Effect of Welding Sequence on Welding Deformation and Residual Stress of Ear Plate Structure

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Abstract. In this study, a three-dimensional finite element model of the welding process of the ear plate structure was established based on the thermal elastic-plastic method. The DOE method was used to design the welding sequence optimization scheme, and the effect of welding sequence on welding deformation and residual stress was studied. The results show that the variation of welding sequence has little effect on the residual stress of the ear plate structure, but has great influence on the post-weld deformation. Considering the field welding conditions, the reasonable welding sequence was determined finally, and it could meet the assembly design requirements of ear plate structure.

1. Introduction
The inhomogeneity of temperature field in the welding heating process and constraints from the adjacent parts in the cooling process of large-scale structure bring about welding stress inside the structure. The existence of welding stress is harmful to the structure, it can lead to welding deformation of the structure and reduction in dimensional stability. In fact, welding deformation is inevitable because of lots of welds and large heat input for large-scale structure, so many methods are used to reduce welding deformation, the reasonable welding sequence is one of more effectively controlling methods, so it is important to establish an appropriate welding sequence. However, in the actual production process, the determination of the welding sequence generally depends on experience or a large number of experiments, but the welding process of large structure is relatively random and less reproducible, which makes the welding deformation difficult to control and often requires mechanical or flame orthopedics, which need a lot of manpower and material resources. What's worse, there is a risk of scrapping. With the development of computer technology, more and more scholars use finite element method to simulate welding process and predict welding deformation. Much work has been done to optimize the welding process of simple joints at home\textsuperscript{1-3}, but the research objects almost were limited to the laboratory specimen. In recent years, the research object has gradually aimed to large-scale welded structure. Yan Dejun and others from Harbin Institute of Technology\textsuperscript{4} studied the welding deformation of large-sized bottom structure on high speed trains. Dong Wenchao et al.\textsuperscript{5} studied the influence of welding assembly sequence on deformation of large thin plate armored steel structures. The structure of heavy machinery in construction machinery industry is much more complicated, the welding deformation in large structures is required to do further research.
In the current work, the study was carried out to solve the serious problem of welding deformation of a large boom ear plate structure. Firstly, the finite element model was established, and the results of simulation and test were compared to verify the correctness of the established finite element model. Secondly, different welding sequence schemes were designed to investigate the effects on the welding deformation and residual stress. Finally, the reasonable welding sequence was determined by using numerical simulation methods, which could help to save the cost of welding tests and post-weld orthopedics, and improve production efficiency and production quality.

2. Establishment of finite element model of ear plate structure

2.1 Physical model of the ear plate structure.
The overall geometrical model of the ear plate structure is shown in Figure 1, which includes the cylinder, the large and small vertical plate, and the ear plate. CO$_2$ gas arc metal welding is assumed to perform the welding with the Fronius TPS5000 welding power in fact. The groove is polished before welding to clean the rust. The welding process parameters are given in Table 1. When the welding is completed, the span d between the two ear plates does not meet the assembly requirement of 230 mm, so the subsequent machining is required.

![Figure 1. Geometry model of the ear plate structure.](image)

| parameters                  | current/A | voltage/V | speed/(mm·s$^{-1}$) | gas-flow rate/(L/min) | wire specification |
|-----------------------------|-----------|-----------|---------------------|-----------------------|-------------------|
| backing weld                | 200–220   | 20–22     | 5                   | 15–25                 | Φ1.2 ER50-6       |
| cosmetic weld /fillet joint | 240–260   | 24–26     | 7                   | 15–25                 | Φ1.2 SLD-70       |

2.2 Establishment of grid model.
The geometrical model of the ear plate structure is divided by the hexahedral solid element mesh, and the mesh model and the weld bead distribution are shown in Figure 2. The number of meshes and nodes is 176550 and 222841 respectively. The thickness direction of work piece plate is divided into two layers in order to ensure the accuracy of calculation, and the minimum mesh size of weld and heat affected zone is controlled within 2 mm, while that of base metal away from the weld is controlled within 6 mm[6]. The technique of 3:1 element transition not only ensure the calculation accuracy, and reflect the change of temperature gradient, but also reduce the number of elements and improve the calculation efficiency.
2.3 Parameter Setting of Finite Element Model.
Double ellipsoidal heat source is used as the equivalent heat source for the welding heat input, because it can take full account of the temperature change in the welding process of CO₂ gas arc metal welding. The material of the ear plate structure is set as BS700, its temperature-dependent thermal-physical and mechanical properties (thermal conductivity, specific heat, elastic modulus, thermal expansion coefficient, etc.) are shown in Figure 3. Constant values are used for Poisson’s ratio and density (0.33 and 7870 kg/m³, respectively.) since they are less temperature dependent than other properties. The principle of establishing mechanical boundary conditions is to restrict the displacement of rigid body by choosing the position with larger rigidity.

Figure 3. The relationship between heat-force parameters and temperature of BS700

3. Test methods

3.1 Test Method for Welding Deformation and Residual Stress.
The span d between two ear plates after welding is measured. The ear plate structure is scanned by Mertra SCAN 3D laser scanner, and its measuring accuracy of the device can reach 0.05mm. The point cloud data will be processed to obtain 17 sets of deformation data on the ear plate, and the distribution of sampling points is shown in Figure 4.
3.2 Optimizing Solution Design of Welding Sequence.
Different welding sequence necessarily corresponds to different welding deformation results. The welding of the large vertical plate at the end is carried out at first because of automatic welding. The remaining four manual welds are mainly investigated, as shown in Figure 2 red marked bead. The full factorial welding simulation test needs large amount of tests, which can reach 24 times. In order to simplify the test process and improve the simulation efficiency, the optimal latin hypercube method is used to design the experiment, so that all the test points are distributed as evenly as possible in the design space, and the number of experiments can be controlled artificially. As shown in Table 2, the experiment scheme is composed of 9 samples, and case A applies the original field welding sequence.

| Case | Welding sequences | P.S                |
|------|-------------------|--------------------|
| A    | W1→W2→W3→W4      | Original welding sequence |
| B    | W2→W3→W4→W1      | Symmetrical welding |
| C    | W2→W4→W3→W1      |                    |
| D    | W1→W4→W3→W2      |                    |
| E    | W2→W3→W4→W1      | Flat welding       |
| F    | W3→W4→W1→W2      |                    |
| G    | W3→W1→W2→W4      |                    |
| H    | W4→W2→W3→W1      |                    |
| I    | W4→W3→W2→W1      |                    |

4. Results and discussion

4.1 Analysis and verification of welding deformation of ear structural parts.
The model is set according to the welding sequence of the case A. When the model is cooled down to room temperature which means that the calculation is completed. After the post-processing of the results, the welding deformation of the ear plate structure is extracted, as shown in Figure 5. The main reason for the deformation of the ear plate structure is that the base metal thermally expands during the welding process, when the refuse metal comes to solidify, the expanded base metal comes to shrink, which leads to the deformation of the ear plate structure. The span d between the two ear plates is reduced to 225.88 mm of 4.12 mm decrement because of the heat input from the weld seam on both sides of the two ear plates. Firstly, the welding deformation data are collected by
on-site tracking and measuring the ear plate structure. Then, the results of computation and measurement are compared. The comparison shows that the welding deformation trend is consistent with the actual situation, indicating that the established model is reasonably accurate representation of reality.

![Y-direction welding deformation cloud diagram of the ear plate structure](image)

**Figure 5.** Y-direction welding deformation cloud diagram of the ear plate structure

4.2 Influence of welding sequence of ear plate structure on welding deformation.

In this section, the influence of welding sequence on the final deformation is discussed. Figure 6 shows the welding deformation of the ear plate in different cases. Case A applies the original welding sequence. Case B-E fully complies with the principle of symmetrical welding, and the number of flips during welding is relatively high. Scheme F-I takes into account the convenience of field welding and reduces the number of flips.

It can be seen that from the figure that the points 1, 2 and 3 in case F are inward and the span becomes smaller. The other points on both sides of the ear plate are outward, deviating from each other and the span becomes larger, so we can find that the deformation tendency of the whole ear plate is inconsistent. In a word, case F is unreasonable and will not be considered. The other eight cases show the same welding deformation tendency, which both sides of the ear plate are inward, and the span \( d \) becomes smaller. From the diagram we can find that the deformation data of sampling points are upward parabolic distribution, and the value of points 4-11 is slightly larger, because these points are located at the free end far from the weld seam, and the restraint degree is relatively small. Baseline is denoted by a red horizontal line, which is the tolerance of 2 mm required by the drawing. It can be seen that only the cases B and G satisfy the conditions below the baseline.

From the comparison of the symmetry scheme (B-E), we can find that these four cases have same deformation tendency, the maximum displacement of the case B is about 1.82 mm, which is the least among the four cases. Comparing with the maximum displacement in the original welding sequence, case B decreases by 55.8%.

From the comparison of the sequential welding (F-I), we can find that these four cases also have same deformation tendency, the maximum displacement of the case I is the largest except for the case F, while the case G is the least, about 1.98mm. Comparing with the maximum welding deformation in the original welding sequence, case G decreases by 51.9%.
4.3 Influence of welding sequence of ear plate structure on welding residual stress.
When welding is completed, the tests and analyses of the residual stress of horizontal weld around the ear plate are carried out. We find that the residual stress mainly concentrates on the intersection of the weld, the position of arc striking and extinguishing. The stress concentration on the connection of the ear plate, the small vertical plate and the cylinder is relatively high. Figure 7 shows the stress concentration ratio of the four cases (F-I). It can be known that there is no significant difference among the four cases. So it can be inferred that the welding sequence adjustment has little influence on the welding residual stress of the ear structure.

5. Conclusions
In this paper, the correctness of the finite element model is verified by establishing the finite element model of large-scale structure, comparing the results of simulation and experimental measurement of deformation, and different welding sequence schemes are designed. The effects of different welding sequence on welding deformation and residual stress are investigated. The following conclusions are drawn through the research:

(1) The finite element model for predicting the welding deformation of the ear plate structure is established based on the thermo-elastic-plastic finite element method. The welding deformation obtained by computation is in good agreement with the actual results.
(2) The welding sequence optimization scheme is designed through DOE experimental analysis method. The welding deformation under the symmetrical welding scheme can be reduced by about 55.8%, but it is difficult to implement symmetrical welding in the field, it may need to flip work pieces several times with the help of craft equipment. Considering the convenience of on-site welding and the reduction of turnover times, the maximum displacement of the case G is the least. Comparing with the maximum displacement in the original welding sequence, case G decreases by 51.9%. So this case can be used to guide the field welding production.

(3) Welding sequence has little influence on the welding residual stress of this ear plate structure.

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