The Effects of Temperature during Post-heating Treatment on Residual Stress of Resistance Spot Welded High-strength Steel Sheets*

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This study investigates the effects of maximum temperature and temperature history during post-heating treatment on residual stress of resistance spot welded high-strength steel sheets. To examine the effects of post-heating treatment, numerical simulations were performed. First, the effect of the phase proportion of tempered martensite and maximum temperature was investigated. This result shows that both of the phase proportion of tempered martensite and maximum temperature affect the residual stress. Second, only the effect of the maximum temperature was examined when the almost all martensite changed to tempered martensite. This result shows that the low maximum temperature decreases the residual stress. Finally, as an example, controlling the temperature history was proposed to satisfy both of the controlling the residual stress and shortening the tempering time. This result shows that controlling temperature history can decrease the maximum temperature in short tempering time and control the tensile residual stress.

Key Words: Resistance Spot Welds, Post-heating Treatment, Residual Stress, Numerical Simulation, High-strength steel

1. Introduction

In recent years, the environmental issues are serious because CO₂ emissions have increased with increasing vehicles. One solution is reduction weight of vehicle body. Now, using high-strength steel sheets is promoted to reduce vehicle body weight.

In manufacturing vehicle bodies, sheet steels are generally assembled by resistance spot welding. However, the fatigue strength of high-strength steel sheets joints welded by resistance spot welding does not increase with increasing the strength of base metal. To improve the fatigue strength, the post-heating treatment is used. Tempering treatment, one of the post-heating method, controls residual stress to improve the fatigue strength of spot welds by softening of martensite in the nugget1).

The softening of martensite generally depends on maximum temperature and temperature history during tempering treatment3). Moreover, residual stress is affected by the hardness of the reheated area5). However, in resistance spot welded joints, the effects of maximum temperature and temperature history during post-heating treatment on the residual stress are not investigated in detail.

In this study, the effects of maximum temperature and temperature history during post-heating treatment on residual stress of 590 MPa grade high-strength steel sheets (hereinafter HT590) welded by resistance spot welding were discussed by using the numerical simulation of resistance spot welding. First, the effect of the phase proportion of tempered martensite and maximum temperature on residual stress was investigated. Second, only the effect of maximum temperature on residual stress was investigated when the almost all martensite changed to tempered martensite. Finally, controlling temperature history at center of the nugget was investigated to satisfy both of controlling the residual stress and shortening tempering time for short process time.

2. Numerical simulation

Figure 1 shows the model used for FE analysis. An axisymmetric model with a restrained upper electrode edge was used to simulate resistance spot welding. The sheet sizes and electrode sizes are shown in Fig. 1. The sheet was 1.2 mm thick and 30 mm wide. The electrode diameter was 6.0 mm and the electrode curvature was 40 mm. Figure 2 and Figure 3 shows the physical properties and the mechanical properties of HT590, respectively11). The phase transformations were considered in this simulation. Kinetics of diffusional phase transformation was expressed by using Leblond-Devaux model5):

\[
\frac{dP_j}{dt} = \frac{P_j^{eq} - P_j(T)}{\tau(T)} \tag{1}
\]

where \(P_j\) is the phase proportion of phase \(j\), \(P_j^{eq}\) is the equilibrium phase proportion of phase \(j\), \(T\) is temperature and \(\tau\) is the delay time before the transformation starts. The delay time is a function of temperature. Phase proportion of martensite was predicted by using Koistinen-Marburger model6):

\[
P_M(T) = P_f(1 - \exp(-0.011(M_S - T))) \tag{2}
\]
where $P_M$ is the phase proportion of martensite, $P_A$ is the phase proportion of austenite and $M_S$ is the start temperature of martensitic transformation. The mechanical properties were calculated as an averaging of the mechanical properties of the individual phases. The physical properties were considered the effect of phase transformation in advance by using the physical properties of martensite below $800^\circ$C and the physical properties of austenite above $800^\circ$C.

Figure 4 shows the measurement area of temperature and residual stress distribution. Measurements were carried out at the nodes of an element on sheet interface.

Before applying tempering current, welding current was applied to the steel sheets for forming the nugget. Welding current was 5.8 kA and welding time was 0.2 s (12 cycles). In addition, power frequency was 60 Hz in this simulation.

**3. Investigation of controlling residual stress with controlling temperature during tempering treatment**

**3.1 The effects of phase proportion of tempered martensite and maximum temperature on residual stress**

In order to control the phase proportion of tempered martensite, the maximum temperature during tempering treatment was controlled to change the tempering current. The tempering current ($I_t$) was changed from 3.2 kA to 6.2 kA. Tempering time ($T_t$) was 0.33 s (20 cycles). The cooling time was 1.65 s (99 cycles) and the hold time was 0.33 s (20 cycles). The electrode force was a constant 3.0 kN. The effect of maximum temperature on residual stress was investigated at center of the nugget.

Figure 5 shows the residual stress distribution in the weld with and without tempering treatment. The tensile residual stress increased by tempering treatment in the nugget as shown in Fig. 5. Figure 6 shows the relationship between residual stress and maximum temperature at center of the nugget during tempering treatment. The horizontal axis represents the maximum temperature and the vertical axis represents the $r$-direction residual stress. Figure 7 shows the relationship between phase proportion of tempered martensite and maximum temperature at center of the nugget during tempering treatment. The horizontal axis represents the maximum temperature and the vertical axis represents the phase proportion of tempered martensite at center of the nugget. Broken lines in Fig. 6 and Fig. 7 indicate $800^\circ$C. As shown in Fig. 6, tensile residual stress increased with increasing the maximum temperature from $500^\circ$C to $800^\circ$C. The phase proportion of tempered martensite also increased with increasing the maximum temperature from $500^\circ$C to $800^\circ$C as shown in Fig. 7. The above results show that the tensile residual stress after tempering treatment have a strong relationship with the phase proportion of tempered martensite. This is because compressive plastic strain increases by softening due to increasing tempered martensite during tempering treatment.
3.2 The effects of maximum temperature during tempering treatment on residual stress

The compressive plastic strain generated during tempering treatment is caused by thermal strain as well as phase proportion of tempered martensite. Therefore, the plastic strain is influenced by the maximum temperature. In order to investigate the effects of only the maximum temperature on the residual stress, tempering time was changed. Figure 8 shows the short tempering time profile (hereinafter called “T_t short”) and the long tempering time profile (hereinafter called “T_t long”). The tempering condition of T_t short shows 0.33 s (20 cycles) time and 5.1 kA current. The tempering condition of T_t long shows 0.67 s (40 cycles) time and 4.6 kA current. Long tempering time lengthens the time for changing from martensite to tempered martensite. Therefore, almost all martensite changes to tempered martensite at low maximum temperature. Tempering current of T_t long was adjusted so that the maximum temperature during tempering treatment in case of T_t long could be lower than T_t short. Figure 9 shows the cross-sectional maximum temperature distribution during tempering treatment in case of T_t short and T_t long. The horizontal axis represents the distance from center of the nugget and the vertical axis represents the temperature. As shown in this figure, the maximum temperature at center of the nugget in case of T_t long was lower than T_t short. Figure 10 shows the cross-sectional phase proportion of tempered martensite distribution. The phase proportions of tempered martensite at center of the nugget were almost same in case of T_t short and T_t long.

Figure 11 shows the cross-sectional residual stress distribution in case of T_t short and T_t long. As shown in Fig. 11, the tensile residual stress in the nugget decreased in case of T_t long. Moreover, the difference of maximum temperature between T_t short and T_t long was about 20°C. The difference of residual stress between T_t short and T_t long was about 80 MPa. These results suggest that the maximum temperature also has powerful influence on the residual stress and the controlling maximum temperature is important for controlling the residual stress.
3.3 The effects on temperature history during tempering treatment on residual stress

Reducing process time is needed in manufacturing vehicle body for cost reduction. Therefore, the shortening of tempering time is needed for applying tempering treatment in manufacturing vehicle body. In tempering time, the time during which the temperature is at tempering temperature needs to lengthen in order to decrease the maximum temperature. Therefore, it is necessary to shorten the time it takes to reach the tempering temperature. Controlling temperature history was examined to short the time it takes to reach the tempering temperature.

Therefore, tempering current was changed to control the temperature history as one of the method to control the residual stress in short tempering time. Figure 12 shows the proposed tempering current profile (hereinafter called “Proposed”). The Proposed shows 7.5 kA and 4.7 kA tempering current and 0.05 s (3 cycles) and 0.28 s (17 cycles) tempering time, respectively. This tempering condition was expected the following effects. First, the short time and high current (hereinafter “SH current”) quickly raises temperature which does not change from martensite to tempered martensite at center of the nugget. Finally, long time and low current (hereinafter “LL current”) raises temperature to change from martensite to tempered martensite in the nugget.

Figure 13 shows the temperature history at center of the nugget and phase proportion history of tempered martensite at center of the nugget during tempering treatment. The horizontal axis represents the time and the vertical axis represents the temperature and phase proportion of tempered martensite. As shown in Fig. 12 and Fig. 13, first, SH current raises the temperature at center of the nugget to about 600°C quickly. Finally, LL current raises temperature and increases tempered martensite in the nugget.

Figure 14 shows the maximum temperature distribution. As shown in Fig. 14, the maximum temperature decreased in the Proposed. Figure 15 shows the phase proportion of tempered martensite distribution. As shown in Fig. 15, phase proportion of tempered martensite was almost same in case of each tempering condition.

Figure 16 shows the cross-sectional r-direction residual stress distribution in case of each tempering condition. As shown in this figure, the tensile residual stress in the nugget was decreased in case of the Proposed. Moreover, the tempering time of the proposed is 0.33 s (20 cycles). This is shorter than in case of Ti long.

The above results show that controlling temperature history can control residual stress in short tempering time.
Conclusions

Controlling temperature during tempering treatment was examined to control the residual stress. The results showed the tempering treatment increased the tensile residual stress due to increasing tempered martensite and temperature. However, the lower tempering temperature decreased the tensile residual stress. Moreover, controlling temperature history reduced tensile residual stress in short tempering time.

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