Preventing nugget shifting in joining of dissimilar steels via resistance element welding: a numerical simulation

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Abstract
Joining the advanced high-strength steels and conventional steels is a critical issue for the manufacturing of lightweight vehicles. Resistance element welding (REW) is an emerging joining method for dissimilar metals and alloys by applying an auxiliary rivet-like resistance element in resistance spot welding (RSW). In this study, an electrical-thermal-mechanical coupled REW model for high-strength dual-phase (DP) steel and Q235 steel was developed by considering contact resistances as functions of temperature and surface contacting area. The results show that the welding element in REW serves to concentrate the current flow and thus Joule heat generation at the faying interface between the element and workpiece. For welding DP600 and Q235 workpieces with a small thickness ratio (≤0.4) or a high electrical resistivity ratio (≥3), REW could effectively mitigate nugget shifting between workpieces and reducing the thermal excursion to the electrode compared to RSW. Adding well-designed insulation layers in REW could further concentrate the current within the welding element, and enables a large-sized nugget at a lower current. This study is significant because it provides a better understanding of the nugget development under the electrical-thermal-mechanical interaction at interfacial contacts in REW and contributes to its further advance.

Keywords Resistance element welding · Dissimilar steels · Nugget shifting · Heat generation · Numerical simulation

1 Introduction
The lightweight and high-strength materials have been widely used in the automotive industry to develop more fuel-efficient vehicles while guaranteeing improved occupant safety and durability [1]. Compared to the traditional low carbon steel, the advanced high-strength steels (AHSS) like the dual-phase (DP) steels have excellent properties such as high strength, low yield rate, high working hardening rate, and high strain energy-absorbing characteristics [2]. Using AHSS instead of low carbon steel in the structural parts of the vehicle body can meet the safety requirement and reduce the plate thickness and weight [3]. As one of the commonly used AHSS, DP steels are increasingly adopted in the automotive industry in recent decades [4, 5]. Meanwhile, the conventional low carbon steel still dominates the complex parts of automotive manufacturing due to its low cost and wide application. Therefore, joining dissimilar steels with different thicknesses is frequently needed for local design requirements in production [6].

Resistance spot welding (RSW) is widely used for joining metallic materials in various industries due to its low cost and high automation [7]. RSW uses the thermal effect of resistance generated by the current flowing through the contact surface and adjacent areas of the workpieces to heat it to a molten or plastic state and then form a metal bond. In the recent decade, some common problems encountered in RSW of different thicknesses sheets and dissimilar steels in the manufacturing processes were of concern, including the rotor steels [8], AISI 1008 low carbon steel/DP600 steel [9], BH180-AISI304/BH180-IF7123 steels [10], and stainless steel/non-stainless steel [11]. The effects of RSW parameters on the failure modes were identified, and it was found that excessive current and energizing time reduced the peak load of the joint. As RSW is a complex process which involves electrical, thermal, mechanical, and metallurgical phenomena and many

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parameters are usually unmeasurable, the numerical simulation provides a cost-effective way to study the RSW process. Charde [12] proved that the force profiles directly influenced the fusion process which affected the heat generation as well as the heat diffusion in the RSW process. Karimi et al. [13] improved the RSW model with aluminum alloy 6061-T6 and found that in the modeling of aluminum alloy spot welding, the thermal contact conductance had a major role in nugget enlargement during the welding process. Wan et al. [14] improved the RSW model with both electrical contact resistance and thermal contact resistance for welding aluminum alloy to zinc-coated steel, and studied the nugget development and intermetallic compound growth during the RSW process.

However, the RSW of dissimilar steels still suffered some serious drawbacks, such as nugget shifting to one workpiece and frequent electrode failure. When the differences (e.g., physical properties and thickness) between the workpieces increase, the degree of weld nugget shifting would become serious, leading to the unqualified weld nugget [15]. For the dissimilar steels, as the chemical composition, physical and mechanical properties are quite different [16], the nugget may shift to the side with greater electrical resistivity although having the same thickness; while for the same steel with different thicknesses, the nugget may shift to the thicker side [17]. For the welding joint with a material combination of SAE1004, SAE1004, and DP600, the critical thickness combination was 0.6, 1.8, and 2.0 mm [15]. On the other hand, the RSW of dissimilar steels has an unbalanced heat flux from the weld nugget to the electrode, and thus, the electrode easily experiences thermal excursion and deformation under the high temperature, leading to the requirement for frequent redressing or replacement of the weld cap [18]. A service life approach could be employed to estimate the allowable heat flux density for a metallic component before failure [19]. Parker [20] examined the electrode tip growth mechanisms when welding uncoated low carbon and galvanized steels. Chatterjee et al. [21] described the main factors affecting electrode wear for RSW of coated steels. It was observed that at 500–550 °C and under the pressure of 50–55 Mpa, the high-temperature plastic deformation and pitting occurred after a few welding cycles [22].

To avoid the above defects, resistance element welding (REW) was developed on the basis of RSW to weld a connecting element such as rivet to the material below by heating them under mechanical loads through a resistive thermal effect [23]. By adding a welding element of a similar material with the lower workpiece, the welding element is directly connected with the lower workpiece to form a nugget; the upper workpiece is mechanically locked by the welding element. Compared to the RSW joints, REW could mitigate the nugget shifting between the workpieces, and forming a joint at lower welding currents [24]. Meschut et al. [25] experimentally compared the shear strength of the REW joint with other connection technologies, and found that the maximum shear load of REW was limited by the surface material part instead of the joining elements. Ling et al. [26] compared the REW and traditional RSW process under different currents, and found that RSW could barely join Al 6061 and boron steel, but REW could join the metals reliably with a high tensile shear force. Manladan et al. [27] compared the nugget formation of magnesium alloy and austenitic stainless steel under RSW and REW, and found that the nugget of REW consisted of a peripheral fusion zone on the stainless steel side and the main fusion zone.

The REW process involves multiple intermetallic contacts, leading to the more complex dynamic current flow, heat generation and transfer, and nugget growth. Manladan et al. [24] simulated the thermal contacts with heat generation between two solids to study the thermal characteristics due to interfacial conditions based on the thermal-electrical analogy. Chen et al. [28] established an experimental setup to measure thermal contact resistance at high temperature based on the steady state method, and found that the thermal contact resistance decreased when the interface temperature increases and the interface pressure decreases, and the effects of pressure on thermal contact resistance were much lower at high temperature. Furthermore, the contact interactions in the REW process are more complicated compared with that in the RSW process, including the electrode-workpiece, electrode-welding element, welding element-workpieces, and workpiece-workpiece. Two surfaces in contact with each other have the same or similar contact stiffness and may be deformed, which directly affects the current distribution and heat generation during the welding process. Therefore, REW increases the thermal contacts between the interfaces, thus leading to more complex electrical, thermal, mechanical, and metallurgical phenomena. As the multiple interfacial thermal contact behaviors with heat generation of REW are unclear yet, it is essential to reveal the underlying mechanisms related to the nugget shifting and mitigation with REW for dissimilar steels.

In this study, by considering the multiple interfacial contacts and hereof electrical, thermal, and mechanical behaviors of the welding process, a 3D fully coupled method was established on Abaqus and employed to simulate RSW and REW processes of dissimilar steels. Due to the introduction of an element in REW, the effects of multiple interfacial interactions on the nugget formation and growth, and the thermal excursion to the copper electrode were studied. By varying the insulation coatings on different interfacial contacts between the element and workpieces, the nugget shifting phenomena were further studied. This study is helpful to understand the fundamentals on the advantages of REW over RSW in improving nugget shifting and extending electrode life, and provide guidance for developing welding schedule for dissimilar steels.
2 Mathematical model

2.1 Model description

In this study, just a quarter of the domain is modelled due to the symmetry along the x-y plane and the y-z plane. Figure 1 shows the schematic sketches for the RSW and REW with the fixed 3D x-y-z coordinate system. During the welding process, the workpieces to be joined are squeezed by using a pair of flat-tip electrodes along the y-direction and the welding current flows directly from the upper electrode in RSW or element in REW to the lower electrode through the workpieces. Thereby, the sufficient heat is generated to heat, melt, and fuse the workpieces together by the Joule heating due to both bulk material resistance and interfacial resistance (electrode/workpiece interfaces and workpiece/workpiece faying interface). It is a process involving many physical phenomena such as mechanical squeezing, electrical current flow, water cooling, material heating, melting, and solidification. The following assumptions are adopted in this model:

1) Materials of workpieces and electrodes are homogeneous and isotropic following the von Mises yield criterion.
2) The magnetic field generated by the current flowing is ignored.
3) The convective heat transfer in the molten pool is ignored due to the weak melt flow.
4) The electrode pressure is uniformly applied to the electrode shaft section.

2.2 Governing equations

The governing equations for the thermal, electrical, and mechanical transport phenomena employed in the present work are given below.

(1) Thermal continuity

\[
\rho c^* \frac{\partial T}{\partial t} = \frac{\partial}{\partial x} \left( k \frac{\partial T}{\partial x} \right) + \frac{\partial}{\partial y} \left( k \frac{\partial T}{\partial y} \right) + \frac{\partial}{\partial z} \left( k \frac{\partial T}{\partial z} \right) + \frac{j_x^2 + j_y^2 + j_z^2}{\sigma_e} \]

(1)

where the latent heat due to the phase transition of the material can be treated with the increment of the equivalent specific heat capacity, and the following expression can be used:

\[
c^*(T) = \begin{cases} 
c_S(T), & T < T_s \\
\frac{c_S(T) + c_L(T)}{2} + \frac{H}{T_L - T_s}, & T_s \leq T \leq T_L \\
c_L(T), & T > T_L 
\end{cases}
\]

(2)

where \( T \) is the temperature; \( j_x, j_y \), and \( j_z \) are x-, y-, and z-direction current densities. The input material properties include density \( \rho \), specific heat \( c_e \), latent heat \( H \), solidus temperature \( T_s \), liquidus temperature \( T_L \), thermal conductivity \( k \), and electrical conductivity \( \sigma_e \).
\( \tfrac{\partial}{\partial x} \left( \sigma_e \tfrac{\partial \phi}{\partial x} \right) + \tfrac{\partial}{\partial y} \left( \sigma_e \tfrac{\partial \phi}{\partial y} \right) + \tfrac{\partial}{\partial z} \left( \sigma_e \tfrac{\partial \phi}{\partial z} \right) = 0 \)  

where \( \phi \) is electrical potential.

(3) Ohm’s law

\[ j_x = -\sigma_e \tfrac{\partial \phi}{\partial x}, j_y = -\sigma_e \tfrac{\partial \phi}{\partial y}, j_z = -\sigma_e \tfrac{\partial \phi}{\partial z} \]

(4) Constitutive equation

In the elastic period,

\[ \{\sigma\} = [D] \{\varepsilon_e + \varepsilon_{th}\} - \{C\} T \]

\[ [D] = [D_e] \]

\[ \{C\} = -[D_e] \left( \{\alpha\} + \tfrac{\partial [D_e]^{-1}}{\partial T} \{\sigma\} \right) \]

In the plastic period,

\[ \{\sigma\} = [D] \{\varepsilon_e + \varepsilon_p + \varepsilon_{th}\} - \{C\} T \]

\[ [D] = [D_p] \]

\[ \{C\} \approx -[D_p] \left( \{\alpha\} + [D_p] \tfrac{\partial [D_p]^{-1}}{\partial T} \{\sigma\} - [D_p] \left( \tfrac{\partial f_e}{\partial \sigma} \right) \left( \tfrac{\partial f_p}{\partial T} \right) \right) U \]

\[ \{\varepsilon_{th}\} = \{\alpha\} T \]

where \( \sigma \) is the vector of stress; \( \varepsilon_e, \varepsilon_p, \) and \( \varepsilon_{th} \) are the elastic, plastic, and thermal strain, respectively; \( [D] \) is the elastic-plastic matrix; \( [D_e] \) is the elastic matrix; \( [D_p] \) is the plastic matrix; and \( U \) is the displacement.

### 2.3 Boundary conditions

The boundary conditions for the solution of the RSW/REW model are given below.

(1) Symmetrical \( x-z \) plane and \( y-z \) plane

\( y-z \) plane \( (x = 0) \)

\[ U_x = UR_y = UR_z = 0 \]

(2) Current continuity

\[ \tfrac{\partial T}{\partial x} = 0 \]  

\[ \tfrac{\partial \phi}{\partial x} = 0 \]  

\[ \tfrac{\partial \phi}{\partial x} = 0 \]  

\[ x-y \) plane \( (z = 0) \)

\[ U_x = UR_x = UR_y = 0 \]  

\[ \tfrac{\partial T}{\partial z} = 0 \]  

\[ \tfrac{\partial \phi}{\partial z} = 0 \]  

\[ \tfrac{\partial \phi}{\partial z} = 0 \]  

where \( U_x \) and \( U_y \) are the translational degrees of freedom along the \( x \) and \( y \) directions, respectively; \( UR_x, UR_y, \) and \( UR_z \) are the rotational degrees of freedom on the \( x, y, \) and \( z \) axis, respectively.

(2) Top surface of the upper electrode

\[ P = \frac{F}{\pi r^2} \]

\[ -\sigma_e \tfrac{\partial \phi}{\partial y} = \frac{I}{\pi r^2} \]

where \( P \) is the pressure; \( F \) and \( I \) are the electrode force and welding current applied on the upper electrode; and \( r \) is the radius of the applied current and force.

(3) External surfaces of workpieces and electrodes

\[ -k \frac{dT}{dy} = \frac{j_x^2 + j_y^2 + j_z^2}{\sigma_e} - q_{conv} q_{rad} \]

The heat loss due to convection is calculated by:

\[ q_{conv} = h_1 (T - T_a) \]

where \( q_{conv} \) is the heat fluxes of convection heat transfer; \( h_1 \) is the convective heat transfer coefficient; and \( T_a \) is the ambient temperature.

At elevated temperature, radiation heat transfer plays a role part in heat loss, which can be considered:

\[ q_{rad} = h_2 (T - T_a) \]

where \( q_{rad} \) is the heat fluxes of radiative heat transfer; \( h_2 \) is the radiative transfer coefficient.

(4) Internal flow tube of electrodes

\[ \therefore \text{Springer} \]
The forced convection is caused by the cooling water flowing through the internal tube of electrodes. To simplify the calculation, it is assumed that the heat transfer coefficient along the underside surface of the electrode is constant.

\[-k \frac{dT}{dy} = h_c(T-T_a) \quad (23)\]

where \(h_c\) is the heat transfer coefficient of cooling water.

### 2.4 Interfacial contact conditions

As shown in Fig. 2, REW involves six contact interfaces: the element/lower workpiece (1), the upper electrode/element (2), the element/lower workpiece (3), the element-upper workpiece (4) and (5), and the workpiece-workpiece (6). The contact electrical and thermal resistances play a decisive role in the distribution of the current and temperature fields during the welding.

In some simulation, a very thin layer of grids is artificially used as the contact surface, which has the specific electrical properties for simulating the heat generation with contact resistance [29]. However, the effect of the gap on resistance cannot be effectively considered. Meanwhile, as a layer of grids is introduced in the model, the temperature and current density distributions may be distorted due to the suddenly varied properties. Therefore, in this study, the gap conductivity method is used to simulate the contact resistance. The relationship between voltage drop across a metal contact interface and contact resistance is presented in Kohlrausch’s model. Based on this model, Li et al. [30] proposed the microscopic contact theory that was satisfactory in the RSW of low carbon steel. Thus, the voltage drop across the contact interface in this model can be estimated as:

\[\Delta \phi^2 = 4L(T_m^2 - T_0^2) \quad (24)\]

where \(\Delta \phi\) is the voltage drop on the contact interface; \(T_m\) is the melting temperature of the material; \(T_0\) is the initial temperature; \(L\) is the Lorentz constant of materials. For most metals, \(L = 2.0 \times 10^{-8} \text{ (V}^2\text{K}^2)\) [31].

Contact electrical conductance can be expressed as gap conductance:

\[\sigma_g = \frac{1}{RA} \quad (25)\]

where \(\sigma_g\) is the gap conductivity; \(R\) is the resistance per unit area; and \(A\) is the contact area.

It can be derived from Ohm’s law:

\[R = \frac{\Delta \phi}{I} \quad (26)\]

It should be noticed that Eq. (27) is proposed based on the assumption that the metal in the contact region (represented by the radius \(r_c\)) is in close contact. Therefore, the contact resistivity required in the electrothermal analysis can be obtained by the geometric information at the contact interface and the temperature-related physical parameters. When the temperature is higher than the melting point, the contact resistance on the contact interface disappears, and the resistivity of the contact area is the bulk resistivity of the workpiece.

In addition, the contact pressure also affects the contact resistance, so the impact of the contact surface clearance on the contact resistance is considered in this model. A large contact pressure leads to a reduced gap and elevated gap conductivity. When the gap exceeds the critical value, the gap conductivity becomes zero.

The thermal conductivity of metal follows the Wiedemann-Franz law [32]:

\[\frac{k_g}{\sigma_g} = LT \quad (28)\]

where \(k_g\) is the thermal conductivity of gap. The thermal contact resistance corresponding to the contact resistance can be calculated by Eq. (28).

### 2.5 Numerical method

In this study, the simulation starts with the mechanical analysis of the squeezing stage, which provides the initial contact conditions under the electrode force for the following welding stage. During the electrical-thermal-mechanical coupled analysis in the welding stage, the electrical current equations...
subject to the boundary conditions are first solved to obtain the current distribution within the workpieces. Secondly, the energy conservation equation with Joule heating through the whole calculation domain is solved subject to the thermal boundary conditions, and then the temperature distributions are obtained. Thirdly, the temperature field is applied as the thermal load for the thermal-mechanical analysis. By solving the elastic and plastic equations with the updated temperature-dependent material properties, the stress and strain fields together with the deformation of the workpieces are obtained. The Newton-Raphson iteration method [33] is used to solve this nonlinear mathematical model, and the convergence criterion is 

\[ |\delta - \delta_0|/\delta_0 \leq 10^{-6} \]  

(29)

where \( \delta = \phi, T \) and \( \sigma \), and \( \delta_0 \) refers to the variable in the last iteration. Then with the updated material properties (including electrical, thermal, and mechanical properties) and contact conditions between the parts, the above procedures are repeated until the welding stage is completed. In the subsequent cooling stage, the weldment is cooled and solidified to form the final welding joint.

This highly nonlinear computation procedure is performed based on ABAQUS. Extensive tests using different grid sizes and time step sizes have been conducted to assure consistent results. A non-uniform grid point system is employed with finer grid sizes near the contact areas. As shown in Fig. 3, in order to verify the mesh independency, the calculated nugget area for RSW of 0.6-mm DP600 and 2.0-mm Q235 at \( t = 200 \) ms with different minimum mesh sizes was compared. The nugget area tends to be stable when the minimum grid size is less than 0.15 mm, while the CPU time significantly increases when the minimum grid size is less than 0.1 mm. Therefore, to compromise the CPU time and calculation accuracy, the final minimum grid size used in the present study is 0.1 mm. During the entire process, the thermal-electrical-structure linear hexahedral solid elements are used for both electrodes and workpieces. To facilitate the convergence of the analysis, the self-adaptive time step is applied as the whole analysis process is highly coupled with large plastic deformation, and the time increment is defined by:

\[ \Delta t > \frac{\rho c}{6k} \Delta t^2 \]  

(30)

where \( \Delta t \) is a typical element dimension. The initial time step size is set as \( 1 \times 10^{-5} \) s.

### 3 Model validation

In order to validate the present model, the REW of 2.0-mm thick 6061 aluminum alloy and 2.0-mm thick boron steel is simulated and compared with the published experiment results [26]. During the welding process, a pre-squeeze cycle is employed with a zero current, and then the electrical current ramps up to 9 kA. The electrode force is kept constant with a value of 3.6 kN, and the welding time is 200 ms. Figure 4 compares the cross sections of experimental and calculated REW joints. As shown in Fig. 4a, the nugget of the REW joint is marked in the red dotted line, which is apparently formed by the welding element and the lower workpiece. The upper workpiece of aluminum alloy is partly melted around the element. As shown in Fig. 4b, the nugget zone between the element and lower workpiece is represented with the gray area in the center of the joint (i.e., the area with a temperature higher than 1500 °C). When the temperature exceeds 600 °C, the aluminum alloy is also melted around the element. It is clear from both the experimental and the calculated results that the nuggets are just located beneath the element and obviously shift downward with a higher penetration rate within the lower workpiece. Therefore, the simulation results are consistent with the experiment by comparing the calculated nugget dimensions and shifting phenomena.

### 4 Results and discussion

#### 4.1 Material properties

Ferrite-martensite DP steels are some of the most common AHSS used in automotive industry, which have the suitable combination of strength and formability [34, 35]. When joining the dissimilar steels, the high-strength DP steels could offer the thinner thickness of workpiece compared to the mild steels. In this study, DP600 and Q235 are selected as the typical materials to show the characteristics in resistance welding of the dissimilar steels. The welding element in the REW process is made of Q235, and the geometrical parameters are \( r_{e1} = 7 \) mm, \( r_{e2} = 2 \) mm and \( h_{e1} = 0.5 \) mm (referring to Fig. 1). Electrodes are made from ZrCu (C15000) with a face diameter of 8 mm and weld face radius of curvature of 25 mm. The density and Poisson’s ratio of C15000 are assumed to be constants, i.e., 8900 kg/m³ and 0.32, respectively. The chemical composition of DP600 and Q235 is shown in Table 1. According to the chemical composition in Table 1, the Young’s modulus, thermal conductivity, and electrical conductivity of DP600 steel at different temperatures are calculated. Thus, the temperature-dependent mechanical, thermal, and electrical properties of C15000, DP600, and Q235 are shown in Fig. 5.

#### 4.2 RSW/REW of DP600 and Q235 workpieces

For welding of DP600 and Q235 workpieces, the welding parameters are selected following the rules given in Ref.
and shown in Table 2. The electrode force is kept at 3.5 kN during the whole welding process. The welding current for RSW and REW is different and determined with the aim to form a suitable weldment with an upper electrode temperature of less than 550 °C [23].

Figure 6 shows the temperature distributions and nugget growth at different instants during RSW/REW of 2.0/0.6-mm thick DP600 and 2.0-mm thick Q235. As shown in Fig. 6 a, for RSW of 2.0-mm DP600 and 2.0-mm Q235, the high-temperature zone first appears at contact surfaces of the copper electrode workpieces and the faying interface (i.e., $t = 50$ ms and $t = 100$ ms) due to the concentrated contacts in these areas. Then the central high-temperature region between the faying interface of workpieces becomes larger and forms the nugget (i.e., $t = 200$ ms). Finally, the nugget grows to its maximum size, and the welding is completed at $t = 300$ ms.

Due to the small difference in volume resistivity between the workpieces, the temperature of the upper workpiece after welding is only slightly higher than that of the lower workpiece. As shown in Fig. 6 b, for RSW of 0.6-mm DP600 and 2-mm Q235, the high-temperature zone first appears at the upper workpiece (i.e., $t = 10$ ms). The metal is first melted around the periphery of the faying interface instead of the center part due to the deformation of the thin upper workpiece (i.e., $t = 50$ ms and $t = 100$ ms). The nugget size in the upper workpiece is much shallower than that in the lower one, namely, the nugget shifts downward the lower workpiece (i.e., $t = 200$ ms). In addition, as the nugget in the upper workpiece is closer to the water-cooled electrode, the heat loss is stronger in the thin plate side, which also contributes to the shallow nugget. However, the size of the nugget has not reached the ideal state at 200 ms. In contrast, for REW...
of 0.6-mm DP600 and 2-mm Q235 shown in Fig. 6 c, the Joule heat initiates at the faying interface between the welding element and the lower workpiece (i.e., $t = 10$ ms), and then the melted zone is formed (i.e., $t = 50$ ms and $t = 100$ ms) within this narrow area with a more concentrated heat generation. The melted zone continues to grow and eventually forms the final nugget in which the width is almost equal to the welding element diameter (i.e., $t = 200$ ms). In REW, the significant nugget shifting between the workpieces is mitigated.

The copper electrode is in contact with the workpiece at a higher temperature, which indicates that the electrode cap is vulnerable to damage due to the high temperature or adhesion to the molten workpiece. It is obvious that at the end of welding, in RSW 2-mm DP600/2-mm Q235 (Fig. 6 a), the temperatures of both the upper and lower electrodes are lower than 550 °C. For 0.6-mm DP600, due to the thinner upper workpiece, a higher temperature occurs at the end face of the electrode due to the larger heat flux density from the faying surface between the workpieces. In RSW 0.6-mm DP600/2-mm Q235 (Fig. 6 b), the highest temperature in the upper electrode exceeds 550 °C. When the copper electrode is subjected to a high temperature above 500–550 °C, the plastic deformation is easy to occur, which would lead to a decrease in nugget size and even joint failure [22, 37]. In REW of 0.6-mm DP600/2-mm Q235 (Fig. 6 c), however, the temperature of the upper electrode is much higher but does not exceed 550 °C when the welding is completed at $t = 200$ ms. Therefore, when welding DP600 and Q235 with a thickness ratio of 0.3, the electrode temperature in the REW process is significantly reduced, indicating an extended electrode life in REW.

To further explain the formation and mitigation of the nugget shifting phenomena shown in Fig. 6, Fig. 7 a and b, respectively, presents the corresponding distributions of pressure and current density along with the faying interface between the workpieces or element/workpiece. It is clearly found that RSW of 0.6-mm DP600 initially has the $M$-shaped distributions in current density (i.e., $t = 50$ ms) with a significantly higher current density beneath the edge of the electrode tip, indicating a hot spot and metal melting in this region (referring to Fig. 6 b). This is because subject to the high thermal expansion and concentrated contact beneath the edge of the electrode tip, the thin DP600 workpiece is obviously deformed, leading to the concentrated pressure and thus concentrated current around the periphery of the faying interface (2.5 mm < $x$ < 4.0 mm).

Table 1 Chemical composition of DP600 and Q235

|       | Mn  | Si  | C   | Al  | Cr  | Fe  |
|-------|-----|-----|-----|-----|-----|-----|
| DP600 | 0.4 | 0.14| 0.11| 0.02| 0.21| Balance |
| Q235  | 1.0 | 0.4 | 0.14| 0.04| 0.02| Balance |

In order to examine the effectiveness of REW on joining the dissimilar steels, the workpieces with different electrical conductivity and thickness are studied with the emphasis on the nugget formation. The welding time for each case is determined at the instant when the temperature at the end of the upper copper electrode just reaches 550 °C.

Figure 8 shows the nugget thicknesses in both the workpieces with the RSW and REW of 2-mm thick low carbon steels with different electrical conductivity. The electrical conductivity ratio of the upper workpiece and the lower workpiece is set to be 2 to 10. The electrode force is 3.5 kN and the welding current is 14 kA. Obviously, as the difference in conductivity between the upper and lower workpieces increases, the nugget thicknesses decrease with small penetration rates. During the RSW process, as the electrical conductivity ratio is larger than 3, the nugget ratio would decrease below 0.5. Therefore, at the high electrical conductivity ratio, the thickness ratio of the upper and lower workpieces becomes small, indicating that the nugget obviously shifts to the lower workpiece with low conductivity. In the REW process, the nugget ratio keeps at about 2.1 although the resistivity ratio increases, which indicates that shifting is significantly reduced with a slight shifting to the upper workpiece due to the addition of rivet-like element. Compared to RSW, the thicknesses of the nugget are significantly increased. In summary, when welding two workpieces with a large electrical conductivity ratio (≥ 3), the REW method can effectively reduce the shifting of the nugget.

Figure 9 presents the nugget thickness under different upper workpiece thicknesses, showing the nugget shifting in the RSW and REW processes with different upper workpiece thicknesses. The upper workpiece thickness is, respectively, set as 0.4 mm, 0.6 mm, 0.8 mm, 1.0 mm, 1.4 mm, and 2.0 mm,
while the lower workpiece thicknesses are fixed at 2 mm. The electrode force is 3.5 kN, and the welding current is 14 kA for RSW and 6 kA for REW. In the RSW process, as the thickness of the upper workpiece decreases, the size and penetration rate of the nugget decrease, and the nugget shifting becomes serious. Especially, as the thickness of the upper workpiece is smaller than 0.8 mm, the nugget in the upper workpiece is thinner than 0.12 mm with the nugget thickness.

Fig. 5 The temperature-dependent material properties of DP600, C15000, and Q235
ratio less than 0.5. During the REW process, at the small thickness of the upper workpiece (0.8 mm), the nugget thicknesses in the lower workpiece and upper workpiece (welding element) are quite identical. When the thickness of the upper workpiece is greater than 1.0 mm, the nugget in the upper workpiece (welding element) is significantly enlarged with an obvious nugget shifting to the upper workpiece. Therefore, it can be concluded that when the thickness of the upper workpiece is less than 0.8 mm, the REW method can reduce the nugget shifting compared to RSW. However, when the thickness of the upper workpiece is greater than 1.0 mm, the REW method becomes less useful while the RSW method could produce the good nugget penetration with the small nugget shifting. In summary, when the workpiece thickness ratio is greater than 0.4, RSW offers the small nugget shifting and the easy operation compared to REW. However, REW shows great superiority against RSW for welding the workpieces with a large difference in thickness.

4.4 Effects of interfacial insulation in REW on the nugget formation

For the REW process, less heat generation between the welding element and the upper workpiece is required, and the nugget shifting between workpieces should be as small as possible. Table 2 shows the operating conditions for welding of DP600 and Q235 workpieces.

**Table 2** The operating conditions for welding of DP600 and Q235 workpieces

| Cases | Welding method | DP600 thickness (mm) | Q235 thickness (mm) | Current (kA) | Welding time (ms) |
|-------|----------------|----------------------|---------------------|--------------|------------------|
| (a)   | RSW            | 2.0                  | 2.0                 | 14           | 300              |
| (b)   | RSW            | 0.6                  | 2.0                 | 14           | 200              |
| (c)   | REW            | 0.6                  | 2.0                 | 6            | 200              |

Fig. 6 Temperature distributions and nugget growth during RSW/REW of DP600 and Q235 with different thickness: (a) RSW 2-mm DP600/2-mm Q235; (b) RSW 0.6-mm DP600/2-mm Q235; (c) REW 0.6mm DP600/2-mmQ235
as possible. Therefore, to improve the REW, it is expected to control the current flows by adding some insulation layers on the contact surfaces of the parts and thus the heat generation at the target area.

Figure 10 shows the distributions of current density and temperature with the nugget dimensions for the REW of DP600 and Q235 workpieces under different insulation conditions at the contact surfaces shown in Fig. 2. The welding current is reduced to 3 kA, and the final welding time is 200 ms. As shown in Fig. 10 a, by examining the current density at the initial stage ($t = 10$ ms) of each welding process, it is clear that the current flow is significantly affected by the insulation layers. Compared to the non-insulation case (the first column in Fig. 10), the insulated contact surface (5) (the second column in Fig. 10) contributes to blocking the current flow from the sidewall of the welding element to the upper workpiece, leading to a slight increase in the heat generation at the faying surface. But this phenomenon is not strong enough so that neither of the cases has formed a high current density at the faying surface. As contact surface (4) is insulated (the third column in Fig. 10), the current flow from the electrode toward the upper workpiece is blocked by the insulation layer, leading to the current concentration within the welding element. For the insulated contact surfaces (4) and (5) (the fourth column in Fig. 10), as the current flows through the welding element, the part of current from the sidewall of the element to the upper

Fig. 8 Nugget thickness under different electrical conductivity ratios of the workpieces. (solid line-nugget thickness, dash line- nugget thickness ratio)
Fig. 9 Nugget thickness under different upper workpiece thicknesses (solid line - nugget thickness, dash line - nugget thickness ratio)

Fig. 10 Distributions of current density and temperature distributions with the nugget dimensions for the REW processes under different insulation conditions: (a) current density at $t = 10$ ms, (b) temperature at $t = 10$ ms; and (c) temperature at $t = 200$ ms (the red solid line refers to the insulation layer)
workpiece is further blocked, leading to the more concentrated current at the bottom of the welding element. As shown in Fig. 10 b, the temperature distributions are corresponding to the current density distributions. For the non-insulation case or adding insulation at the surface (5), the nugget is never effectively formed at \( t = 200 \text{ ms} \), and some Joule heating is generated at the contact surface (4) with a result of the wider thermal affected zone, showing the electrical energy is dispersed (as shown in Fig. 10 c). Adding insulation at the surface (4), a medium-sized nugget is formed at \( t = 200 \text{ ms} \) because the current is concentrated underneath the welding element. It is also found that part of the current flows from surface (5) to the workpiece without passing through the faying surface. Further adding insulation at both surfaces (4) and (5), a large-sized nugget is observed at \( t = 200 \text{ ms} \) due to the more concentrated current flows through the faying surface. However, for the insulated contact surfaces (4) and (5), the current flowing from the electrode to the upper workpiece is blocked, leading to higher temperatures in the welding element and more thermal excursion to the electrode.

To further explain the nugget development for the REW of DP600 and Q235 workpieces under different insulation, Fig. 11 shows the corresponding distributions of current density along with the faying interface between the workpieces or element/workpiece. At the beginning of the welding stage \((t = 10 \text{ ms})\), for the non-insulation case and the insulated contact surface (5), the current density distributions are very similar that are developed evenly along the contact surface, which is much lower than the other cases underneath the welding element \((x < 2.0 \text{ mm})\). For the insulated contact surface (4) and the insulated contact surface (4) and (5), the current density becomes much higher, while the latter case shows the more concentrated case. At the latter stage \((t = 200 \text{ ms})\), compared to the non-insulation case, the current density for the case with the insulated contact surface (5) significantly increases, resulting in a higher temperature at the contact surface. Adding insulation at the surface (4) or at the surface (4) and (5), due to the formation of the nugget on the contact surface, the contact resistance is reduced and the current concentration is reduced that has the M-shaped distributions, which contributes to widening the nugget.

5 Conclusion

Resistance element welding (REW) is a novel joining method developed on the basis of resistance spot welding (RSW) by applying an auxiliary element (i.e., rivet) to connect the lower workpiece and fastening the upper workpiece. In this paper, the 3D finite element models are developed to study underlying physics during RSW and REW processes of dissimilar steels such as AHSS and mild steel. The superiority of REW against RSW in dissimilar steels with unequal thickness is elaborated.

In RSW of the thin DP600 and thick Q235, the current concentration initially occurs around the periphery of the faying interface due to the thin workpiece deformation, leading to a relatively dispersive energy distribution at the faying surface. As a result, the shallow and wide nugget is formed within the thinner workpiece, leading to the nugget shifting toward the thicker workpiece. In addition, the copper electrode adjacent to the thinner workpiece experiences an extremely high temperature (over 550 °C) that would reduce the electrode life. For welding of workpieces with equal thickness and large different resistivity, a longer time is required for the RSW process to form a suitable nugget due to the smaller resistivity on one side, and the nugget shifts to the workpiece with the high resistivity.

In REW, when adding a welding element inside the thinner workpiece or the workpiece with a low resistivity, the welding current could be concentrated beneath the welding element and thus reduce the nugget shifting. The nugget is only formed at the faying interface between the welding element and workpiece with a smaller welding current and a shorter welding time. The use of REW technology can effectively reduce the electrode temperature and thus extend the electrode life. Compared to RSW, the REW method can effectively reduce the nugget shifting when welding two workpieces with a large difference in thickness (workpiece thickness ratio \( \geq 0.4 \)) or welding two workpieces with a large resistivity difference (electrical resistivity ratio \( \geq 3 \)). Adding an insulation layer could control the current flow and further concentrate the current in the welding element. A large-sized nugget is formed by adding an insulation layer between both the contact surfaces of the welding element and the upper workpiece. Only by adding an insulation layer on the side of the welding element, the effects of the insulation layer on the current distribution

![Fig. 11 The current density distributions along with the interface between the faying interface between the workpieces or element/workpiece](image-url)
and welding results are insignificant. **Nomenclature**

A, Contact area; \( h \), Specific heat; \( [D] \), Elastic-plastic matrix; \([D_p]\), Elastic matrix; \([D_s]\), Plastic matrix; \( F \), Electrode force; \( f \), Yield stress; \( h_1 \), Convective heat transfer coefficient; \( h_2 \), Radiative transfer coefficient; \( \Delta h \), Heat transfer coefficient of cooling water; \( H \), Latent heat; \( j \), Welding current; \( k \), Current density; \( k_t \), Thermal conductivity coefficient; \( k_{\text{fr}} \), Thermal conductivity of the gap; \( L \), Lorentz constant of materials; \( P \), Pressure; \( q_{\text{conv}} \), Heat flux of convective heat transfer; \( q_{\text{rad}} \), Heat flux of radiative heat transfer; \( r \), External radius of electrode; \( r_c \), Contact radius; \( R \), Resistance; \( t \), Welding time; \( T \), Temperature; \( T_0 \), Initial temperature; \( T_{\text{m}} \), Ambient temperature; \( T_{\text{mc}} \), Melting temperature of the material; \( T_{\text{Ce}} \), Temperature at center of copper electrode contact face; \( T_{\text{fg}} \), Temperature at edge of copper electrode contact face; \( U \), Displacement; \( UR \), Rotational degrees of freedom

**Greek symbols**

\( \alpha \), Coefficient of thermal expansion; \( \varepsilon_e \), Elastic strain; \( \varepsilon_{in} \), Plastic strain; \( \varepsilon_{in} \), Thermal strain; \( \rho \), Density; \( \sigma \), Stress; \( \sigma_g \), Total electrical conductivity; \( \sigma_{ge} \), Gap conductivity; \( \phi \), Electrical potential; \( \Delta t \), Typical element dimension; \( \Delta t \), Time increment; \( \Delta \phi \), Corrections of incremental electrical potential

**Superscript**

\( L \), Liquidus; \( S \), Solidus; \( x \), x-Direction; \( y \), y-Direction; \( z \), z-Direction

**Author contribution**

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**Data availability**

The datasets generated and analyzed during this study are included in this published article, and the raw data are available from the corresponding author on reasonable request.

**Declarations**

**Ethical approval**

Not applicable.

**Consent to participate**

Not applicable.

**Consent to publish**

Not applicable.

**Competing interests**

The authors declare no competing interests.

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