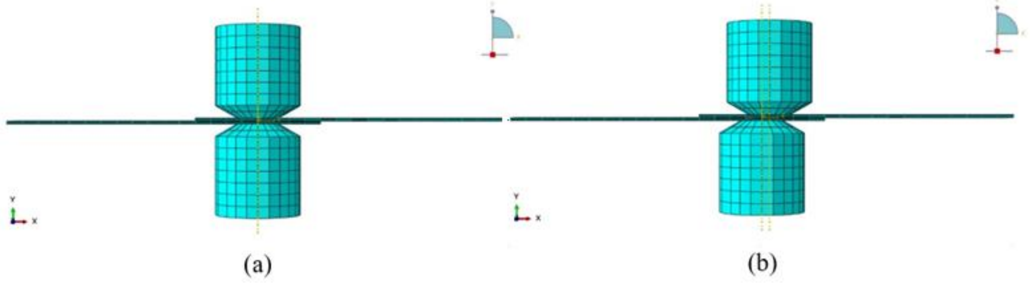

Figure 5. (a) The configuration of the RSW without the misalignment (b) The configuration of the RSW with 2.5 mm misalignment

2.3 Sensitivity analysis

Importance of Sensitivity Analysis

Sensitivity analysis is an essential step in the finite element method (FEM), ensuring that simulation results are both accurate and computationally efficient. This process involves adjusting key parameters, such as the number of elements in the mesh, to evaluate their impact on simulation outcomes. Doing so helps identify the optimal configuration that delivers precise results while minimizing computational demands.

Sensitivity Analysis Results and Chosen Parameters

The sensitivity analysis involved varying the number of elements in the mesh and observing the resulting changes in nugget diameter and area. Figure 6 illustrates the relationship between the number of elements in the workpieces and two essential properties of the weld nugget: its diameter (Figure 6a) and approximate area (Figure 6b). The results showed that as the number of elements increased, the calculated nugget diameter and area initially exhibited variability but eventually stabilized within a specific range. This convergence indicated that further refinement of the mesh would yield diminishing returns in accuracy. Based on these findings, an optimal element size was selected to balance accuracy and computational efficiency. For the workpieces, 1,629 elements were used, which fell within the "best range" identified during the analysis. This configuration was sufficient for accurately modeling the thermal and mechanical behavior of the isolated RSW process, including the effects of electrode misalignment.

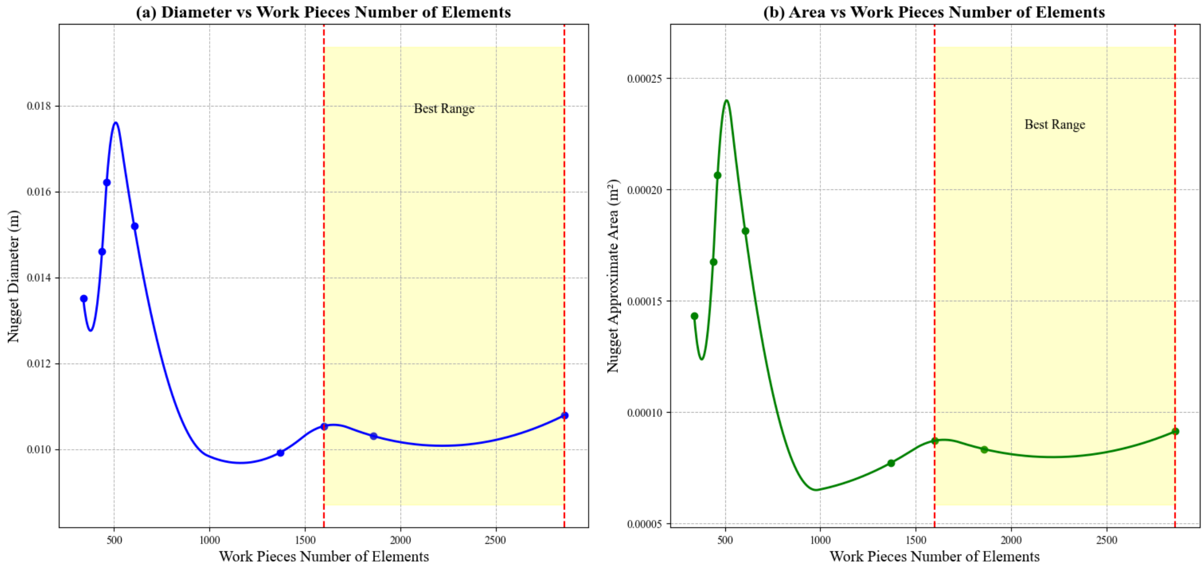

Figure 6. Sensitivity analysis of nugget properties as a function of the number of elements in the workpieces (a) nugget diameter and (b) nugget approximate area, with the shaded region indicating the optimal range of element numbers for accurate simulation results

Data Extraction and Processing Using Python Scripts

Custom Python scripts were developed to extract and analyze the data from the ABAQUS simulations. These scripts automated the extraction of critical data points, including temperature distribution, stress patterns, and nugget size, at various stages of the welding process. The scripts were designed to capture data at specific intervals during the simulation, allowing for a detailed analysis of how the misalignment influenced the welding process over time. This approach ensured that the thermal effects of misalignment were thoroughly documented and could be analyzed in the context of nugget formation and thermal-induced stresses.

2.4 Isolating Thermal Effects

This study specifically focused on isolating the thermal impacts of electrode misalignment in RSW. The simulation was designed to control or exclude other potential influences, such as mechanical stresses resulting from external forces. By isolating thermal effects, the study aims to clarify the impact of misalignment on thermal distribution and its effects independently of mechanical factors. In conventional, real-world RSW applications, welding typically leads to material fusion, producing a blend of thermal- and mechanical-induced residual stresses. These stresses are inherently intertwined and difficult to separate in practical scenarios. However, this study employed a novel approach to distinguish between these two types of stresses as much as possible. The upper electrode was fixed in the simulation to ensure continuous contact with the workpieces during the welding and cooling phases while deliberately preventing the formation of new elements typically occurring during the fusion process. This method effectively isolated the thermal-induced and mechanical-induced stresses by maintaining the materials in an unfused state. Although these two types of residual stresses are usually inseparable, the chosen approach allowed for a more distinct analysis of their effects.

It is essential to acknowledge that this approach, while providing valuable insights into the thermal effects of misalignment, also represents a significant study limitation. The findings are specific to the controlled simulation conditions and do not fully capture the complexities of an actual RSW process, where thermal and mechanical interactions simultaneously occur. This study does not simulate an entirely realistic welding process but rather an isolated analysis focused on thermal effects. Despite these limitations, the results offer a foundational understanding of how thermal-induced stresses develop without mechanical influences. This understanding could inform future research and the design of RSW machines, potentially leading to innovations that better manage and leverage these stresses for improved weld quality. By isolating these effects, the study provides a unique perspective that could be valuable in further optimizing the RSW process.

3. Results and discussion

3.1 Nugget Size Comparison: Aligned vs. Misaligned Cases

Figure 7 compares the maximum dimensions of the weld nugget formed under both aligned and misaligned cases across different planes: longitudinal (X), width (Z), and depth (Y) directions, as well as the maximum chords in the XY, XZ, and YZ planes.

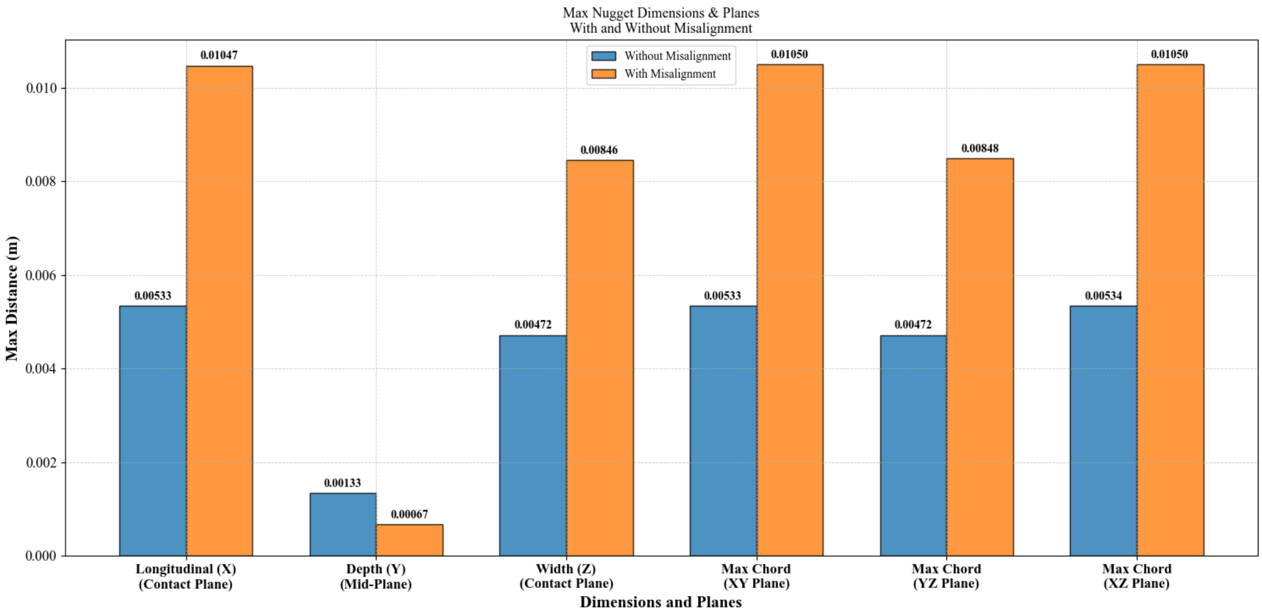

Figure 7. Comparison of maximum nugget dimensions and chords across various planes in both aligned (without misalignment) and misaligned scenarios

The nugget formation in both cases presents unique advantages and drawbacks, which are summarized in Table 1.

Table 1. Comparison of nugget dimensions in aligned (without misalignment) and misaligned scenarios

Dimension/Plane	Without Misalignment	With Misalignment	Discussion
Longitudinal (X)	0.00533 m	0.01047 m	Misalignment elongates the nugget, increasing the bonding area.
Width (Z)	0.00472 m	0.00846 m	Width also increases in the misaligned case, expanding surface area, but may affect the uniformity of the weld.
Depth (Y)	0.00133 m	0.00067 m	Reduced depth in misalignment may weaken the weld, while the weld provides a better fusion depth in the aligned case.
Max Chord (XY Plane)	0.00553 m	0.00950 m	Misalignment increases nugget spread, but the aligned case offers a more symmetrical shape, which is beneficial for strength.
Max Chord (XZ Plane)	0.00533 m	0.00950 m	Similar to the XY plane, aligned case causes focused nugget formation.
Max Chord (YZ Plane)	0.00472 m	0.00854 m	YZ plane shows greater nugget size in the case of misalignment, but in the aligned case, it delivers a balanced nugget.

Key insights of the Table 1 and Figure 7 can be summarized as:

- Nugget Shape Consistency: In the aligned case, the largest nugget dimensions (X and Z) correspond to the maximum chords in their respective planes, indicating a focused, symmetrical nugget with intense bonding and even heat distribution.
- Impact of Misalignment: The misaligned case increases nugget size in the X and Z directions, expanding the bonding area but reducing depth (Y) to 0.00067 m, potentially weakening the weld.
- Advantages of the Aligned Case: The more concentrated nugget formed in the aligned case offers better structural integrity, consistent material fusion, and balanced dimensions, leading to a stronger weld.
- RSW Machine Design Implications: While misalignment can increase bonding area, it does pose a risk of reduced depth and potentially weaker welds. However, given that most other parameters, such as nugget size in the X and Z directions, are significantly enhanced, misalignment could be strategically utilized in new RSW designs. The trade-offs could be managed with careful adjustments to welding parameters, making misalignment a viable option for applications where increased surface bonding and other enhanced parameters are desirable.
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3.2 Temperature Distribution Analysis

Temperature Distribution during Nugget Formation

This section presents the temperature distribution within the nugget at the final stage of the welding process for both aligned and misaligned cases. The figure displays several views, as showcased in Figure 8 and Table 2.

Table 2. Summary of temperature distribution during the final stage of nugget formation in aligned and misaligned cases across different views and planes

View/Plane	Aligned Case	Misaligned Case
Perspective	Symmetrical temperature distribution was observed, ensuring even heat spread and consistent melting across the nugget (Figure 8a)	Uneven heat distribution with higher concentration on one side, potentially leading to irregular melting and solidification (Figure 8b)
Top View	Circular heat distribution indicates uniform heating across the nugget, suggesting a balanced and robust weld structure (Figure 8c)	Elliptical heat distribution with off-center concentration may cause uneven microstructure and localized weaknesses in the weld (Figure 8d)
XY Plane	Consistent temperature gradient along the XY plane, supporting uniform fusion and solidification throughout the weld (Figure 8e)	Uneven temperature distribution, which could result in varying cooling rates and potentially weaker areas within the weld (Figure 8f)
YZ Plane	Balanced temperature distribution along the YZ plane, promoting equal material fusion and maintaining weld strength (Figure 8g)	Shifted heat pattern, indicating potential for weaker weld due to uneven thermal effects and material properties (Figure 8h)

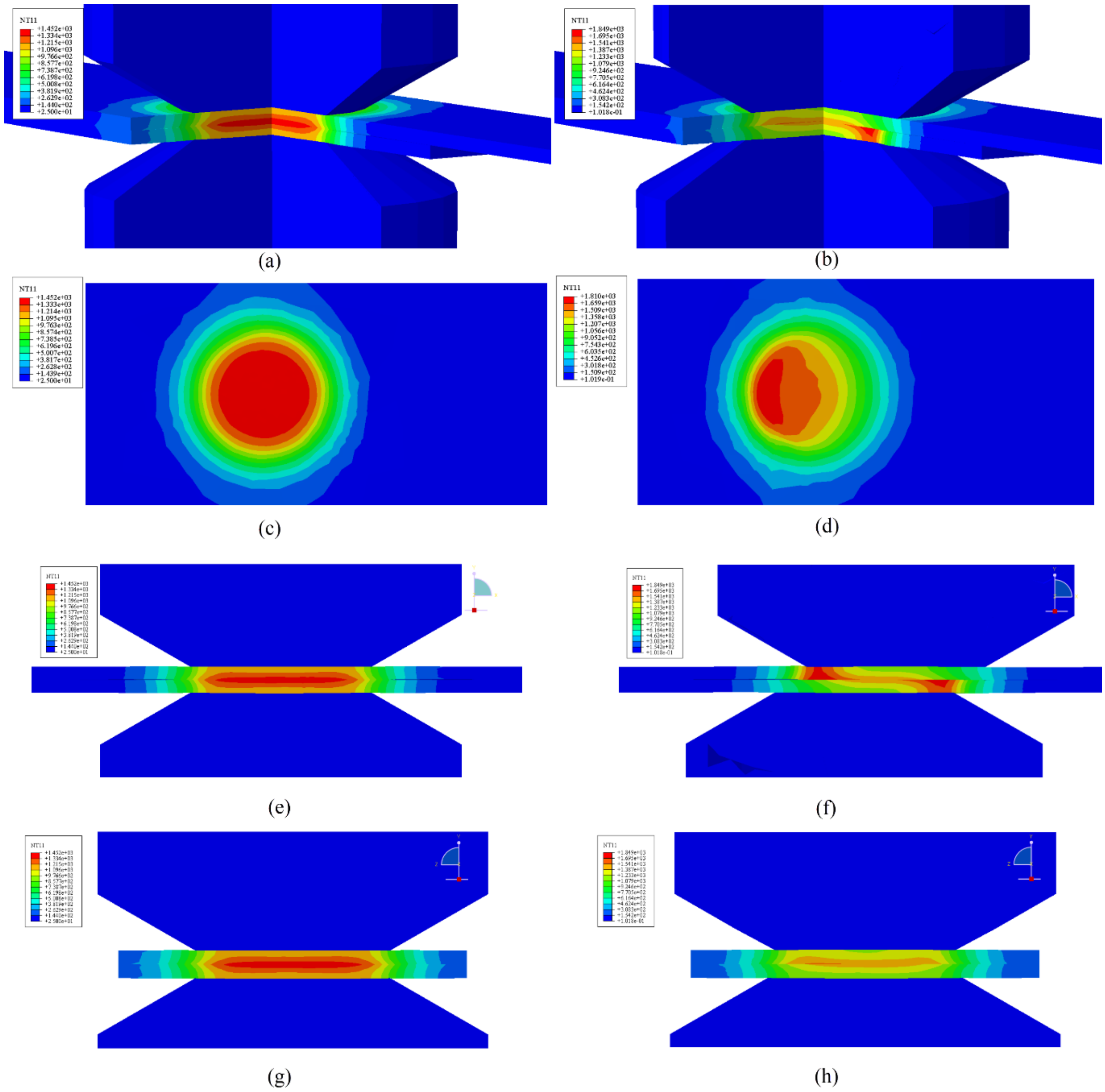


Figure 8. Temperature distribution during the final stage of the welding step in the RSW process. (a) and (b) are perspective views for the aligned and misaligned cases. (c) and (d) are top views showing the heat spread across the nugget for both cases. (e) and (f) illustrate the temperature distribution in the XY plane, while (g) and (h) show the temperature distribution in the YZ plane for aligned and misaligned cases

The aligned case demonstrates a uniform temperature distribution across all views, leading to consistent melting, solidification, and a robust weld. The symmetry in temperature distribution suggests a more uniform microstructure, enhancing the weld's mechanical properties. In contrast, the misaligned case presents an uneven temperature distribution, with significant asymmetry in the heat spread, particularly in the perspective and top views. This uneven heating can lead to differential cooling rates, resulting in localized weaknesses that could compromise the weld's integrity. The elliptical temperature spread in the top view indicates that misalignment might introduce areas with varying microstructural properties, which could affect the overall strength and durability of the weld. However, these microstructure and heat distribution variations could also present opportunities for improved design. By understanding and controlling these effects, optimizing the RSW process for specific applications might be possible, potentially leading to innovative welding techniques that leverage misalignment for enhanced performance in specific contexts.

The temperature distribution observed in this study is supported by its alignment with findings from multiple prior studies in the field. For instance, the results correspond well with those reported by Yongki Lee et al. [39], Jiwoong Lee et al. [40], Rohit Verma et al. [41], and Zixuan Wan et al. [42], where cohesive and predictable temperature gradients were demonstrated under similar resistance spot welding conditions. This consistency across studies reinforces the validity of the temperature distribution at each stage of the welding process in the present research, indicating that the thermal dynamics captured here accurately represent typical behavior within resistance spot welds. Such agreement with established research underscores the robustness of the model's predictive capabilities.

Average Nugget and Workpiece Temperature across Welding Stages

The average temperature of the nugget and the entire workpiece during each stage of the welding process-squeezing, welding, forging, and cooling—was recorded for both aligned and misaligned cases. The temperature data provided critical insights into how thermal dynamics evolve throughout welding.

- Nugget Temperature (Figure 9): The misaligned case consistently exhibited higher temperatures than the aligned case across all stages. During the welding phase, the peak average nugget temperature reached approximately 1500°C for the misaligned scenario, compared to around 1350°C for the aligned scenario. This difference persisted into the cooling phase, where the nugget in the misaligned case retained higher temperatures for longer.
- Workpiece Temperature (Figure 10): Similar trends were observed for the overall workpiece temperature. The misaligned configuration led to higher average temperatures throughout the welding process. Notably, during the welding stage, the workpieces average temperatures reached approximately 850°C in the misaligned case, compared to about 800°C in the aligned case.

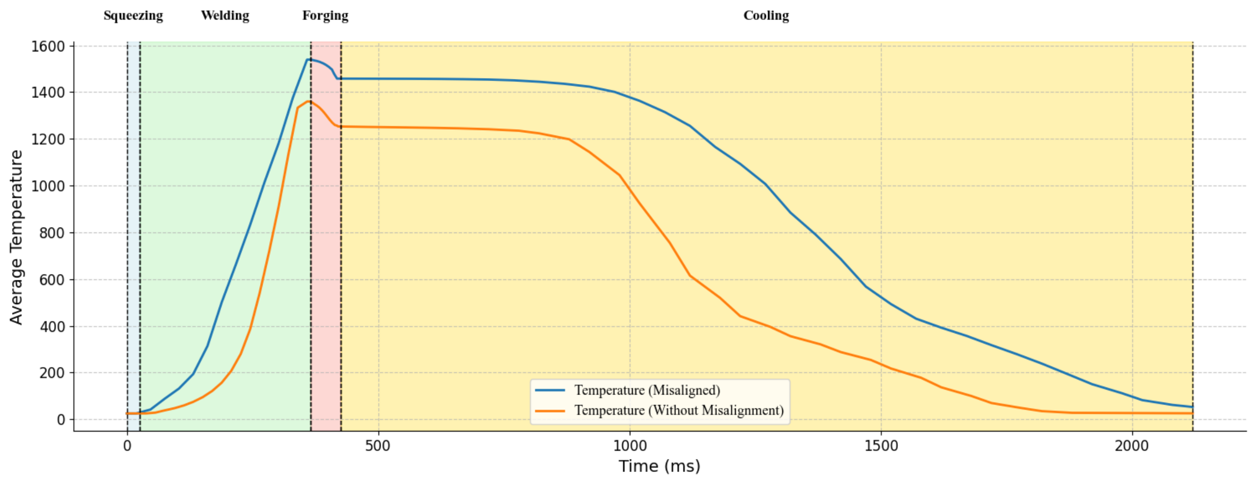


Figure 9. The average temperature of all elements within the nugget across the welding stages—squeezing, welding, forging, and cooling—for both aligned and misaligned cases

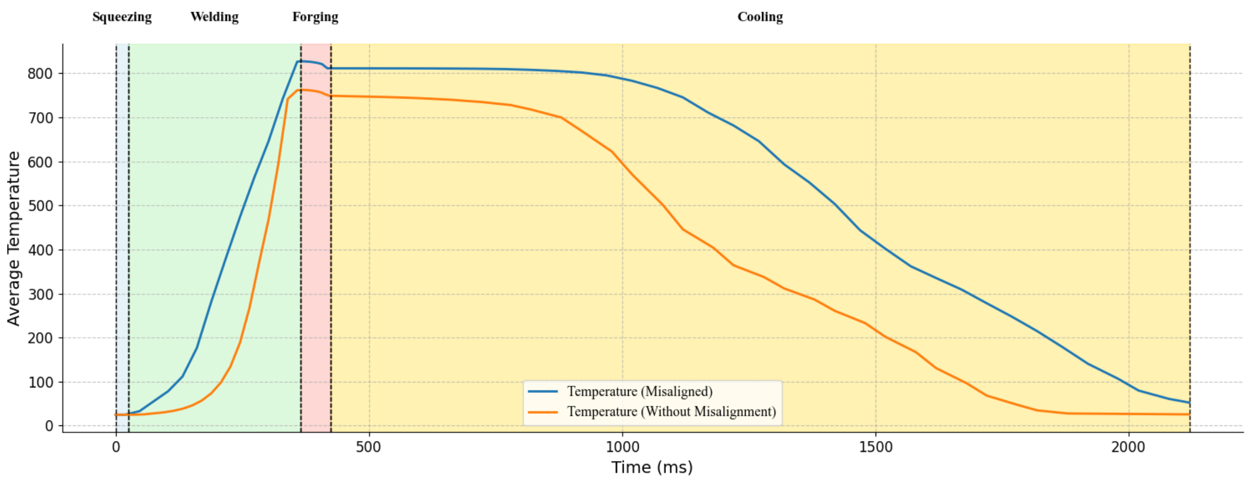


Figure 10. The average temperature of all elements within the work pieces across the welding stages—squeezing, welding, forging, and cooling—for both aligned and misaligned cases

The higher temperatures in the misaligned scenario suggest a more intense and prolonged thermal exposure. Depending on the application, this could be both an advantage and a disadvantage. The key insights of these plots are given in Table 3.

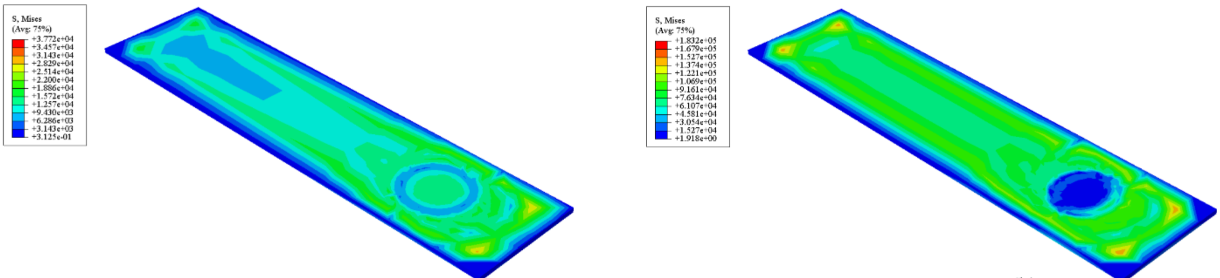
Table 3. Comparative analysis of average temperature distribution for aligned and misaligned RSW Cases

Aspect	Aligned Case	Misaligned Case	Implications
Nugget Temperature	Peaks at 1350°C	Peaks at 1500°C	Increased temperature may enhance nugget size but introduce irregularities.
Cooling Phase	Faster cooling, consistent solidification	Slower cooling	Slower cooling reduces quenching effects but may increase residual stresses.
Nugget Structure	Consistent and uniform	Potential irregularities	Misalignment requires parameter adjustments to maintain integrity.
Potential Benefits	Concentrated, symmetrical nugget	Increased bonding area	Misalignment could enhance bonding in specific applications.

3.3 Thermal-induced Residual Stresses Analysis

Thermal-Induced Stress Distribution at the Final Cooling Stage

The final frame of the cooling step reveals the distribution of thermal-induced stresses within the nugget and the surrounding workpiece for both aligned (Figure 11a) and misaligned (Figure 11b) cases. The stress distribution patterns highlight regions of high-stress concentration, which are critical for understanding potential failure points in the welded assembly.



(a) (b)

Figure 11: The distribution of thermal-induced stresses within the nugget and the surrounding workpiece for both (a) aligned and (b) misaligned cases for the last frame of the cooling step

The aligned configuration shows a more uniform stress distribution, particularly within the nugget, where the stresses are symmetrically centered. In contrast, the misaligned case presents a more irregular stress distribution, with higher concentrations on one side of the nugget. This case suggests that misalignment results in uneven cooling, leading to differential contraction and elevated localized stress—average Nugget and Workpiece Thermal-Induced Stresses Across Welding Stages.
The study examined the average thermal-induced stresses within both the nugget and the workpiece across the different stages of the welding process (squeezing, welding, forging, cooling) for both aligned and misaligned cases. Figures 12 and 13 present these stress distributions.

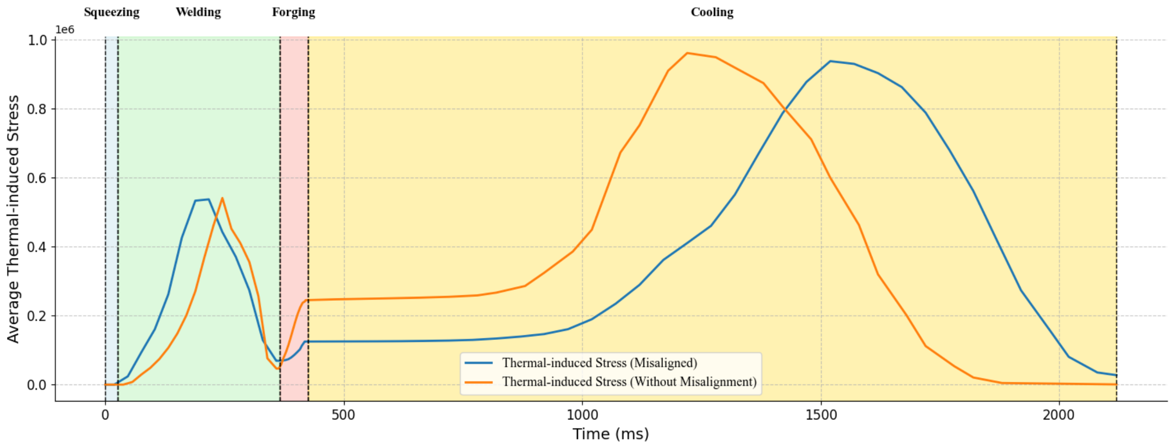


Figure 12. The average thermal-induced stress of all elements within the nugget across the welding stages—squeezing, welding, forging, and cooling—for both aligned and misaligned cases

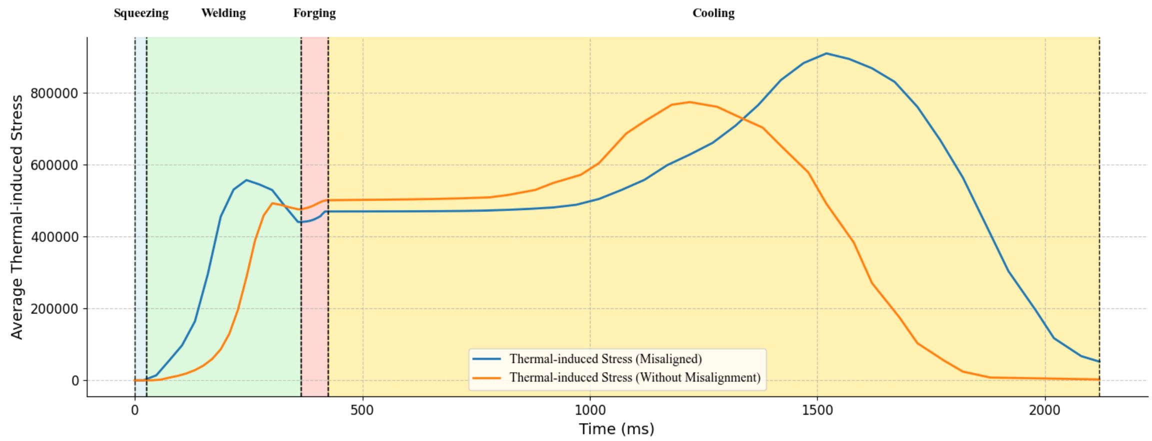


Figure 13: The average thermal-induced stress of all elements within the workpiece across the welding stages—squeezing, welding, forging, and cooling—for both aligned and misaligned cases

The comparison between the aligned and misaligned cases reveals distinct differences in thermal-induced stress behavior during the welding and cooling phases. In the welding phase, misalignment causes the stresses in the nugget and workpiece to peak more rapidly, indicating an earlier thermal stress concentration. During the cooling phase, the aligned case begins stress relief sooner but at a slower and more gradual pace, resulting in lower residual stresses by the end of the cooling stage. On the other hand, the misaligned case sees a delayed onset of stress relief, but once it starts, the stress decreases more rapidly. However, despite this faster rate of stress reduction, the misaligned case retains higher residual stresses overall.

The key insights of the thermal-induced stresses are summarized in Table 4.

Table 4. Comparative analysis of average thermal-induced stress distribution for aligned and misaligned RSW Cases

Parameter	Aligned Case	Misaligned Case	Implications
Nugget Stress During Welding	Gradual increase, peaks at ~550,000 Pa	Rapid increase, peaks at ~550,000 Pa	Misalignment would cause the diagram to peak sooner in the welding step.
Nugget Stress During Cooling	Gradual increase, peaks at ~950,000 Pa	Rapid increase, peaks at ~950,000 Pa	Misalignment would cause the diagram to peak later in the cooling step.
Nugget Stress Drop During Cooling	Slower, steadier decrease	A faster drop begins later, with higher residual stress	Misalignment accelerates stress relief but leaves higher residual stresses.
Workpiece Stress During Welding	Gradual increase, peaks at ~500,000 Pa	Rapid increase, peaks at ~580,000 Pa	Misalignment would cause the diagram to peak sooner in the welding step.
Workpiece Stress During Cooling	Gradual increase, peaks at ~900,000 Pa	Peaks higher at ~880,000 Pa, drops sooner and faster	Misalignment would cause the diagram to peak later in the cooling step.
Residual Stresses at the End of Cooling	Present, lower in aligned case	Present, higher in misaligned case	Misalignment accelerates stress relief but leaves higher residual stresses.

4. Conclusion

This study explored the impact of electrode misalignment in Resistance Spot Welding (RSW) on key factors such as nugget formation, temperature distribution, and thermal-induced residual stresses. By

employing a detailed finite element model in ABAQUS, the research aimed to isolate the thermal effects of misalignment and assess its influence on the welding process. The goal was to determine whether misalignment, often considered detrimental, could present benefits that might be leveraged for optimizing RSW processes and potentially changing future RSW machines' design.
The findings revealed that misalignment leads to significant changes in the welding dynamics. Specifically, misalignment increased the nugget's longitudinal and width dimensions while reducing its depth. Expanding the bonding area could be beneficial, but it also introduces risks of weakened structural integrity due to the shallower weld. Conversely, the aligned case produced a more symmetrical and concentrated nugget, which ensured consistent material fusion across all planes and enhanced weld strength. Regarding temperature distribution, the aligned case demonstrated uniform heat spread, resulting in consistent melting and solidification of the nugget and, ultimately, a robust weld structure. The misaligned case, however, showed uneven heat distribution, leading to irregular nugget formation and potential weaknesses in the weld. The analysis of thermal-induced stresses indicated that during the welding phase, misalignment caused both the nugget and workpiece to experience a more rapid increase in stress, peaking earlier than in the aligned case. During the cooling phase, the misaligned case exhibited a delayed onset of stress relief, followed by a rapid decrease. However, despite this faster rate of stress reduction, higher residual stresses remained, potentially compromising the weld's long-term durability. On the other hand, the aligned case began relieving stress earlier and more gradually, resulting in lower residual stresses by the end of the cooling phase.
In conclusion, although electrode misalignment in RSW presents particular challenges, including increased residual stresses and potential structural weaknesses, it also offers advantages, such as an enlarged nugget size and expanded bonding area, which may prove beneficial for specific applications. These findings suggest that the trade-offs associated with misalignment can be effectively managed with precise adjustments to welding parameters, making it a promising consideration for future RSW machine designs. By strategically leveraging the benefits of misalignment, such as enhanced bonding in targeted contexts, future RSW systems could be optimized for both quality and efficiency, building upon the insights provided by this study.
Further research should explore the effects of varying degrees of misalignment and different electrode shapes and materials on the welding process. Additionally, combining thermal and mechanical stress analysis could provide a more comprehensive understanding of controlling and utilizing misalignment in RSW for improved industrial applications. Experimental validation of the simulation results would also be crucial to ensure their practical applicability, potentially leading to RSW technology innovations that improve weld quality and machine performance.

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