Effect of electrode force condition on nugget diameter and residual stress in resistance spot welded high-strength steel sheets

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Abstract. This study examines the effect of the electrode force condition on the nugget diameter and residual stress in spot welded high-strength steel sheets. Numerical simulations of spot welding were performed to examine the nugget diameter and residual stress. The results indicate that adjusting the force profile changes the current density and stress state at the spot welds. Therefore, choosing an appropriate force profile extends the nugget diameter and reduces the residual stress.

1. Introduction

In recent years, global warming has been considered an important issue that must be solved. Therefore, various provisions have been considered, and various statutes have been established to improve the environmental situation. In the automotive industry, the ULSAB (UltraLight Steel Auto Body), ULSAC (UltraLight Steel Auto Closure), ULSAS (UltraLight Steel Auto Suspension), and ULSAB-AVC (UltraLight Steel Auto Body - Advanced Vehicle Concept) projects were promoted from 1994 to 2002. These projects were intended to reduce the environmental load and improve collision safety. Since then, the application of high-strength steel sheet to automobile structural components has been promoted for the same reasons. Now, high-strength steel sheet is being used extensively for automobile bodies and is having a positive impact on the industry and the environment.

Resistance spot welding is a common joining method used for assembling steel sheets. To use high-strength steels in automobiles, it is necessary to ensure the strength of their spot welded joints. A previous report stated that the nugget diameter [1-3] and residual stress [4-6] influence the static and fatigue strengths of spot welded joints. Therefore, generating a large nugget and decreasing the residual stress are crucial for increasing the static and fatigue strengths. Previous studies focused on decreasing the residual stress, and some provisions have already been reported [7-9]. However, these provisions are performed after the spot welding. Therefore, the efficiency of the spot welding is reduced, and the environmental load increases. Instead, it would be very useful to extend the nugget, which would reduce the residual stress without requiring additional processes.

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In this study, the nugget diameter and residual stress in spot welded high-strength steel sheets were investigated using coupled electrical-thermal-microstructural-mechanical numerical simulations. Moreover, in order to control the nugget size and residual stress, the effect of the electrode force condition on these characteristics were examined.

2. Numerical simulation

Resistance spot welding is a joining method that utilizes Joule heating. In this process, electric current and electrode force are applied to the sheets. The electrode force influences the current pathway and the contact resistance, and these influence nugget formation. Therefore, they must be taken into account to accurately simulate spot welding. In addition, a phase transformation occurs due to thermal processes above the spot welded area. In a numerical simulation, the change in material properties due to the phase transformation must also be taken into account to accurately predict the residual stress. For this reason, we used a coupled electrical-thermal-microstructural-mechanical numerical simulation to account for not only the effect of the electrode force and the applied current but also the change in the material properties due to the phase transformation [10]. For the spot welding simulations in this study, we used the commercial finite element analysis software SYSWELD [11].

2.1. Analytical model

Figure 1 illustrates the sheets used for the finite element analysis. The sheet was 1.6 mm thick and 62.5 mm wide. To simulate resistance spot welding, an axisymmetric model with a restrained upper electrode edge was used. Figure 2 shows the finite element model. Solid elements were used with an element size of 0.1 × 0.2 mm in the weld area.

![Figure 1. Model used for numerical simulation of resistance spot welding.](image1)

![Figure 2. Finite element model used to simulate resistance spot welding: (a) overall view, (b) enlarged view at the spot weld area.](image2)
2.2. Material properties

Figure 3 shows the material properties of the high-strength steel sheets used in the resistance spot welding simulation. The physical and mechanical properties were measured experimentally and also obtained from a database [12]. Phase and temperature dependencies were considered for the thermal conductivity, specific heat, yield stress, and thermal strain. Only the temperature dependence was considered for the density and Young’s modulus. In the numerical simulation of spot welding, contact resistance is an essential parameter for thermal analysis. The contact resistance depends on the surface state (unevenness, oxide film, etc.), and these resistances disappear in the early stages of applying the electrical current. Therefore, in this study, a contact resistance was assigned to the contact area as a temperature-dependent parameter to imitate the change in contact state during spot welding, as shown in Figure 3(b). When the temperature is low, the value of the contact resistance becomes high, but if the temperature becomes high enough (melting section, etc.), the value of the contact resistance becomes negligible.

![Figure 3](image)

**Figure 3.** Material properties used in the resistance spot welding simulation: (a) physical properties of the high-strength steel sheets, (b) thermal and electrical contact resistances, (c) mechanical properties of the high-strength steel sheets, (d) thermal strain and transformation properties.

3. Results and discussion regarding nugget diameter

First, a numerical simulation was performed for the basic spot welding condition. Figure 4(a) shows the basic welding condition (hereafter 3.5 kN). The electrical current source was DC, and the profiles
of the current and electrode force did not change during spot welding. Figure 4(b) shows the time histories of the nugget diameter and penetration ratio during the spot welding simulation. The nugget diameter and penetration ratio increase until 0.12 s, which is the time at which the current is applied. However, the increases in the nugget diameter and penetration ratio after 0.12 s are small. This phenomenon is caused by changes in the contact area between the sheet and electrode and between each of the sheets. The contact area changes during spot welding, and the current density at the center of the nugget changes with a change in the contact area. In the early stages of spot welding, because the contact area is small, the current density at the center of the nugget is high, and the nugget expands in the thickness and longitudinal directions. However, in the later stages of spot welding, because the contact area is large, the current density at the center of the nugget decreases, and the nugget size does not increase.

Figure 4. The progression of the nugget diameter and penetration ratio: (a) basic welding condition, (b) time history results for the nugget diameter and the penetration ratio.

Therefore, in order to prevent the decrease in the current density, the welding condition that controls the force profile was applied. This condition is shown in Figure 5(a). The force profile decreases when the growth of the nugget subsides (hereafter 3.5-2.0 kN). Figure 5(b) shows the time history results for the nugget diameter and penetration ratio during spot welding, which can be compared with the results in Figure 4(b). The nugget diameter and penetration ratio increase when the force profile decreases. Figure 6 shows the maximum temperature distribution for each welding condition, and the highest temperature region corresponds to the nugget. The size of the nugget for 3.5-2.0 kN is larger than for 3.5 kN. Figure 7 shows the current density at the center of the nugget. The results for 3.5 kN show the decrease in current density. However, the results for 3.5-2.0 kN show that the current density does not decrease. This is because the contact area becomes small due to the decrease in the force profile. However, the corona bond area for 3.5-2.0 kN is smaller than that for 3.5 kN. As shown in Figure 6, the corona bond is formed between the edge of the nugget and the point of sheet separation. This region represents the weld defect known as expulsion, which causes a decrease in joint strength. Therefore, a corona bond with sufficient width is required.
Therefore, in order to form a corona bond with sufficient width, the welding condition that controls the force profile even further was applied. The considered conditions are shown in Figure 8. When the nugget forms to a sufficient size, the force profile is increased to form a corona bond with sufficient width (hereafter 3.5-2.0-3.5 kN). The results for the maximum temperature distribution are shown in
Figure 9. Figure 9(a) shows the results for 3.5-2.0 kN, and Figure 9(b) shows the results for 3.5-2.0-3.5 kN. The width of the corona bond for 3.5-2.0-3.5 kN is larger than for 3.5-2.0 kN. Therefore, these results show that choosing an appropriate force profile extends the nugget diameter and forms a corona bond with sufficient width.

Figure 8. The force controlled condition profile used to form a corona bond with sufficient width.

Figure 9. Maximum temperature distributions: (a) result for 3.5-2.0 kN, (b) result for 3.5-2.0-3.5 kN.

4. Results and discussion regarding residual stress
Figure 10 shows the residual stress distribution results for 3.5-2.0 kN and 3.5-2.0-3.5 kN at the spot welds. The residual stress distribution is different for each welding condition. This result indicates the possibility of changing the residual stress state in the spot welds.

Figure 10. θ-direction residual stress distributions: (a) result for 3.5-2.0 kN, (b) result for 3.5-2.0-3.5 kN.
Therefore, in order to control the residual stress state, the welding conditions that change the force profile were applied. In these conditions, which are shown in Figure 11, the increase in the electrode force is varied (hereafter 3.5-2.0-5.5 kN and 3.5-2.0-7.5 kN).

Figure 11. The force controlled condition profiles used to control the residual stress state.

Figure 12 shows the residual stress distribution results for each welding condition. Increasing the changed electrode force tended to decrease the high tensile residual stresses in the heat-affected zone. Figure 13 shows the residual stress distributions at a cross section of the spot welds. Figure 13(a) shows the calculated position of the cross section, and Figure 13(b) shows the residual stress distributions at that cross section. The shapes of the distributions are almost the same, but the peak values of the residual stress decrease compared with 3.5-2.0-3.5 kN and 3.5-2.0-7.5 kN.

Figure 12. θ-direction residual stress distribution for each condition: (a) result for 3.5-2.0-3.5 kN, (b) result for 3.5-2.0-5.5 kN, (c) result for 3.5-2.0-7.5 kN.
Additionally, it is well known that the residual stress at the corona bond influences the fatigue strength [4-6]. Therefore, the residual stresses at the corona bond in these numerical simulations are shown in Figure 14. The residual stress is tensile, as shown in previous research [13], and increasing the electrode force tends to decrease the tensile stress.

Finally, Table 1 shows a comparison of the nugget size and residual stress between the basic condition and electrode force controlled condition. As shown here, the appropriate force profile, which is considered the mechanism of formation for the nugget and residual stress, extends the nugget diameter and decreases the residual stress at the spot welds.

Table 1. Comparison of the nugget diameter, penetration ratio, and residual stress at the corona bond for the 3.5 kN and 3.5-2.0-7.5 kN force conditions.

| Force Condition | Nugget Diameter (mm) | Penetration Ratio (%) | Residual Stress at Corona Bond (MPa) |
|-----------------|----------------------|-----------------------|--------------------------------------|
| 3.5 kN          | 5.2                  | 71                    | 351                                  |
| 3.5-2.0-7.5 kN  | 5.7                  | 77                    | 271                                  |
5. Conclusions
In this study, the nugget diameter and the residual stress in spot welded high-strength steel were investigated using coupled electrical-thermal-microstructural-mechanical numerical simulations, and the effect of the electrode force profile on these characteristics were examined. The results indicate that an appropriate force profile extends the nugget diameter and decreases the residual stress at the spot welds.

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