Residual stress and distortion in thick-plate weld joint of AF1410 steel: finite element simulations and experimental studies

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Abstract
The quantification of the residual stress and distortion in the thick-plate weld joint of AF1410 steel has great significance, which is the basis for the safety and process design of the component. Therefore, this paper systematically investigated the welding residual stress and distortion distribution in the 10 mm thick welded plate for AF1410 steel by tungsten inert gas welding. The residual stress measurements were carried out by the X-ray diffraction method and advanced contour method, and the distortion was determined by coordinate measuring machine. The developed thermo-metallurgical-mechanical finite element model was applied to predict the residual stress and distortion in multi-pass welding considering solid-state phase transformation (SSPT) and transformation plasticity. The measured residual stress and distortion distribution were in good agreement with the finite element simulation results. The comparison results revealed that the residual stresses in the upper and lower parts of the welding plate were small, and there was apparent stress concentration in the center of the welding joint. SSPT and the subsequent thermal cycle had a significant influence on the magnitude of final residual stress. The accurate finite element model and the understanding of stress formation mechanism are helpful to control the residual stress and distortion distribution of aviation parts reasonably.

1. Introduction

With the development of the aviation industry, the high Co-Ni secondary hardening ultra-high strength steel (UHSS) has attracted extensive attention [1–4]. AF1410 steel, as a typical UHSS, is a significant material for the vital bearing structure of aircraft, including landing gear and horizontal stabilizer shaft due to its excellent plastic toughness and welding performance. The welding residual stress is relatively large, and the distortion is difficult to control due to the huge heat input of welding and the high strength of UHSS [5, 6]. Especially in multi-layer and multi-pass welding, the severe distortion of part is caused by continuous heat input [7]. In addition, the mechanical properties and the specific volume of different phases vary greatly due to the martensitic transformation of UHSS in cooling, which brings more uncertainty to the distribution of welding residual stress [8].

High residual stress, especially tensile stress, will accelerate the stress corrosion cracking of welded joints in the corrosive environment. In addition, the residual tensile stress will increase the crack driving force in the welded joint and reduce the fatigue life. The irrational residual stress distribution brings great risks to the safe service of aircraft. Therefore, understanding the residual stress and distortion caused by welding in advance will help the safe design of the parts with welding joints and the formulation of the manufacturing process.

In recent years, computational welding mechanics has been widely used in actual production applications. Researchers began to utilize finite element software to predict welding residual stress and distortion. Lin et al [9]
investigated the influence of multi-beam shape and heating group offset on residual stress in titanium alloy welding joint by finite element method (FEM). Banik et al.[10] successfully predicted the residual stress and distortion in the thick plate of austenitic stainless steel. Zhang et al.[11] simulated the angular distortion in thick-plate multi-pass T-joints and determined the accurate initial value of presetting method based on the simulated results. Besides, the influence of solid-state phase transformation (SSPT) and transformation plasticity on welding residual stress and distortion has attracted increasing research interest. Sun et al.[12] simulated the residual stress distribution in S355 steel weld plate considering the influence of SSPT and mixed hardening model. Fang et al.[13] demonstrated that the low-temperature phase transformation considering the transformation plasticity has a tensile stress relaxation effect in the single-track laser metal deposition. Wang et al.[14] reported that the large compressive stress was generated in the weld zone due to the martensite transformation in the multi-pass weld. Overall, SSPT should be taken seriously in the welding thermo-mechanical coupling analysis.

The reliability of simulation results also needs to be verified by the experiment method. Concerning residual stress, the traditional methods such as hole drilling method and XRD method can only characterize the residual stress distribution on the surface, and there are great challenges in measuring the internal stress of parts. As a complex or thick welded component, the residual stress distribution inside the part cannot be ignored. Ahn et al.[15] used neutron diffraction to measure the residual stress inside the weld plate, which had good agreements with the simulation results. Roy et al.[16] measured the residual stress distribution in the laser cladded rails by neutron diffraction technique. Nevertheless, the scarcity of neutron sources is an inevitable problem.

As a new way developed in recent years to measure residual stress through destruction, the contour method was first proposed by Prime[17]. Clausen et al.[18] used the neutron diffraction and contour method to measure the residual stress of a valve housing made from 316 L stainless steel powder. Sun et al.[19] investigated the residual stress in stationary shoulder friction stir welded plate by neutron diffraction and contour method. The good agreements between neutron diffraction and contour method results verify the accuracy of the contour method. Compared with neutron diffraction, the advantages of the contour method lie in the low cost and providing the cross-sectional residual stress perpendicular to the cutting face, but the disadvantage is that the residual stresses in three directions cannot be measured by a single cut, as demonstrated by Schajer[20]. However, Pagliaro et al.[21] proposed an advanced contour method (ACM) that the original residual stress in the other two components could be determined by the superposition of stresses measured post-cutting surface with data from the contour method. The data of the superposition method is similar to the results obtained from neutron diffraction measurements on the uncut surface.

To date, researchers pay more attention to improving the properties of high Co-Ni UHSS, including strength, fracture toughness, and corrosion resistance. Li et al.[22] optimized the comprehensive mechanical properties of laser additive manufactured AF1410 steel by heat treatment method. However, few studies on the residual stress and distortion in multi-pass welding for high Co-Ni UHSS restrict the further application of UHSS in practice. This paper adopted a systematic method to predict and measure the residual stress and distortion in the welding joint of the 10 mm thick plate in AF1410 steel. The thermo-metallurgical-mechanical coupled model was developed to simulate the welding residual stress and distortion. The accurate temperature and phase distribution were used as the boundary conditions of mechanical analysis. Besides, Abaqus user

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**Figure 1.** (a) Schematic of the plate dimensions and clamping conditions, (b) the images of the welding plate.
subroutine UMAT was programmed to consider the influence of SSPT and transformation plasticity on residual stress and distortion. The residual stress on the middle-length cross-section was determined by the advanced contour method and XRD method. The accuracy of finite element results was proved by comparing simulations with experimental results for residual stress and distortion. Then, the formation mechanism of residual stress, especially the influence of SSPT on stress in multi-pass welding, was discussed. This work provided technical support and powerful help for optimizing the residual stress and distortion to enable the regular use of aviation components.

![Figure 2](image)

**Figure 2.** Contour method: (a) the welding plate cut by EDM, (b) surface contour measurement of the cutting surface using CMM, (c) the smoothed data of surface contour, and (d) the elastic finite element model after calculation completed.

| Material | C    | Co   | Ni   | Cr   | Mo   | Mn   | Si   | S    | P    | Fe  |
|----------|------|------|------|------|------|------|------|------|------|-----|
| BM       | 0.17 | 14.11| 9.86 | 2.02 | 1.04 | <0.02| 0.02 | <0.003| 0.005| Balance |
| FW       | 0.16 | 14.4 | 10.3 | 2.07 | 1.06 | <0.01| 0.01 | <0.001| 0.002| Balance |

**Table 1.** Chemical composition of AF1410 steel for base material and filler wire (wt.%).

**Table 2.** The thermal expansion coefficient of different phases.

| Phase    | Thermal expansion coefficient |
|----------|------------------------------|
| Initial state | 1.2E-5                      |
| Austenite    | 2.2E-5                      |
| Bainite      | 1.1E-5                      |
| Martensite   | 1.2E-5                      |
2. Experiment procedures

The multi-pass welding with the dimension of 200 × 150 × 10 mm was performed with the manual TIG welding. The welding current is around 100–120 A, the welding voltage is about 10–12 V, and the welding speed is approximately 0.1 m min⁻¹. The filler wire (FW) composition summarized in table 1 is similar to the base metal value, which meets the composition requirements of AF1410 steel according to SAE AMS 6533C. The material parameters of different microstructure in AF1410 steel, including thermophysical properties and mechanical properties at different temperatures, were taken from the published data [23]. The thermal expansion coefficients of different phases have been modified in the current study, as presented in table 2. The hardness of the welded joint was measured by Qness Q10A Vickers hardness tester with a force of 500 gf and a dwell time of 15 s. The plate was clamped to avoid distortion and movement during the welding experiment, as shown in figure 1(a). The image of the plate after welding is displayed in figure 1(b).

The surface residual stress of the welding plate along Path 1 was measured by PROTO LXRD residual stress measurement systems. The basic principle of measuring the residual stress by XRD is to measure the diffraction displacement according to the $\sin^2 \psi$ method. The results reflect the surface stress distribution of workpiece because the penetration depth is limited, accounting for the low energy of x-ray.

The contour method is a destructive residual stress measurement method and was used to measure the residual stress distribution in the mid-length cross-section of the welding plate. First, the plate was cut by low-speed wire electrical discharge machining (LS-WEDM) along Path 1, as shown in figure 2(a). The specimens were fixed with the purpose-made clamp to prevent the cutting surface from moving as the stresses were relaxed to obtain high-quality measurement results. Then, the out-of-plane displacements of the cutting surface were measured by coordinate measuring machine (CMM) with ZEISS Dotscan, as displayed in figure 2(b). The measurement data from both surfaces were averaged and smoothed to eliminate the roughness and noise, as shown in figure 2(c). After data processing, the elastic finite element model was created in ABAQUS software. The out-of-plane displacements with reversed direction were applied to the surface of the finite element model as the node boundary condition [17]. The total number of elements and nodes was 1105770 and 1153656 with the C3D8R element type, as presented in figure 2(d). The elastic properties of AF1410 steel at room temperature were adopted, for which Young’s modulus was 200 GPa and Poisson’s ratio was 0.33. Besides, the distortion of the welding plate along the thickness direction could also be obtained while measuring the surface contour. Concerning the advanced contour method, XRD was utilized to measure the transverse and normal stress components of the cutting face along Paths 2, 3, and 4 respectively, as presented in figure 1(a). The measured data plus the stress from the contour method was the original transverse and normal stress components stress. The detailed information and guidelines have been elaborated in the work of Hosseinzadeh et al [24].

3. Finite element modeling

The welding joint was corroded with 4% Nital, and there were six weld passes in the welding joint, as displayed in figure 3. The corresponding finite element model was divided into six parts according to the actual dimension, and the boundaries of the parts are simplified to the straight line. Considering the symmetry of the welding experiment and the massive computation simulated the whole welding plate, the finite element model was simulated one half of the actual plate. The finite element model was shown in figure 4 and solved by ABAQUS/...
Standard. The mesh type was DC3D8 in heat analysis and C3D8 in mechanical analysis. The transitional mesh was utilized to balance the calculation time and accuracy. In order to match the mesh division of the whole welding plate, the mesh size in the HAZ is not uniform, about 0.8 mm × 0.8 mm × 1 mm. The mesh convergence had been studied, and the size of the mesh had enough accuracy. The total number of mesh elements and nodes was 60000 and 68490, respectively. As displayed in figure 4, the mechanical boundary conditions were imposed on the finite element model to simulate the actual constraint conditions. Symmetrical constraints, named YSYMM, are applied to the model to simulate the stress distribution of the entire welded plate.

3.1. Thermal analysis
The accurate welding thermal field is the prerequisite for the following welding analysis. The temperature distribution of the finite element model is solved by heat equation, as presented in equation (1).

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

where \( T \) is the temperature (°C), \( t \) is the time (s), \( \lambda \) is the thermal conductivity (W·m⁻¹·K⁻¹), \( \rho \) is the density (kg·m⁻³), \( c \) is the specific heat (J·kg⁻¹·K⁻¹), \( q_v \) is internal heat source intensity (W·m⁻³).

The thermal boundary conditions considering natural convection and radiation are defined by equations (2) and (3), respectively.

\[
q_{\text{conv}} = h_{\text{conv}}(T_i - T_0)
\]

\[
q_{\text{rad}} = \varepsilon \sigma [(T_i - T_{\text{abs}})^4 - (T_0 - T_{\text{abs}})^4]
\]

where \( h_{\text{conv}} \) is the heat transfer coefficient, \( T_i \) is the actual temperature of the plate, \( T_0 \) is the surrounding temperature (20 °C), \( T_{\text{abs}} \) is the absolute zero temperature, \( \varepsilon \) is the emissivity (0.8), and \( \sigma \) is the Stefan-

\[\sigma\]

\[\sigma\]
Boltzmann constant \( (5.67 \times 10^{-8} \text{ J} \cdot \text{K}^{-4} \cdot \text{m}^{-2} \cdot \text{s}^{-1}) \). The heat transfer coefficient is set to 30 W·m\(^{-2}\)·K\(^{-1}\) at 600 °C and 10 W·m\(^{-2}\)·K\(^{-1}\) at 20 °C. The value is interpolated linearly between 600 °C and 20 °C, and the value is still 30 W·m\(^{-2}\)·K\(^{-1}\) when the temperature exceeds 600 °C. The thermal boundary conditions are applied to all outer surfaces of each weld pass.

Goldak et al [25] proposed the double ellipsoidal heat source, as presented in figure 5, of which the size and shape could change easily. The double ellipsoidal heat source is appropriate for arc welding and has been used widely in relevant research. The double ellipsoidal heat source is employed in this work, and the heat density could be described as follows:

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

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

\[
q(x, y, z, t) = q_f + q_r, f_f + f_r = 2
\]

where \( q_f \) and \( q_r \) are power density within the front and rear ellipsoidal, respectively. \( q \) is the total power density of the heat source. \( Q \) is the effective heat power, and \( Q = \eta U I \). \( \eta \), \( U \), and \( I \) are the efficiency of the heat source, welding voltage, and welding current, respectively. \( a_f, a_r, b, \) and \( c \) are the geometric parameters of the double ellipsoids.

* I- Initial state, A- austenite, B- bainite, M- martensite

Figure 6. The flowcharts of the thermo-metallurgical-mechanical coupled model in multi-pass welding.
ellipsoidal heat source, as shown in figure 5. $f_f$ and $f_r$ represent the energy distribution coefficients of the front and rear ellipsoidal heat source, respectively.

3.2. The thermo-metallurgical-mechanical model for multi-passes welding

There are different microstructures in the welding and subsequent cooling for AF1410 steel, including austenite, bainite, martensite, and the initial state microstructure. The developed metallurgical and mechanical models of AF1410 steel are utilized to predict the phase fraction, residual stress, and distortion, which the accuracy and details have been elaborated in the published paper [23]. Leblond model [26] and K-M equation [27] are used to calculate phase fraction. In addition, the mechanical model adopts the small strain increment theory considering SSPT and transformation plasticity [28]. Noting that the martensite or bainite generated in the previous welding pass may be transformed into austenite in the heating of the next welding pass. Then, the austenite is transformed again in the cooling. Therefore, the thermo-metallurgical-mechanical model for multi-passes welding needs to be modified. The flowcharts of the developed model, taken example as one of the weld passes, are displayed in figure 6.

The thermo-metallurgical-mechanical model is implemented in ABAQUS user subroutines DFLUX, USDFLD, and UMAT. DFLUX, which could define the complex heat flux, is utilized to develop the double ellipsoidal heat source model. The temperature and temperature increment (dT) in each increment is passed to USDFLD for metallurgical calculation. The constitutive model of AF1410 steel, the calculation of transformation strain, the transformation plasticity strain, and the mechanical properties for the mixed microstructure are implemented in UMAT. The results of temperature, phase fraction, stress, and distortion are output when the model is solved by the ABAQUS solver.

The depositing process of the welding zone is simulated by the element birth and death technique, using the ‘model change’ option in ABAQUS software. All elements represented the deposited metal are killed in the initial step and gradually activated in the corresponding step. When the welding simulation is finished, an analysis step named ‘release’ is added to the finite element model to simulate the process of removing the clamp. It is

| Weld pass | Experiment (mm) | Simulation (mm) |
|-----------|----------------|-----------------|
|           | Length         | Height          | Length | Height |
| 1         | 3.66           | 2.53            | 3.52   | 2.6    |
| 2         | 4.74           | 1.23            | 4.7    | 1.4    |
| 3         | 5.56           | 1.14            | 5.48   | 1.5    |
| 4         | 6.04           | 1.22            | 6      | 1.35   |
| 5         | 7.02           | 1.21            | 6.98   | 1.5    |
| 6         | 9.21           | 2.23            | 8.6    | 2      |

Figure 7. The metallurgical results: (a) the contour results of simulated martensite fraction, (b) the macrograph of corroded AF1410 steel welding joint, (c) the inverse pole figure of fusion zone, (d) optical micrographs of HAZ and FZ in the welding joint.
necessary to constrain one point at the bottom center of the welding plate to ensure the convergence of the calculation and to ensure that the welding plate does not have a large displacement in the horizontal direction. In addition, the finite element model needs to give the initial value for the newly generated mesh.

4. Results and discussion

4.1. Thermal and metallurgical results

The dimension of the experimental fusion zone is measured and summarized in table 3. The parameters of the heat source model are modified correspondingly until the morphology of the heat source agrees with the actual value. It can be concluded from table 3 that the simulated length and height of the heat source have great consistency with the experimental results.
The simulated phase distribution in the phase transformation area, as shown in figure 7(a), is all martensite without bainite. The maximum cooling rate of bainite transformation is around \(1 {^\circ}C \cdot s^{-1}\) according to the dilatometric experiment. The bainite cannot generate due to the fast cooling rate. The electron backscatter diffraction (EBSD) experiment is conducted to verify the microstructure of the fusion zone (FZ). It can be seen from figure 7(c) that the grains of the fusion zone are large, and the martensite blocks are visible. Besides, the EBSD experiment also shows that the phase is all body-centered cubic structure. The optical micrographs of the welding joint corroded with 4\% Nital are displayed in figure 7(d). The metallography results prove that the microstructure in FZ and HAZ near the fusion line is also martensite. The columnar grains in the fusion zone are caused by the huge temperature gradient. In addition, the hardness results of the welded joint are shown in figure 8. The hardness of martensite in AF1410 steel is about 490. The hardness of the FZ proves that the fusion zone has martensitic transformation instead of bainite transformation. Combined with the above analysis, the experimental and simulated results have a good agreement.

4.2. Welding residual stress and distortion distribution
The welding residual stress and distortion significantly influence the load-bearing capacity and service life to some extent. Therefore, the research of welding residual stress and distortion has both theoretical significance and essential practical significance. There are three components in residual welding stress. The residual stress along the welding direction is known as longitudinal stress. The residual stress transverse to the welding direction is called transverse stress. The direction of normal stress is along the thickness direction.

The simulated welding longitudinal stress and the experimental values are shown in figure 9. It can be seen from figure 9(a) that the simulated longitudinal stresses are agreed with the actual residual stress distribution. There is an apparent stress concentration zone in the middle of the welding joint, but the magnitude of residual stress at the upper and lower ends is insignificant. Besides, both the simulated and experimental stress in the region of the last weld pass is minor. The residual stresses along Paths 1 and 3 are respectively presented in figures 9(b) and (c) for further comparison. The compressive stress generated in the welding zone of the last weld pass is due to the influence of SSPT and transformation plasticity, which is similar to the phenomenon in the work of Wang et al [14]. In addition, there is great compressive stress in the base material due to the constraint. The stress distribution has changed in the subsequent release analysis step, but the overall variations in the fusion zone and HAZ are not significant.

The simulated stress along Path 3 is consistent with the distribution trend of the contour method, and the only difference is that the maximum value of the weld center is different. The peak simulated longitudinal stress is around 1280 Mpa, and the martensite yield strength of AF1410 steel is 1137 MPa. Some references have reported that the longitudinal residual stress in multi-pass welding could be very high, reaching or exceeding material yield strength [29, 30], similar to the stress distribution of AF1410 steel. The stress evolution curves and stress distribution are discussed in detail in section 4.3.

In addition, the test principle of contour method assumes that the material elastically unloads when the residual stress is released. Prime and Dewald [31] reported that the high-stress concentration at the cutting tip might cause local yielding, affecting the measured out-of-plane displacement and leading to errors. The

![Figure 10. The transverse stress distribution along Paths 1, 2, 3, and 4.](image-url)
phenomenon is evident in the stress measurements of the welding zone. Therefore, the low peak stress determined by contour method is acceptable. In general, the residual stresses measured by the three methods have good agreements.

The transverse stresses acquired by experimental and simulated methods along four paths are plotted in figure 10 to compare the difference intuitively. The simulated transverse stress has good agreements with experimental values determined by XRD and ACM. Nevertheless, the maximum transverse stress along Path 3 is different, caused by the same reason as the phenomenon shown in figure 9(c). The results by ACM in the center of Path 4 have a large error bar. Fitzpatrick et al[32] reported that the large grain size might affect the XRD results in that fewer grains contributed to the diffraction peak. The bottom of the welding joint experiences complex thermal cycles, resulting in larger grains or preferred orientation, which brings great uncertainty. Ren et al[33] simulated the residual stress distribution of a P92 steel butt-welded joint with six welding layers and eight welding passes. Despite the similar welding parameters and the existence of martensitic transformation in P92 steel, the final distribution of transverse stress is utterly different from the results of this work. The different stress distribution of AF1410 steel shows the particularity of ultra-high strength steel, which deserves attention.

The normal stress distribution is presented in figure 11. As shown in figure 11(a), the normal stress distribution is uniform, and the magnitude is minor. According to the comparison results along Paths 2, 3, and 4, both the magnitude of the simulated and experimental results is small, and the changing trend is consistent with each other. Ahn et al[34] reported that the maximum longitudinal and normal stress measured by neutron diffraction in fiber laser welded Ti6Al4V had a significant difference, around 800 MPa and 100 MPa respectively. Considering that AF1410 steel has a similar yield strength with Ti6Al4V and the thickness of the welded plate is 10 mm, the small normal stress distribution in this work is rational.

The distortion results of the mid-length cross-section are presented in figure 12. As shown in figure 12(a), the distortion at about 50–75 mm from the weld center is around zero due to the restrained conditions imposed in the finite element model. Notably, the distortion direction of 1st weld pass is convex. Then, the convex
distortion is reduced to around zero in the 3rd weld pass. With the increase of weld pass, the distortion direction is changed to concave, and the distortion magnitude is increased. The maximum distortion is around 0.3 mm when the welding process is finished. The overall distortion of the welding plate is not very large due to the existence of constraints, as displayed in figure 12(b). When the constraints are released, the distortion of the plate is increased immediately. The simulated and experimental Z-coordinates are presented in figure 12(c). The simulated results have great agreements with the experimental distortion.

4.3. The reason for stress distribution in the fusion zone

Based on the above analysis, the residual stress and distortion of the multi-pass welding in AF1410 steel are successfully predicted. For controlling the welding stress reasonably, it is significant to understand the mechanism of stress evolution. The advantage of the finite element method can provide credible stress evolution data in each weld pass when the simulated results have enough accuracy. The temperature, phase fraction, and longitudinal stress curves in the center of the welding zone at the mid-length cross-section are plotted in figure 13, taken 1st, 3rd, 5th weld pass as examples.

As shown in figure 13(a), the material is subjected to the thermal expansion of the previous material to generate compressive stress when the heat source approaches in 1st thermal cycle. The initial state microstructure transforms into austenite at high temperatures. When the heat source leaves, the temperature decreases rapidly, and the longitudinal tensile stress is increased due to the restriction of surrounding material on the thermal contraction. The magnitude of tensile stress is closely related to the mechanical property of the microstructure. Hence, the tensile stress accumulated before Ms is small due to the low mechanical property of austenite. In the cooling stage, austenite begins to transform into martensite when the temperature is below Ms. Then, the longitudinal stress is significantly decreased under the influence of transformation strain and transformation plasticity. However, the martensitic transformation rate is also reduced as the cooling rate slows down. The increase in the specific volume of martensite is not enough to offset the stress caused by the heat shrinkage of the weld plate, leading that the stress begins to increase slowly.

In the 2nd thermal cycle, part of martensite in the 1st deposited metal region is transformed into austenite again in the heating, and the martensite is regenerated in the cooling. The stress experiences similar changes to 1st weld pass again under the influence of SSPT. In the 3rd-6th thermal cycle, due to the increase in the distance from the heat source, the maximum temperature does not exceed Ac1, leading to no SSPT. The huge tensile stress is generated in the 3rd weld pass due to the existence of full martensite. Then, the peak stress in the cooling also decreases as the peak temperature drops in the subsequent thermal cycle, which means that part of the stress generated by the previous welding process can be eliminated and redistributed during the following thermal cycle. Therefore, the final stress magnitude at the position of the 1st weld pass is relatively small, as shown in figure 13(d).

Figure 13(b) shows that the phase fraction curves and the stress curves of the 3rd and 4th weld passes have the same changes. Differently, a partial austenite transformation has occurred in the 5th pass because the peak temperature is just between Ac1 and Ac3, and there is still partial martensite. A minor amount of martensite leads to higher tensile stress than the values of 3rd and 4th weld passes in the cooling. Subsequently, in the 6th thermal cycle, a large tensile stress is generated due to no phase transformation and the strong restraint at the center of the weld joint. In addition, there is no subsequent thermal cycle to relieve release stress. Therefore, a tensile stress concentration displayed in figure 13(d) is formed at the position of the 3rd weld pass.

At the center of the 5th weld pass, there are two thermal cycles with complete solid-state phase transformation, as displayed in figure 13(c). The influences of transformation strain and transformation plasticity make the final longitudinal stress small.

The longitudinal stress contour results of each weld pass confirm the above analysis, as presented in figure 13(d). It can be clearly seen that the stress distribution in the newly welding zone is small tensile or compressive stress. Besides, a large stress concentration is generated at the center of the welding joint with the increase of weld pass.

In summary, it can be concluded that the stress distribution is inseparable from the role of SSPT. The small stress distribution at the bottom of the weld joint is caused by the redistribution of stress on subsequent passes, eliminating the previous stress accumulation. The high stress in the weld center is caused by the strong restraint at the location and the absence of phase transformation to offset the tensile stress. The minor tensile stress or compressive stress on the surface is caused by martensitic transformation. It also means that the accurate phase distribution is vital for predicting welding stress and distortion. The accurate metallurgical model can accurately predict the distribution of phase transformation, thereby determining whether to consider the influence of SSPT in the stress evolution and finally obtaining correct stress and distortion distribution.

The results also provide new ideas to control residual stress distribution in multi-pass welding for AF1410 steel. On the premise of ensuring the mechanical properties, the Ms of the deposited metal is controlled by
selecting a low-temperature transformation welding wire [35]. When the large tensile stress is generated in the low-temperature stage of the cooling process, the martensitic transformation can still offset the stress to achieve reasonable stress control.

4.4. Satoh test simulated multi-pass welding thermal cycles

Satoh test [36] is utilized to investigate the welding stress evolution by a simplified constrained model and become a powerful tool in welding simulation. It was challenging to conduct Satoh test since the maximum temperature shown in figure 13 exceeded the melting point of AF1410 steel. In this work, numerical simulation of the Satoh test, as shown in figure 14(a), was performed to investigate the stress evolution in multi-pass welding joint. Both ends of the finite model were fully constrained to restrict the thermal expansion or contraction. As displayed in figure 12, the 1st weld pass was experienced the most complex thermal cycles. Therefore, the thermal cycles shown in figure 13(a) were imposed in the finite element model to investigate the residual stress evolution.

As shown in figure 14(b), the compressive stress is generated in the heating, and the magnitude is decreased with the increasing temperature. The maximum temperature of the 1st weld pass is larger than $A_3$, so austenite transformation occurs. In the cooling process, the tensile stress is increased with the decreasing temperature in a small range due to the low mechanical property of austenite. Then, the stress is decreased rapidly, attributed to the transformation strain and transformation plasticity. Although the martensite has a high yield strength, the final residual stress is only around 200 MPa. The stress evolution of 1st thermal cycle is a typical curve with martensitic transformation [37]. The 2nd thermal cycle has a similar variation to the 1st thermal cycle. The stress increases monotonically to a high value in the cooling of 3rd thermal cycle in that the microstructure is always
martensite. The stress evolution curves of 4th-6th weld passes are shown in figure 14(c). The stress-time curves are found to be similar to the curves displayed in figure 13(a). The stress-temperature curves are approximately a straight line due to no phase transformation, unlike the curves of the previous three thermal cycles. The stress is only related to the thermal expansion and contraction caused by increasing or decreasing temperature.

The conclusions obtained from the Satoh test and welding experiment are consistent. That is, the SSPT has significant influences on the magnitude of the final stress. Besides, the accurate metallurgical model and material parameters are the keys to successfully predicting stress magnitude.

5. Conclusions

In this work, the multi-pass welding experiment and simulation were performed to investigate residual stress and distortion distribution. The conclusion could be drawn as follows:

1) The accurate thermo-metallurgical-mechanical coupled model for AF1410 steel multi-pass welding is developed. The microstructure in the welding joint is martensite due to the fast cooling rate.

2) The simulated residual stress distribution of the mid-length cross-section is validated by the experimental results of the advanced contour method. There is an apparent stress concentration in the middle of the welding joint. The simulated distortion has a good agreement with the measured values.

3) The residual stress evolutions in welding experimental and Satoh test are investigated by the coupled model. The phase transformation and the subsequent thermal cycle together determine the magnitude of final residual stress. Developing the accurate finite element model and understanding the formation mechanism of residual stress is helpful to stress and distortion control and precise manufacturing of aviation components.

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Data availability statement

All data that support the findings of this study are included within the article (and any supplementary files).

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