Parameter analysis and optimization of welding sequence for the aluminum alloy sidewall in a high-speed train body

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Abstract. The sidewall is the most complex structure and welding process part in the aluminum alloy train body, and its welding deformation is greatly influenced by welding sequence parameters. In this paper, the relationship between the welding residual stress and welding deformation of the sidewall and welding sequence parameters is studied, and the optimal welding sequence is determined. Using a verified finite element model of one intercepted sidewall, the relationships between the welding residual stress and welding deformation of the sidewall and the welding of welds, welding sequences of welds and the weld sequence are studied, respectively. Some conclusions can be drawn from the analysis results. One is that the welding results at one weld are only determined by self-welding, and have nothing to do with other welds, and welding results outside one weld are affected by welds on both sides. The second is that for a single weld, the from-one-end-to-the-other welding sequence is best, and the identical welding sequence is best for each weld. The third is that the fixed welds are firstly welded and a cross weld sequence is best.

1. Introduction
A high-speed train body is welded with hollow extruded aluminum parts. Since aluminum alloys have the characteristics of large thermal expansion coefficient, high thermal conductivity, and low density, the welding heat transfer rate is high during a welding process and large welding deformation will be generated. The welding quality directly affects the high speed and safety of the train. In order to eliminate these welding deformation, additional flame repair work is often required after the welding. Although the repair can guarantee the size of the assembly to a certain extent, it also increases the extra workload, making the efficiency lower, and the flame repair will cause some degree of damage to welds. Therefore, it is necessary to study the influence mechanisms of train body welding deformation and establish its control method to decrease welding deformation and reduce or even cancel the repair process. Among these the welding sequence parameters are important influencing factors of the welding deformation, so the welding sequence parameter analysis and optimization must be greatly paid attention to in this paper.
So far there have been a lot of research results on welding sequence analysis and optimization. Tsai et al studied the distortion mechanisms and the effect of welding sequence on panel distortion and found that the joint rigidity method was effective in determining the optimum welding sequence for minimum panel warping [1]. Kadivar et al utilized genetic algorithm method with a thermo mechanical model to determine an optimum welding sequence and the thermo mechanical model developed for this purpose could predict residual stress and distortion in thin plates [2]. Liao thought that a gap might be generated at each weld pair because of sheet metal manufacturing randomness, and proposed a genetic-algorithm-based optimization method to search automatically for the optimal weld pattern so that assembly deformation was minimized [3]. Ji et al analyzed welding residual stress of 2219 aluminum alloy flat with one groove by ellipsoid heat source model and a more reasonable welding sequence was educed to meliorate the distribution of residual stress [4]. Zhang et al simulated the effect of welding sequence on welding residual stress filed of T joint from the view of multibead welding, subsection welding and multilayer welding on the basis of ensuring reasonable welding heat source and establishing the finite model to get the optimizing scheme of T type joint’s welding sequence [5]. Ozcatalbas and Vural investigated the effect of various welding sequences on welding distortion in steel lattice beams, in which 20 various combinations of welding sequences on distortion forces in the lattice beam were investigated, and found that minimum distortion tendencies were observed for welding sequence which had homogenous heat gradient[6]. Gannon et al used numerical simulation based on finite element modelling to study the influence of welding sequences on the distribution of residual stress and distortion generated when welding a flat-bar stiffener to a steel plate [7]. Keivani et al carried out a three-dimensional t000thermomechanical finite element analysis to model and predict the influence of welding sequence on the generation of distortions and residual stresses in large size T-joints [8]. Chen et al dealt with welding simulation of a stiffened plate structure with longitudinal and transverse stiffeners using a thermal elasto-plastic FE method. Welding parameters of heat input, welding speed and welding sequence were considered in the analysis and results demonstrated the specific influences of the different welding parameters on residual distortion and stress in a stiffened plate structure [9]. Fu et al used a sequentially coupled thermo-mechanical finite element model that considered temperature-dependent material properties, high temperature effects and a moving volumetric heat source to investigate the effect of welding sequence on the residual stresses and distortions in T-joint welds [10]. Chen and Guedes simulated the welding process by a nonlinear thermo-elasto-plastic approach and investigated experimentally and numerically the temperature distribution, weld-induced distortion, and residual stress in stiffened plates [11]. Guo et al applied the nonlinear thermoplastic-plastic finite element theory to the thin-walled structure of aluminum alloy vehicle bumper, and obtained the welding sequence to effectively reduce the residual stress[12].

The aluminum alloy train body welding is a complex process, especially the sidewall is the most complex structure and welding part in the aluminum alloy train body. The sidewall is about 22 meters long, and welded with four kinds of extruded long sheet metal parts and multiple window panels. Fig. 1 shows a part sidewall structure intercepted from the whole model. The third panel is the window panel and others are all long sheet metal parts. The welds lie in two surfaces of the sidewall, and every surface has four welds between parts. Because welds are long and numerous, the welding sequence of welds have an important effect on the welding residual stress and weld deformation. The welding sequence here includes the welding direction of a single long weld that is, the problem of how to weld, and the welding order between the multiple welds. In this paper, four welds on one surface are taken as the research object, and the influence of these welding parameters on the welding residual stress and welding deformation is analyzed, and the welding sequence is optimized.
The remainder of this paper is organized as follows. Section 2 discusses the finite element modeling and verification of the sidewall welding. Welding sequence analysis and optimization of the sidewall is in section 3. Finally, Section 4 draws the conclusions.

2. Finite element modeling and verification of the sidewall welding
To analyze the influencing relationship between the welding deformation and welding sequence parameters, a finite element method is used in this research. The finite element model is shown in Fig. 2. It is created by cutting out one three meters long part from 22 meters long part, and extracting the midplane. The assembly contains five parts, then there are four welds in every surface between two parts. The width of every part is 0.5m.

In this analysis, since the thickness of all parts is small and all 4mm, shell units are adopted in gridding parts, and the grid size is 5mm *5mm. To increase the computing efficiency, a relatively fast welding speed is adopted. The following Tab. I shows the relationship between the welding speed and computing efficiency. In this analysis, 0.03m/s is adopted.
Table 1. Relationship between welding speed and computing efficiency.

| Welding speed (m/s) | 0.03 | 0.02 | 0.01 | 0.005 |
|---------------------|------|------|------|-------|
| Heat source temperature (°C) | 1013.91 | 1014.41 | 1009.73 | 1014.54 |
| Computing time | 2 | 5.5 | 10 | 17 |

The heat source is key to the welding, so a suitable heat source model must be chosen. The Gaussian heat source model is widely used in finite element analysis to compute the welding temperature field. When the impact of the weld pool is not significant, a more accurate computation result can be obtained. Therefore, the heat source adopted in this research is Gaussian heat source.

In this analysis, the whole sidewall is located by two sets of vertical fixtures shown in Fig. 2. Every vertical fixture contains four locating positions which constrain z direction movements of the sidewall, i.e., F11, F12, F15 and F16, or F13, F14, F17 and F18. And lateral fixtures F21, F22, F23 and F24 constrain the y direction movements of the sidewall. In this model, the origin of the coordinate lies in the lower left corner of the model, along the direction of welding is the x direction and perpendicular to the direction of the weld is the y direction.

The method adopted for the analysis is the thermal-force indirect coupling method. The technical route is shown in Fig. 3. The element used in the thermal analysis process is SHELL132. After the thermal analysis, the element conversion is required and the thermal unit is transformed into the stress analysis element SHELL281. The material of the sidewall adopts aluminum alloy A6N01S-T5.

During the welding process, the position of the welding heat source changes over time. When the welding point moves to one welding position, the temperature rises sharply in this position. The maximum temperature is concentrated in the center of the heat source area. When the heat source leaves the original welding position as the time changes, the temperature rapidly decreases as shown in Fig. 4. The temperature field after the welding is shown in Fig. 5.
Figure 4. Time history of temperature along a weld (longitudinal) and perpendicular to a weld (transverse).

Figure 5. Temperature field cloud after the welding.

The overall welding residual stress and welding deformation in x and y directions are shown in Fig. 6 and Fig. 7. From these two figures, it can be found that the biggest welding residual stress and welding deformation all lie in welds, and because of the heat source movement, the biggest value is in the center of the heat source.
In the actual manufacturing process, the sidewall must be measured by a simple checking fixture after welding shown in Fig. 8. The measurement positions are shown in Fig. 9. In the longitudinal direction, about ten sections are selected for measurement positions. And in every section, about 14 measurement points are designed. These measurement points are usually located on both sides of welds and in the middle of each part.

**Figure 6.** Overall welding residual stress.

**Figure 7.** Overall welding deformation.

**Figure 8.** Checking fixture of the sidewall.
Figure 9. Measurement positions.

Tab. II gives the data comparison between actual measurement data and finite element simulation results on the measurement points in Fig. 9(b). The measurement data are the average values of all longitudinal measurement positions in Fig. 9(a). The comparison Figure is shown in Fig. 10. From these results, it can be found that the change characteristic in these measurement points between measurement data and finite element simulation results is consistent and their date values are also similar. Then it shows that the finite element model can effectively simulate the welding process of the sidewall. In the next research this finite element model is used to analyze the influencing relationship between welding deformation and welding sequence parameters.

Table 2. Measurement data and finite element simulation results.

| Measurement point | 01   | 02   | 03   | 04   | 05   | 06   | 07   |
|-------------------|------|------|------|------|------|------|------|
| Measurement deformation (mm) | 2.93 | 2.97 | 2.61 | 2.53 | 2.8  | 2.55 | 2.49 |
| Simulation deformation (mm)    | 2.5  | 2.52 | 2.23 | 2.21 | 2.45 | 2.11 | 2.12 |
| Measurement point | 08   | 09   | 10   | 11   | 12   | 13   | 14   |
| Measurement deformation (mm) | 1.19 | 1.18 | 1.49 | 1.45 | 1.37 | 1.12 | 0.053|
| Simulation deformation (mm)    | 0.98 | 0.98 | 1.21 | 1.05 | 1.17 | 1.03 | 0.005|

Figure 10. Comparison between measurement data and finite element results
3. Welding sequence analysis and optimization of the sidewall

3.1. Welding analysis in the one weld region influenced by other welds

In this analysis, one weld is chosen to analyze the welding residual stress and welding deformation along this weld region when four welds are welded. Then four kinds of welding options are given as follows. The longitudinal direction distance of two sets of vertical fixtures adopts 1.8m and the weld 1 is analyzed.

Option1: Only the weld 1 is welded.
Option2: The weld 1 and weld 2 are welded.
Option3: The weld 1, weld 2 and weld 3 are welded.
Option4: All four welds are welded.

The analysis results of the welding residual stress and welding deformation from nodes in the weld 1 after the welding process are shown in Fig. 11 and Fig. 12. They all contain the results of four welding options.

It can be found that the welding residual stress and welding deformation of the weld 1 in four welding options are all identical. Then it shows that the welding residual stress and welding deformation of the weld 1 depend only on its own welding and are independent of the welding of other welds.

Some other phenomena can also be found. In Option1, when only the weld 1 is welded, the third, fourth, and fifth panels hardly generate welding residual stress and welding deformation. In Option2, when the weld 1 and weld 2 are welded, the third panel produces welding residual stress and welding deformation, and the 4th and 5th panels hardly generate welding residual stress and welding deformation. In Option3, when the weld 1, weld 2 and weld 3 are welded, the fourth panel produces welding residual stress and welding deformation, and the fifth panel has almost no change. In Option4, when all four welds are welded, the five panels all produce welding residual stresses and welding deformation.

3.2. Welding analysis outside one weld region influenced by all welds

In this analysis, the welding residual stress and welding deformation outside one weld region are given to analyze the influencing relationship between the welding residual stress and welding deformation of one panel and welding of welds.

Here the first and second panels are chosen as the analysis objects. The welding residual stress and welding deformation of two longitudinal sections at x=0.5m and x=1m are obtained shown in Fig. 13, Fig. 14, Fig. 15 and Fig. 16.
It can be found that the welding residual stress and welding deformation of the first panel are identical in all welding options, then it shows the welding residual stress and welding of the first panel depend only on the welding of the weld 1 and are independent of the welding of other welds. And it can also be found that the welding residual stress and welding deformation of the second panel are different in Option1 and other options, and those of the second panel are identical in Option2, Option3 and Option4. It shows that the welding residual stress and welding deformation of the second panel depend on the welding of the weld 1 and weld 2 and are independent of the welding of other welds.

Combining the first two sections, it can be found that a certain weld will only affect itself and the welding panels directly related to it, and the areas away from it are basically unaffected. That is, when the welding deformation of a certain area is studied, the effects of welding processes that are not adjacent to it can be ignored, which will simplify the research process.

3.3. Welding sequence analysis of one weld

For a single weld, there may be four welding sequences which are from the left end to the right end, from the right end to the left end, from the middle to both sides, and from both sides to the middle. Therefore, here the influencing relationship between the weld 1 and these four different welding sequences will be explored. Fig. 17 and Fig. 18 give the welding residual stress and welding deformation comparison of the weld 1 in two different welding sequences. It can be found that there
are no major changes in the overall welding residual stress and welding deformation in the two welding sequences.

**Figure 17.** Welding residual stresses of the weld 1 in two different welding sequences.

**Figure 18.** Welding deformation of the weld 1 in two different welding sequences.

Fig. 19 and Fig. 20 show the welding residual stress and welding deformation of the weld 1 in from the left end to the right end, from both sides to the middle and from the middle to both sides.

**Figure 19.** Welding residual stress of the weld 1 in three different welding sequences.

**Figure 20.** Welding deformation of the weld 1 in three different welding sequences.

From the above figures, it can be found that the overall trend of the three welding sequences is relatively close. The maximum difference is at x=1.5m. Compared to the left-to-right welding sequence, the other two welding sequences will generate larger values. The welding residual stress and welding deformation, especially in the from-both-sides-to-the-middle welding sequence, produces the most obvious value. Tab. III gives the maximum welding residual stress and welding deformation at x=1.5m section in three different welding sequences. Then the from-one-end-to-the-other welding sequence is the best welding sequence and considered for a single weld design.
Table 3. Welding residual stress and welding deformation at x=1.5m.

| Welding sequences          | Residual Stress (Pa) | Deformation (mm) |
|----------------------------|----------------------|------------------|
| Left to right              | 1.20E+08             | 2.51             |
| Both sides to the middle   | 1.68E+08             | 4.20             |
| Middle to both sides       | 1.30E+08             | 2.81             |

3.4. Combined welding sequence analysis of two welds

From the former research, the welding residual stress and welding deformation of one welding panel are determined by the welding of its both side welds, so the influencing relationship between the welding residual stress and welding deformation and different welding sequences adopted at two welds will be analyzed here.

Based on this analysis demand, the welding sequence of the weld 1 is fixed with from the left end to the right end, and the welding deformation of the second panel is studied when the welding sequence of the weld 2 adopts four different welding sequences. Taking x=1.5m and x=1.8m as the research object, and four nodes at y=0.6m, y=0.7m, y=0.8m and y=0.9m are selected for analysis. When the weld 2 adopts the welding sequences with from the left end to the right end, from the right end to the left end, from the two sides to the middle and from the middle to both sides, respectively, analysis results can be obtained as shown in Fig. 21 and Fig. 22.

![Figure 21. Welding deformation of the second panel at x=1.5m.](image1)

![Figure 22. Welding deformation of the second panel at x=1.8m.](image2)

From these results, it can be found that different welding sequences of the weld 2 will importantly affect the welding deformation of the second panel. Among them, the from-left-end-to-the-right-end welding sequence produces the smallest welding deformation, and adopting the reverse welding sequences for both side welds of the second panel can’t offset the welding deformation.

Based on these analysis results, in the welding sequence optimization, only the identical welding sequence with from the left end to the right end for each weld is considered.

3.5. Optimization analysis of different weld sequences

Previous work has focused on the effect of welding direction between welds on the weld deformation. The “welding sequence” refers to the weld’s welding direction. Since the entire sidewall is welded by four welds on one side, the influence of the welding order of all welds on the welding deformation is analyzed here. The “weld sequence” is used to describe the welding order of welds.

Because the model structure is almost symmetric, all weld sequences need not be considered and only some typical weld sequences are chosen to be analyzed. From the previous analysis results, the
welding sequence from one end to the other can reduce the welding residual stress and welding deformation, so all welds adopt this welding sequence in the weld sequence analysis.

The following gives five typical weld sequences. In this analysis, the fixture longitudinal distance is 1.8m, and two sides of weld 1 and weld 3 are constrained shown in Fig. 2. The maximum welding residual stress and welding deformation can be obtained listed in Tab. IV.

Sequence1: weld 1 - weld 2 - weld 3 - weld 4
Sequence2: weld 4 - weld 3 - weld 2 - weld 1
Sequence3: weld 1 - weld 4 - weld 2 - weld 3
Sequence4: weld 2 - weld 3 - weld 1 - weld 4
Sequence5: weld 1 - weld 3 - weld 2 - weld 4

It can be found from the above results that the welding residual stress in each weld sequence is completely uniform, and the welding deformation has a small difference. This indicates that the welds have certain mutual independence, and the welding results between different weld sequences are relatively small. This is consistent with the conclusions of the former results.

Among these five weld sequences, the welding deformation produced by the Sequence5 is the smallest. This may be because the weld 1 and the weld 3 are fixed, and they are not welded firstly to produce large welding deformation. In addition, the cross weld sequence of weld 1, weld 3, weld 2, and weld 4 also helps reduce welding deformation.

To sum up, for the side wall welding, a cross weld sequence of weld 1, weld 3, weld 2, and weld 4 is chosen and each weld is identically welded from one end to the other.

Table 4. Analysis results in every weld sequence.

| Results      | Sequence1 | Sequence2 | Sequence3 | Sequence4 | Sequence5 |
|--------------|-----------|-----------|-----------|-----------|-----------|
| Deformation(mm) | 2.72      | 2.73      | 2.65      | 2.81      | 2.63      |
| Stress(Pa)    | 1.24E+08  | 1.24E+08  | 1.24E+08  | 1.24E+08  | 1.24E+08  |

4. Conclusion

In this paper, the relationship between the welding residual stress and welding deformation of the sidewall in a high-speed train body and welding sequence parameters is studied, and the optimal welding sequence is determined.

Firstly, the relationship between the welding residual stress and welding deformation and the welding of welds is studied. Two conclusions are drawn that the welding results at one weld are only determined by self-welding, and have nothing to do with other welds, and welding results outside one weld are affected by welds on both sides.

Secondly, the relationship between the welding residual stress and welding deformation and welding sequences of welds is studied. Two conclusions are drawn that for a single weld, the welding sequence from one end to the other is best, and the identical welding sequence is best for each weld.

Finally, the relationship between the welding deformation and the weld sequence is studied. One conclusion is drawn that the fixed welds are firstly welded and a cross weld sequence is best.

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References

[1] Tsai CL, Park SC, and Cheng WT. “Welding distortion of a thin-plate panel structure,” Weld J, 1999, 78: 156s - 165s.
[2] Kadivar MH, Jafarpur K, and Baradaran GH. “Optimizing welding sequence with genetic algorithm,” Comput Mech, 2000, 26: 514 - 519.
[3] Liao YG. “Optimal design of weld pattern in sheet metal assembly based on a genetic
algorithm,” Int J Adv Manuf Tech, 2005, 26: 512 - 516.

[4] Ji SD, Liu XS, Fang HY, and Meng QG. “Influence of welding sequence on welding residual stress of aluminum alloy flat butt welding,” T Nonferr Metal Soc, 2005, 15: 51 - 55.

[5] Zhang LG, Ji SD, Fang HY, and Liu XS. “Influence of welding sequence on welding stress of joint,” Chin J Mech Eng-En, 2007, 43: 234 - 238.

[6] Ozcatalbas Y and Vural HI. “Determination of optimum welding sequence and distortion forces in steel lattice beams,” J Mater Process Tech, 2009, 209: 599 - 604.

[7] Gannon L, Liu Y, Pegg N, and Smith M. “Effect of welding sequence on residual stress and distortion in flat-bar stiffened plates,” Mar Struct, 2010, 23: 385 - 404.

[8] Keivani R, Jahazi M, Pham T, Khodabandeh AR, and Afshar MR. “Predicting residual stresses and distortion during multi sequence welding of large size structures using FEM,” Int J Adv Manuf Tech, 2014, 73: 409 - 419.

[9] Chen Z, Chen ZC, and Shenoi RA. “Influence of welding sequence on welding deformation and residual stress of a stiffened plate structure,” Ocean Eng, 2015, 106: 271 - 280.

[10] Fu GM, Lourenço MI, Duan ML, and Estefen SF. “Influence of the welding sequence on residual stress and distortion of fillet welded structures,” Mar Struct, 2016, 46: 30 - 55.

[11] Chen BQ and Guedes SC. “Effect of welding sequence on temperature distribution, distortions, and residual stress on stiffened plates,” Int J Adv Manuf Tech, 2016, 86: 3145 - 3156.

[12] Guo PC, Cao SF, Yi J, and Li LX. “Numerical simulation and sequence optimization on the welding process of aluminum alloy vehicle bumper,” Automot Eng, 2017, 39: 915 - 921.