

Article

Prediction of Residual Stress Distribution in NM450TP Wear-Resistant Steel Welded Joints

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Abstract: This study developed a thermo-metallurgical-mechanical simulation method to calculate the temperature field and residual stress distribution in the NM450TP wear-resistant steel welded joints. During the simulation, the solid-state phase transformation and softening effect of NM450TP wear-resistant steel was considered. The simulation results were compared with the experimental results, which verified the feasibility of this method. The influences of solid-state phase transformation and softening effect on the welding residual stress distribution were discussed. The numerical simulation results showed that the solid-state phase transformation had a more significant effect on the magnitude and distribution of the longitudinal residual stress than that of the transverse residual stress. The softening effect had a significant influence on the peak value of the longitudinal residual stress and had little influence on the transverse residual stress. Comparing the numerical simulation results with the experimental results, it could be seen that the calculation results of the welding residual stress were in the best agreement with the experimental measurement results when the solid-state transformation and softening effects were considered at the same time.



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Keywords: NM450TP wear-resistant steel; solid-state phase transformation; softening effect; welding residual stress; numerical simulation

1. Introduction

The rapid development of the manufacturing and construction industries result in increasing requirements for the mechanical properties of steels [1,2]. Due to their high strength, hardness, and wear resistance, the low-alloy ultra-high-strength steels, such as NM450TP wear-resistant steel, have received more and more attention. The low-alloy ultra-high-strength steels usually have a martensitic structure, which have high yield strength and hardness, and low plastic toughness [3]. Compared with traditional steels, the welding of low-alloy ultra-high-strength steels is much more difficult, and many welding problems have yet to be solved [4–7].

Among them, the welding residual stress problem is the most challenging, and has a great influence on structure safety. The peak residual stress in the welded joint is related to the yield strength of material [8]. The higher the yield strength of the material, the greater the peak residual stress in the welded joint [9]. Low-alloy ultra-high-strength steels are often used to manufacture thin-plate or thin-walled structures. Due to the low structural stiffness and the high yield strength [10], the welding residual stress and deformation problems of low-alloy ultra-high-strength steels are more prominent than those of conventional low-carbon steels [11,12]. The transient stress generated during welding is the driving force for hot and cold cracking. Tensile residual stress may lead to brittle fracture, fatigue failure, and stress corrosion of the structure in the service process. Large compressive residual stresses also increase the risk of structural instability. Studies have shown [13] that under dynamic load service conditions, when residual stress and

load stress are superimposed, the embrittlement and softening zones in the welded joint are more likely to become the initiation point of fatigue cracks, leading to instantaneous fracture. Therefore, in-depth research on the welding residual stress of low-alloy ultra-high strength steel is an urgent need.

Recent advances in computational welding mechanics have shown that numerical simulation methods are the most promising method to study welding residual stresses. The low-alloy high-strength steels have a martensitic structure. The material in the heat-affected zone undergoes a martensite–austenite transformation and softens due to the heating of the welding thermal cycle, which may greatly influence the calculation accuracy of welding residual stress. Related studies have been conducted by other researchers. Deng et al. [14] studied the effect of solid-state phase transformation on the residual stress calculation of P92 steel welded joints. The results showed that solid-state phase transformation had a significant impact on the residual stress magnitude and distribution trend in the welded joint. Fang et al. [15] studied the effect of solid-state phase transformation on stress evolution in martensitic steel during laser cladding. The results showed that the finite element calculation results were more consistent with the experimental values when the solid-state phase transformation was considered. Rna et al. [16] studied the residual stress in the welded joint of a steel with a yield strength of 1180 MPa. The results showed that the softening of the base metal adjacent to the heat-affected zone had a significant effect on residual stress distribution in the joint. Li et al. [17] studied the microstructure and properties of dissimilar steel welded joints. The results showed that the wear resistance and overall strength of the welded joints decreased significantly near the softening zone. The higher the yield strength of the steel, the more severe the softening effect in the joint. Although previous studies have demonstrated that solid-state phase transformation and the softening effect have important effects on residual stress calculation, existing studies have not considered both effects when investigating the welding residual stress in low-alloy ultra-high-strength steels.

In this study, a thermo-metallurgical-mechanical simulation method was developed to calculate the temperature field and residual stress distribution in NM450TP wear-resistant steel welded joints. During the simulation, both solid-state phase transformation and the softening effect were considered. Based on the numerical simulation and experimental results, the influence mechanism of solid-state phase transformation and softening effect on the welding residual stress was discussed. The research results obtained in this study will provide the experimental basis and theoretical support for an in-depth understanding of the welding residual stress distribution characteristics of low-alloy ultra-high-strength steels.

2. Materials and Methods

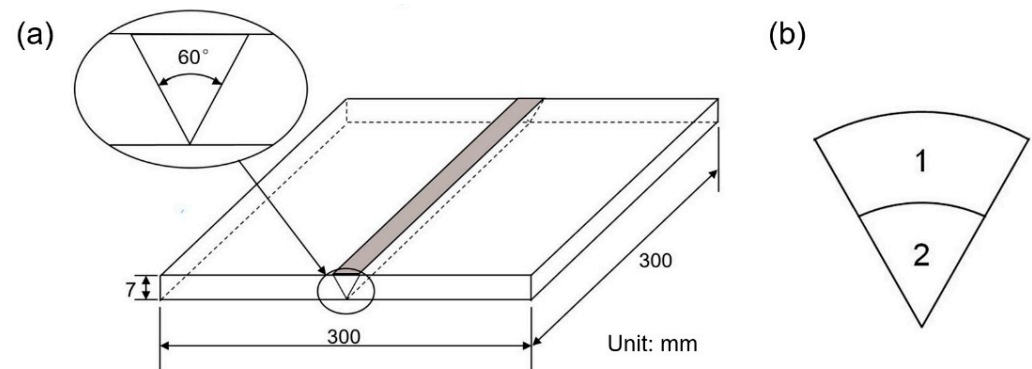
The base metal used in the experiment was NM450TP wear-resistant steel in quenched state. The welding filler material was ER100S-G wire with a diameter of 1.2 mm. The Gas Metal Arc Welding (GMAW) method was used to fabricate the butt-welded joint. The welding machine (NB-350IGBT) is shown in Figure 1. The main chemical compositions of the base metal and welding wire are shown in Tables 1 and 2, respectively. Figure 2 shows the geometric dimensions of the welded joint and the pass arrangement. The size of the specimen was 300 mm × 300 mm × 7 mm. The groove form was unilateral V-shaped and the groove angle was 60°.

Table 1. Chemical compositions of NM450TP wear-resistant steel (wt.%).

Materials	C	Si	Mn	P	S	Al	Nb	Ti	B
NM450TP	≤0.28	≤1.80	≤2.00	≤0.025	≤0.010	≤0.015	≤0.22	≤0.22	≤0.0060

Table 2. Chemical compositions of ER100S-G (wt.%).

Materials	C	Si	Mn	Cr	Ni	Mo
ER100S-G	<0.1	0.5	1.6	0.3	1.4	0.2

**Figure 1.** Welding machine.**Figure 2.** (a) Dimensions of welded joint and (b) pass arrangement.

Before welding, the surface of the base metal was ground to remove the rust and oil from the surface. The NM450TP wear-resistant steel plates were welded by the mixed gas shielded welding method. The welding shielding gas was (80% Ar + 20% CO₂), and the gas flow was 10 L/min. Table 3 shows the optimal welding process parameters. During the welding process, three K-type thermocouples were used to measure the welding thermal cycle during the second welding pass. The measurement point was located on the upper surface of the specimen. The distances between the measurement points and the weld groove were 3 mm, 5 mm, and 8 mm, respectively, as shown in Figure 3. The NM450TP wear-resistant steel plates were welded without any external restraints.

Table 3. Welding parameters.

Welding Pass	Current (A)	Voltage (V)	Welding Speed (mm/s)
1	164	17	2.0
2	168	17	2.4



Figure 3. Temperature field measurement.

After the welding, the residual stresses were measured using the hole-drilling (HD) method. Figure 4 shows the positions of the residual stress measurements. The type of strain gage was BE120-2CA-K. The parameters of the strain gage were resistance of 120.2 ± 0.3 and gage factor of $2.23 \pm 1\%$. As shown in Figure 3, there were three wire grids facing three directions. The angle of those three wire grids with the welding bead were 0° , 45° and 90° , respectively. Adopting elastic mechanics, the longitudinal stress and transverse stress could be calculated using the measured value of three strain gages [18,19].

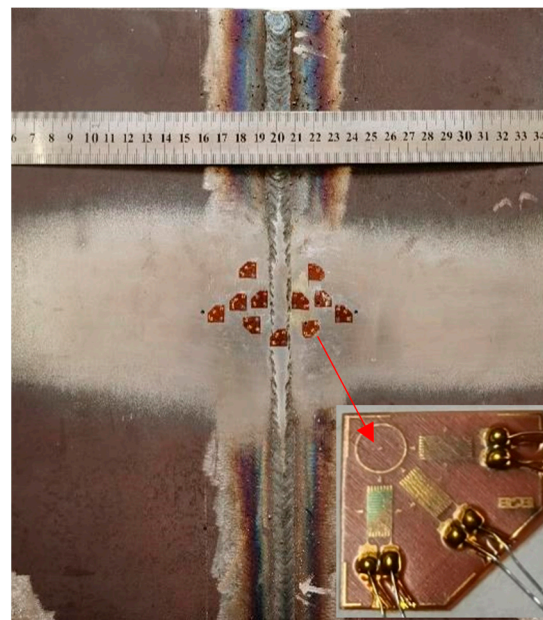


Figure 4. Stress measurement.

After the residual stress measurement, the specimen was cut from the center of the welded joint and the micro-hardness of the joint was measured. The measurement points were distributed along a line L1 as shown in Figure 5.

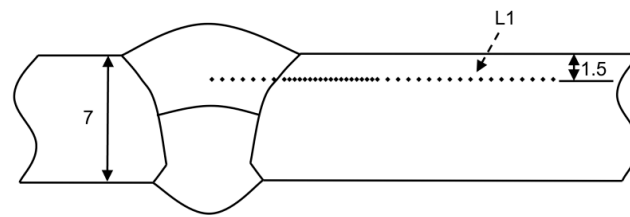


Figure 5. Hardness measurement.

3. Finite Element Analysis

In the numerical simulation of welding residual stress, possible phase transformations in the base metal were considered. During the heating process, when the temperature was lower than the austenite transformation start temperature (A_{c1}), the quenched martensite in the base metal transformed into the softening phase. When the heating temperature was above the A_{c1} temperature, the softening phase began to transform into the austenite phase. When the temperature reached the austenite transformation end temperature (A_{c3}), the austenitization was completed. During the cooling process, the supercooled austenite in the heat-affected zone transformed into normalized martensite. In this study, the same material parameters were used for the quenched and normalized martensite phases due to their small difference in hardness values.

In this paper, the welding filler material was ER100S-G (austenitic stainless steel). Its thermophysical properties and mechanical properties parameters were from reference [20]. For austenitic stainless steel, the influence of work hardening and annealing softening effects on residual stress needed to be considered. In this study, the isotropic hardening model [21] was used to consider work hardening, and the step annealing model [22] was used to consider the annealing softening effect. Previous work [22] indicated that when the annealing temperature was 1000 °C, the calculated residual stresses at fusion zone and its vicinity agreed well with the experimental results. Thus, in this study, the annealing temperature of austenitic stainless steel was set to 1000 °C.

3.1. Finite Element Model

In this paper, a “thermal-metallurgical-mechanical” coupling computational approach was developed based on the software SYSWELD. In the numerical simulation, a finite element model, whose dimensions were consistent with the actual welded joint, was established, as shown in Figure 6. To balance the calculation efficiency and calculation accuracy, fine meshes were used in the weld and its vicinity, and sparse meshes were used in the area far from the weld. All elements were 8-node hexahedral elements, and the number of degrees of freedom for the finite elements in this paper was 24. The numbers of the elements and nodes were 60,000 and 69,794, respectively.

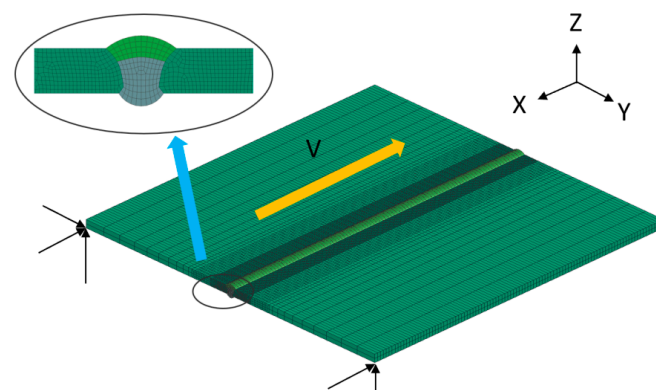


Figure 6. Finite element model.

3.2. Temperature Field Calculation

When calculating the temperature field, the heat transfer equation shown in Formula (1) was used to describe the heat transfer process. The heat generated by the welding arc was defined as interior heat source.

$$\rho c \left(\frac{\partial T}{\partial t} \right) = \lambda \left(\frac{\partial^2 T}{\partial x^2} \right) + \lambda \left(\frac{\partial^2 T}{\partial y^2} \right) + \lambda \left(\frac{\partial^2 T}{\partial z^2} \right) + q_v \quad (1)$$

where ρ , c , T , t , λ and q_v are density ($\text{g} \cdot \text{mm}^{-3}$), specific heat ($\text{J} \cdot \text{g}^{-1} \cdot ^\circ\text{C}^{-1}$), temperature ($^\circ\text{C}$), time (s), heat transfer coefficient ($\text{W} \cdot \text{mm}^{-1} \cdot ^\circ\text{C}^{-1}$) and internal heat generation rate ($\text{W} \cdot \text{mm}^{-3}$), respectively.

In the temperature field calculation, the double ellipsoid heat source model proposed by Goldak [23] was used. The heat conduction process inside the welded joint was described by the nonlinear heat transfer equation [24] shown in Formulas (2) and (3).

$$q_m(x, y, z) = \frac{6\sqrt{3}f_f Q}{\pi\sqrt{\pi}a_f b c} \exp \left[-3 \left(\frac{x^2}{a_f^2} + \frac{y^2}{b^2} + \frac{z^2}{c^2} \right) \right] \quad (2)$$

$$q_r(x, y, z) = \frac{6\sqrt{3}f_r Q}{\pi\sqrt{\pi}a_r b c} \exp \left[-3 \left(\frac{x^2}{a_r^2} + \frac{y^2}{b^2} + \frac{z^2}{c^2} \right) \right] \quad (3)$$

where q_m , q_r , f_f , f_r are front heat flux of ellipsoidal source, rear heat flux of ellipsoidal source, front fractions, and rear fractions, respectively; a_f , a_r , b , and c are the parameters of the double ellipsoid heat source, which are 5, 10, 8, and 5, respectively.

The Newton cooling equation [25] was used to describe the convective heat exchange between the joint and the environment. The Stefan–Boltzmann law was used to describe the radiation heat dissipation of the joint. The initial temperature of the joint and the ambient temperature was set to be 30°C . The welding parameters used in the simulation were exactly the same as those used in the experiment. Figure 7 shows the thermophysical properties of the martensite phase and austenite phase. These parameters were calculated by the JMatPro software according to the chemical composition of NM450TP wear-resistant steel. Among them, the thermophysical properties of the softening phase was the same as those of martensite [26,27].

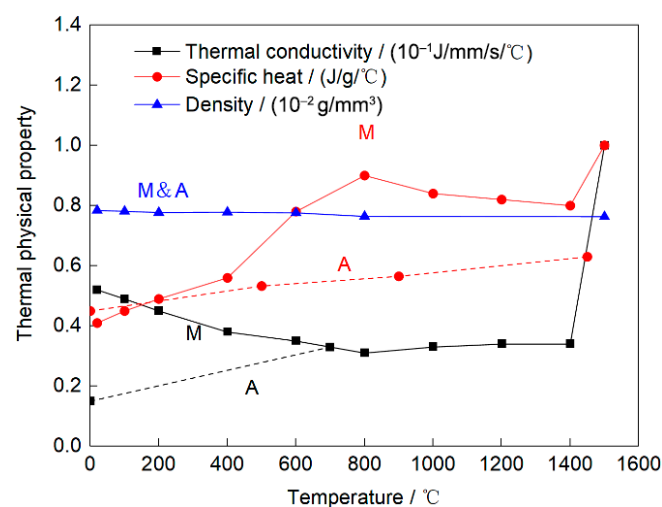


Figure 7. Temperature-dependent thermal properties of NM450TP wear-resistant steel (M, martensite; A, austenite).

3.3. Phase Composition Calculation

During the heating and cooling process, the NM450TP wear-resistant steel underwent austenitic–martensitic transformation. Figure 8 shows the thermal expansion test results of

the NM450TP wear-resistant steel. It can be seen from the figure that the A_{c1} temperature, A_{c3} temperature, and martensitic transformation start temperature (M_s) were 720 °C, 850 °C, and 525 °C, respectively. The thermal expansion coefficients of martensite and austenite could be determined from the temperature–strain curves in Figure 8. In the numerical simulation, it was assumed that the thermal expansion coefficient of the softening phase was the same as that of the martensite. The Johnson–Mehl–Avrami relation [28] and the Koisten–Marburger relation [29] were used to describe the austenite transformation process and the martensitic transformation process, respectively.

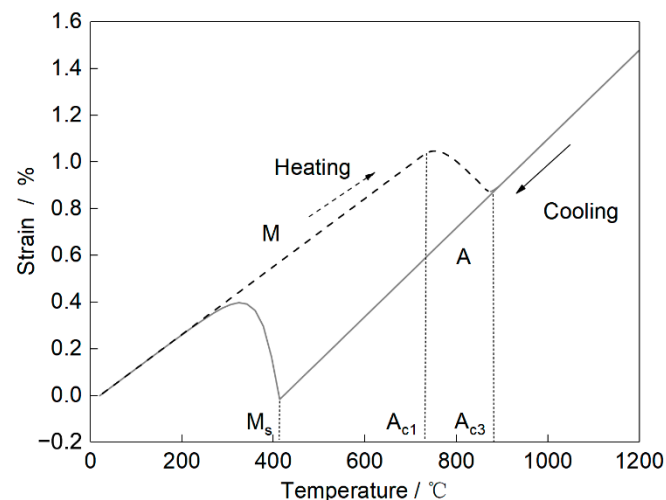


Figure 8. Temperature–strain curves of NM450TP steel during heating and cooling (M_s —martensite transformation start temperature, A_{c1} —austenization start temperature, A_{c3} —austenization finish temperature).

3.4. Softening Model

Since the NM450TP wear-resistant steel was quenched martensite, during welding, the base metal adjacent to the heat-affected zone would soften. The yield strength and hardness of the material decreased. The softening effect influenced the residual stress distribution in the joint, which should be considered in the numerical simulation.

In this study, a model including softening coefficient and maximum softening degree was established to consider the softening phenomenon of NM450TP wear-resistant steel during the welding process. According to the calculation results of the peak temperature distribution and the measurement results of the hardness distribution, the corresponding relationship between the peak temperature and the softening coefficient was determined. Since the base metal was quenched martensite, the position corresponding to A_{c1} had the highest softening degree. The lower the peak temperature, the smaller the softening degree. From the hardness measurement and the temperature field results, the hardness was hardly affected when the peak temperature was below 230 °C. Thus, the softening temperature range was determined as 230 °C to 720 °C (A_{c1}). To quantitatively evaluate the softening coefficient, the softening coefficient was set to be 0 when the peak temperature was 230 °C and was set to be 1 when the peak temperature was 720 °C. The relationship between the peak temperature and the softening coefficient f_t was defined as follows:

$$f_t = \frac{T_t - T_L}{T_H - T_L} \times 100\% \quad (4)$$

where T_H is 720 °C, T_L is 230 °C, T_t is the peak temperature at any position in the softening zone, $T_L \leq T_t \leq T_H$.

The maximum softening degree D was determined according to the difference between the lowest hardness in the softening zone and the average hardness of the base metal and was defined as follows:

$$D = \frac{HV_{BM} - HV_{min}}{HV_{BM}} \times 100\% \quad (5)$$

where HV_{BM} is the average hardness of the base metal, and HV_{min} is the minimum hardness in the softening zone.

Since the yield strength of the softening zone was not measured in this study, the maximum softening degree of hardness was equivalent to the maximum softening degree of yield strength. According to the hardness test results, when the peak temperature was 720 °C, the hardness value and the corresponding yield strength at this position were the lowest. The yield strength σ_f of the base metal after cooling to room temperature at this position could be calculated from Formula (3).

$$\sigma_f = \sigma_s \times (1 - D) \quad (6)$$

When the peak temperature T_t experienced by the base metal was between T_H and T_L , the yield strength σ_t of each temperature below T_t during the cooling process was calculated by the softening coefficient f_t . Figure 9 shows the schematic diagram of the softening model established in this study.

$$\sigma_t = \sigma_f \times f_t + \sigma_s \times (1 - f_t) \quad (7)$$

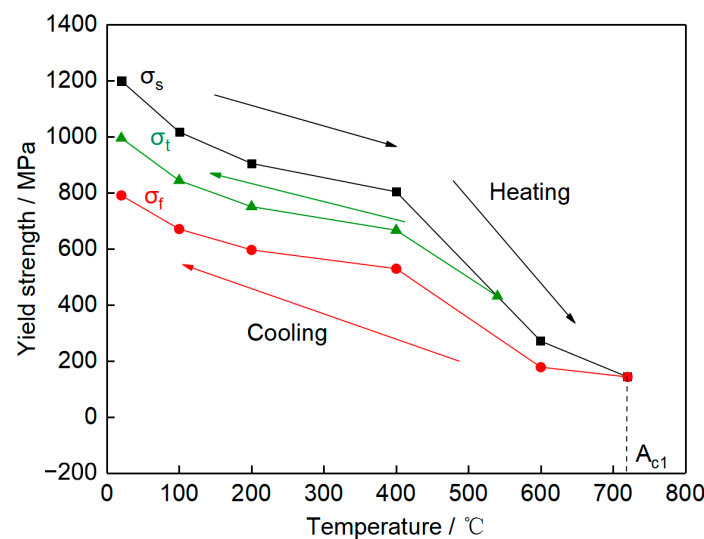


Figure 9. Softening model.

3.5. Stress Calculation

The total strain of the material consisted of elastic strain, plastic strain, thermal strain, phase transformation strain, and creep strain. However, considering the short high-temperature residence time during the welding process, the creep strain was not obvious. Thus, the creep strain could be ignored. The elastic and plastic strains were calculated using Hooke's law and the Von Mises yield criterion, respectively. Thermal strain was reflected by the thermal expansion coefficient. The phase transformation strain was described using the Leblond model [30]. The softening effect was considered using the model proposed in this study.

Due to the high strength of NM450TP wear-resistant steel, the effect of work hardening was not obvious. Thus, it was defined as an ideal elastic–plastic model [31,32] in the material model, and the effect of work hardening was not considered. The mechanical properties of NM450TP wear-resistant steel are shown in Figure 10. In Figure 10, the yield strengths

at room temperature, 200 °C, 400 °C, 600 °C, 800 °C, and 800 °C were obtained by the tensile tests, and other material performance parameters were calculated by the JMatPro software through material composition. The initial state of NM450TP wear-resistant steel was the quenched martensite, and its yield strength decreased continuously during the welding heating process. Austenitization occurred in the interval from the A_{c1} temperature to the A_{c3} temperature. When the temperature was higher than A_{c3} , the martensite was completely transformed into the austenite phase, so the yield strength of the material was very low. During the cooling process, the austenite temperature decreased continuously, and the supercooled austenite phase formed when the temperature was lower, leading to the continuous increase of the yield strength. When the temperature was lower than M_s , the normalized martensite phase was formed due to the martensitic transformation, and the yield strength increased rapidly until it reached the yield strength of the initial phase.

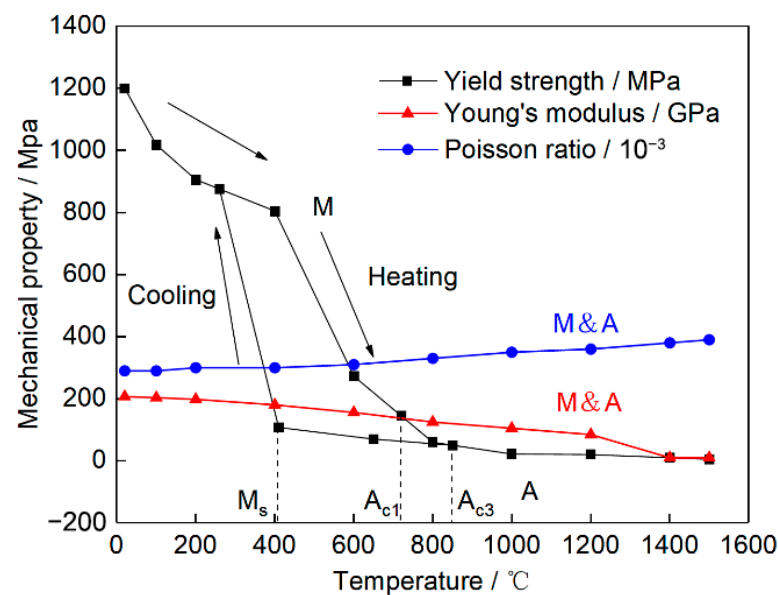


Figure 10. Mechanical properties of NM450TP wear-resistant steel.

No external constraints were used in the experiment, so only three nodes and six degrees of freedom were used in the finite element model to prevent rigid body displacement. Figure 6 shows the mechanical boundary conditions.

3.6. Calculation Case

The main purpose of this study was to clarify the influence of solid-state phase transformation and softening effects on the welding residual stress of NM450TP wear-resistant steel joints, so a total of three calculation cases were designed, as shown in Table 4. The first case did not consider the solid-state phase transition and softening effect, the second case only considered the solid-state phase transition, and the third case considered both the solid-state phase transition and the softening effect.

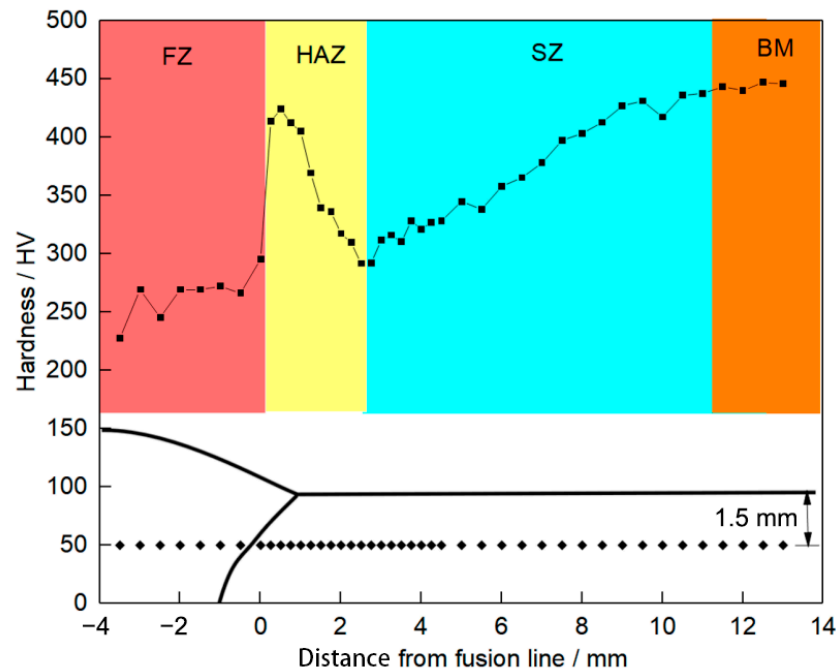
Table 4. Calculation cases.

Case	Solid-State Phase Transformation	Softening Effect
A	No	No
B	Yes	No
C	Yes	Yes

4. Results and Discussion

4.1. Microhardness Distribution

Figure 11 shows the microhardness distribution of the welded joint along L1. As can be seen from this figure, there was a wider softening zone (SZ) on the base metal side adjacent to the heat-affected zone. Since the base metal was quenched martensite, temper softening occurred in this area under heating of welding thermal cycling. The softening phenomenon near the heat-affected zone was severe, and its hardness value was 283 HV. The degree of softening decreased with increasing distance from the heat-affected zone. The maximum softening degree D calculated by the Formula (2) was about 40%.



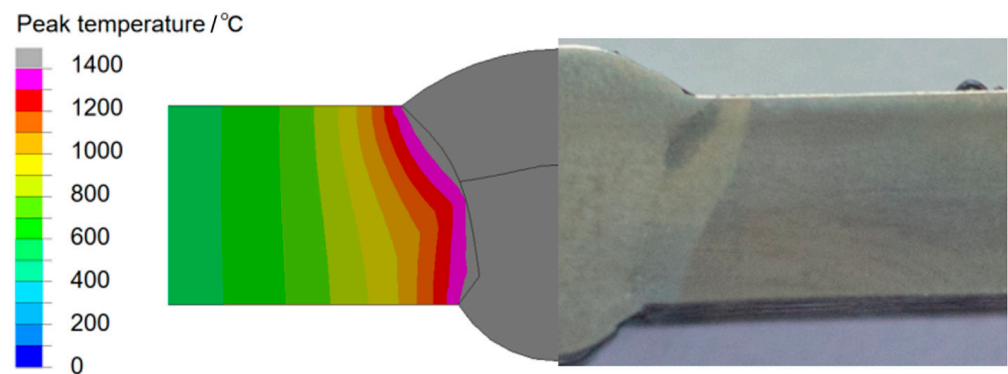


Figure 12. Computational and experimental fusion zone.

Thermal cycles at 3 mm, 5 mm, and 8 mm from the weld toe were measured. Figure 13 shows the calculated results and the experimental results. It could be seen from this figure that the peak temperature obtained by the experimental measurement was very close to the numerical simulation result, and the difference between the two was less than 10 °C. The curve of the heating part indicated that within 0 s to 25 s, there was a specific difference between the experimental value and the measured value in the heating speed. In the cooling part, when the time was 60 s, the difference between the experimental value and the measured value was the largest. The peak temperature distribution of the central section along L1 was extracted from the numerical simulation temperature field results and compared with the microhardness distribution of the welded joint along L1, as shown in Figure 14. It indicated that the highest peak temperature in the softening zone was 720 °C (Ac1), and the lowest peak temperature in the softening zone was 230 °C.

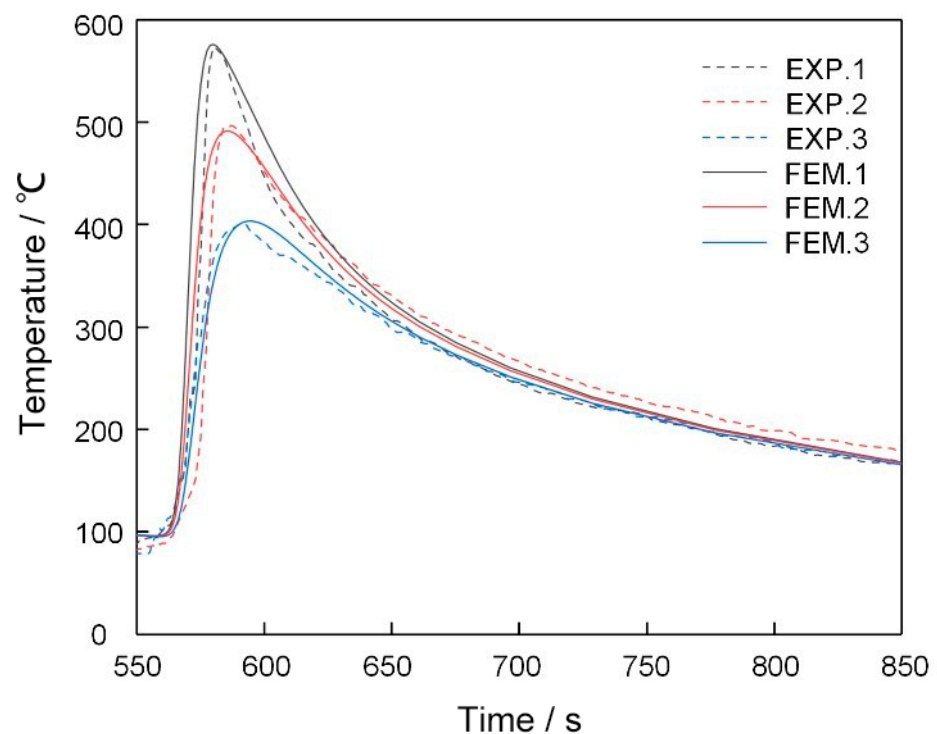


Figure 13. Simulation results and experimental results of welding thermal cycles.

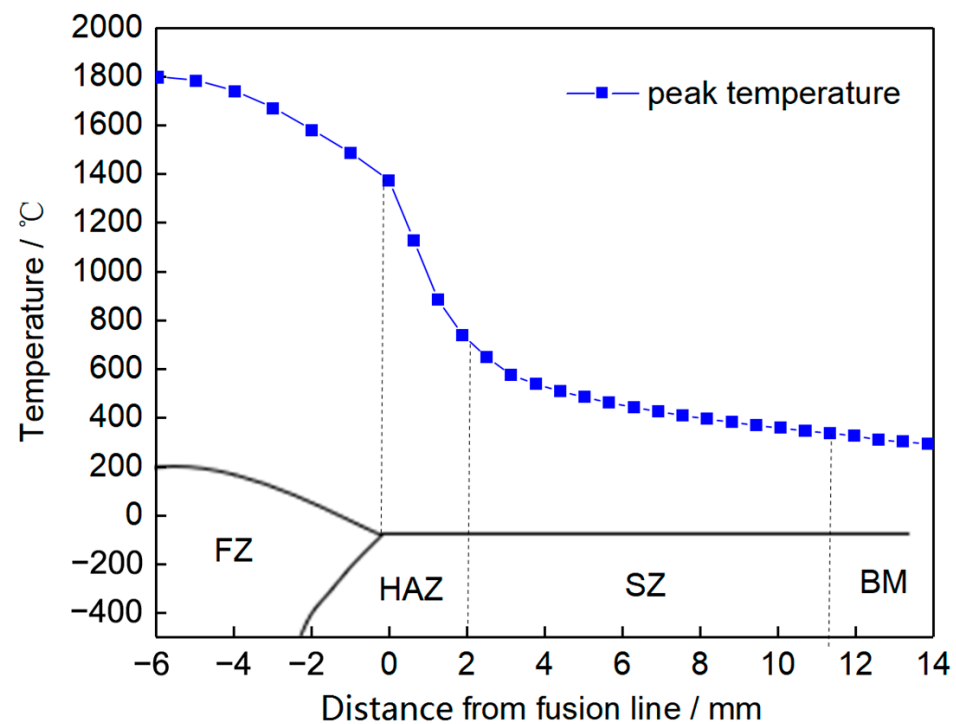


Figure 14. Peak temperature distribution along L2.

4.3. Residual Stress

Figure 15 shows the longitudinal residual stress distribution on the upper surface of the NM450TP wear-resistant steel welded joint. It could be seen that the longitudinal residual stress in the three calculation cases was symmetrically distributed. Due to the geometric end effect [33], the longitudinal stress distribution at both ends of the joint was complicated. The distribution of longitudinal residual stress was nearly the same in the regions other than the two ends and their vicinity. The longitudinal residual stress distribution in Case B was different from that in Case A. The peak tensile stress on the upper surface of Case B was lower than that of Case A. In the central area of the upper surface, the tensile stress zone in Case B was wider than that in Case A. In addition, the compressive stress zone on the upper surface of Case B was different from that of Case A. From the comparison of the two, it could be seen that the solid-state phase transformation had a significant impact on the magnitude and distribution of the longitudinal residual stress calculation results. Compared with Case B, although Case C considered the softening effect, the longitudinal stress distribution on the upper surface had no significant change.

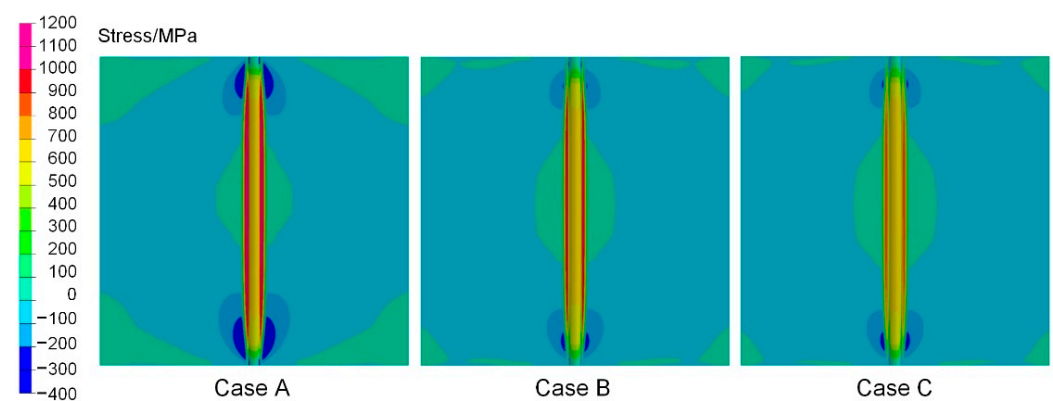


Figure 15. Longitudinal residual stresses distributions on upper surfaces.

Figure 16 shows the longitudinal residual stress distribution in the central section of the NM450TP wear-resistant steel welded joint. In the heat-affected zone of Case A, the peak longitudinal tensile residual stress was close to the room-temperature yield strength of the NM450TP wear-resistant steel. As the distance from the weld increased, the residual stress gradually decreased and turned to compressive stress. Compared with Case A, the tensile residual stress in the heat-affected zone of Case B decreased significantly. This was due to the martensitic transformation of the heat-affected zone structure during the cooling process. The volume expansion reduced the tensile stress at this location so that the high longitudinal residual stress zone was significantly reduced. In the central section of Case B, the peak tensile residual stress appeared in the base metal adjacent to the heat-affected zone. Compared with Case B, the magnitude and distribution of longitudinal tensile residual stress in the heat-affected zone of Case C did not change significantly, while the peak value of longitudinal tensile residual stress adjacent to the heat-affected zone was significantly reduced.

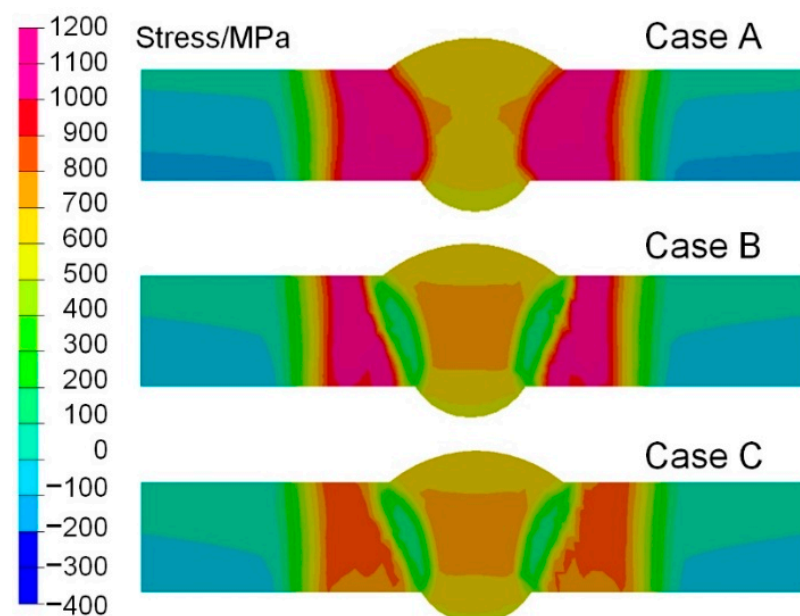


Figure 16. Longitudinal residual stresses distributions on central section of welded joint.

Figure 17 shows the comparison between the calculated and experimental results of the longitudinal residual stress distribution on the upper surface. In the calculation results, the longitudinal tensile residual stress was mainly distributed in the zone about 10 mm from the weld center. In Case A, a high tensile stress (1170 MPa) formed in the heat-affected zone. Since Case B considered the solid-state phase transformation, the peak value of longitudinal residual stress in the heat-affected zone and the high-stress region decreased slightly compared with Case A. Case C considered both solid-state phase transformation and softening effect; the peak value of longitudinal residual stress in the heat-affected zone and the range of high-stress region decreased significantly, and the peak value of tensile stress was about 870 MPa. From the comparison between the calculation and experimental results of longitudinal residual stress distribution, it could be seen that the calculation results of Case C are in good agreement with the experimental measurement results. Therefore, for NM450TP wear-resistant steel, to obtain higher-precision residual stress calculation results, it was necessary to consider both solid-state phase transformation and softening effects.

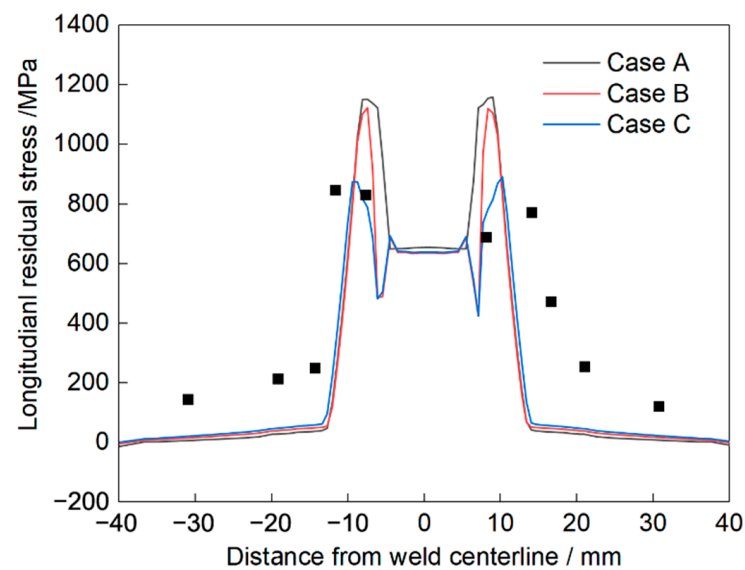


Figure 17. Computational and experimental results of longitudinal residual stress.

Figure 18 shows the transverse residual stress distribution on the upper surface of the NM450TP wear-resistant steel welded joint. The compressive residual stress zone in Case A and Case B were different with each other. From the comparison, it can be seen that the solid-state phase transformation influenced the calculation results of the transverse residual stress. Compared with Case B, although Case C considered the softening effect, there was no significant change in the transverse stress distribution on the upper surface of both cases.

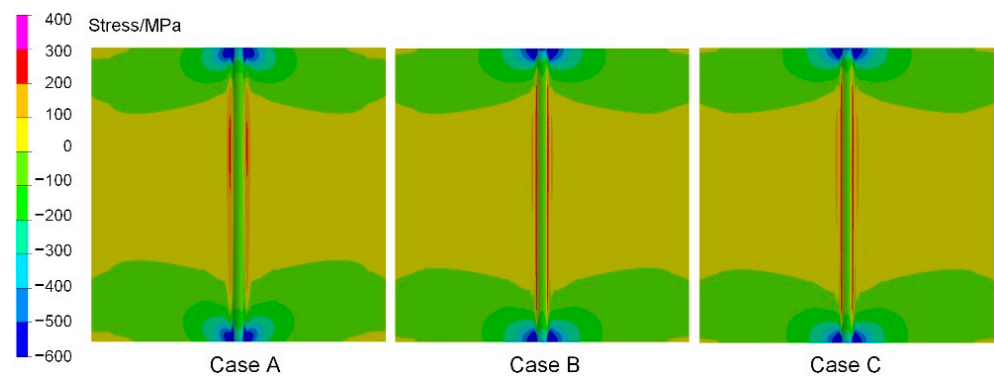


Figure 18. Transverse residual stress distribution on the upper surface of the joint.

Figure 19 shows the transverse residual stress distribution at the central section of the NM450TP wear-resistant steel welded joint. It could be seen that the calculation results in the three calculation cases were significantly different. The most obvious difference was the location of high transverse tensile residual stress. In Case A, the high transverse tensile stress was located in the heat-affected zone. In Case B and Case C, the high tensile stress was distributed at the weld toes, which was more consistent with the actual situation. In all three cases, there was large compressive stress on the upper surface of the weld filler metal. However, after considering the solid-state phase transformation, a high compressive stress region also appeared inside the joint in Case B. When the solid-state phase transformation and softening effects were considered at the same time, two high compressive stress regions appeared at the interface between the weld and the base metal on both sides. In addition, since the restraint of the weldment in the transverse direction was smaller than that in the longitudinal direction, the transverse residual stress value of the joint was significantly lower than the longitudinal residual stress value.

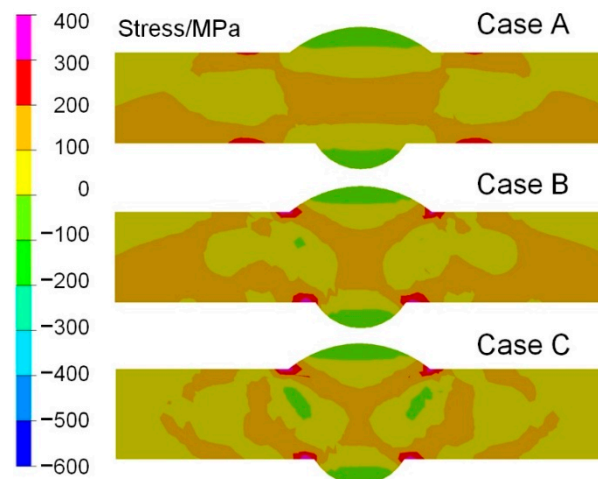


Figure 19. Transverse residual stresses distributions in central section.

Figure 20 shows the calculated and experimental results of the transverse residual stress on the upper surface of the welded joint. It could be seen from the calculation results that the transverse residual stresses at the weld center were close to each other. However, in the rest of the weld, Case A was quite different from Case B and Case C. After considering the solid-state phase transformation, the peak transverse residual stress (370 MPa) in Case B increased significantly. The transverse residual stress distributions in Case B and Case C were almost the same. It could be seen from the figure that there was a specific deviation between the calculated results and the measured results. This was mainly due to the large stress gradient in the heat-affected zone. During the stress measurement process, the experimental results could not accurately reflect the actual situation due to the limitations of the hole-drilling method and the measurement error. In future research, stress measurement methods with higher precision will be adopted to improve the accuracy of stress-testing.

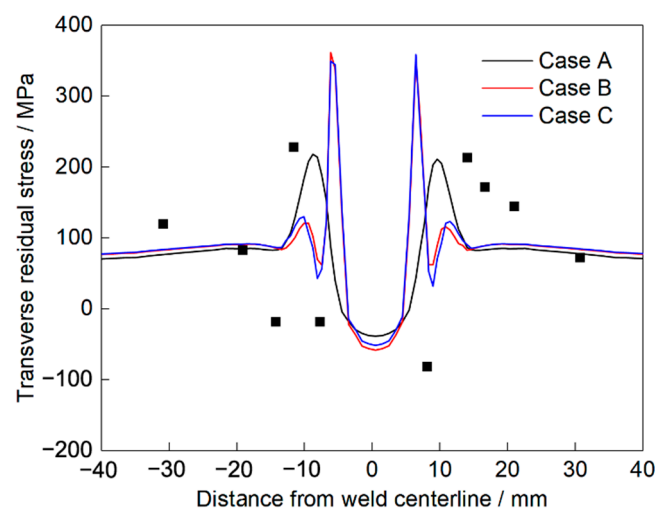


Figure 20. Computational and experimental results of transverse welding residual stress distribution.

5. Conclusions

- (1) The average microhardness of the base metal of NM450TP wear-resistant steel was about 450 HV. The maximum microhardness of the heat-affected zone in the joint was 426 HV. The minimum microhardness of the softening zone was about 290 HV, and the width of the softening zone was about 9 mm. The welding thermal cycle had a more significant influence on the hardness of the softening zone than that of the heat-affected zone.

- (2) The solid-state phase transformation had a significant effect on the calculation results of longitudinal residual stress. When considering the solid-state phase transformation, the longitudinal residual stress in the heat-affected zone decreased significantly, and the longitudinal residual stress peak was transferred from the heat-affected zone to the base metal adjacent to the heat-affected zone. The solid-state phase transformation had a certain influence on the calculation results of the transverse residual stress. When considering the solid-state phase transition, the calculated peak value of the transverse residual stress increased.
- (3) The softening effect had little effect on the distribution of longitudinal residual stress but influenced the peak longitudinal residual stress in the softening zone. The peak stress on the base metal adjacent to the heat-affected zone was 870 MPa, which decreased by 300 MPa compared to the calculated result without considering the softening effect. The softening effect had little effect on the distribution shape and peak value of the transverse residual stress. The peak value of the transverse residual stress was 370 MPa, which was much smaller than the room-temperature yield strength of the base metal.
- (4) The comparison between the numerical simulation results and the experimental results indicated that the calculation results of the welding residual stress in the joint were in the best agreement with the experimental values when the solid-state phase transformation and softening effects were considered at the same time. When calculating the welding residual stress of similar materials, it was recommended to consider both solid-state phase transformation and softening effects.

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