Numerical Analysis of Influence of Welding Sequence on Welding Deformation of Magnetic Separator Dielectric Box

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Abstract. Aiming at the problem that the welding sequence has a great influence on the welding deformation of the dielectric box, this paper uses the nonlinear finite element method to numerically simulate the four welding sequences of the magnetic separator dielectric box, and analyzes the transverse deformation and longitudinal deformation. The welding sequence with the smallest amount of deformation was obtained, and the correctness of the simulation results was verified by experiments.

1. Introduction
The magnetic separator is an important iron ore screening equipment in the iron ore smelting industry, which can screen iron powder from crushed iron ore. The dielectric box is one of the most important parts of the magnetic separator, which determines the purity and efficiency of the iron powder screening. The welding of the dielectric box is to weld the two ends of the soft magnetic rod to the surface of the soft magnetic alloy plate, as shown in Figure 1(b).

![Figure 1. Magnetic separator dielectric box](image)

(a) Before the dielectric box is welded (b) After the dielectric box is welded
1-the soft magnetic rod 2-the soft magnetic alloy plate

In the multi-pass welding process, due to the locality and non-uniformity of the temperature field\cite{1}, residual stress and welding deformation of the dielectric box weld bead are formed, which affects the dimensional accuracy of the dielectric box, and thus affects the assembly relationship with other parts. For multi-pass welding, different welding sequences have different effects on residual stress and deformation during the welding process. If the welding sequence is not properly selected, the residual stress after welding will be large and the amount of welding deformation will be large\cite{2}. It is of great significance to numerically simulate the welding deformation of different welding sequences by numerical simulation technology, and to select the optimal welding sequence.
2. Welding finite element model establishment

2.1. Grid partition
Since the weld bead are concentrated on the surface of the alloy plate during the welding process, the welding deformation is mainly concentrated on the alloy plate, and the assembly accuracy of the dielectric box is mainly determined by the dimensional accuracy of the alloy plate. Therefore, in order to simplify the analysis model and improve the efficiency of the solution, the welding simulation of the dielectric box is simplified to the multi-pass welding simulation of the thin plate. Study the effect of different welding sequences on the welding deformation of dielectric box alloy plates. Firstly, a finite element model of 10 weld beads with a thickness of 5mm was established by using finite element simulation analysis technology. In the process of dielectric box welding simulation, in order to further improve the efficiency of the solution, the following assumptions were made:
1) The surrounding environment of the welding process and the initial temperature of the dielectric box is 20°C;
2) Ignoring the difference between the soft magnetic alloy plate and the soft magnetic bar, unified into the same isotropic material;
3) The movement speed of the welding torch during the welding process is constant, and the heat generated by the arc strictly obeys the Gaussian heat distribution;
4) Ignore the heat transfer between the dielectric box and the fixture, only consider the convective heat transfer and radiative heat transfer between the media box and the surrounding environment.

The weld bead formed by the welding of the dielectric box is shown in Figure 1(b), and the weld bead is a smooth straight bead. Therefore, the weld bead can be set to a long rectangular shape during the welding simulation, and the weld bead size is 400mm long, 5mm wide and 5mm thick. The soft magnetic alloy plate is 400mm long, 150mm wide and 5mm thick. In order to reduce the calculation amount and simulation complexity, and to achieve the purpose of this simulation test, this paper only simulates the soft magnetic alloy plate. The welding stress and welding deformation are studied. The geometric model of the alloy plate is shown in Figure 2(a).

In the meshing, a smaller structured grid is used for the melting zone and the heat-affected zone of the weld bead, and a sparse structured grid is adopted for the non-heat-affected zone far from the bead[3]. The result of the meshing is shown in the Figure. 2(b).

2.2. Material thermodynamic parameters
The alloy plate is a nickel-iron alloy, and its physical properties and mechanical properties change with temperature. For performance parameters above 800 °C, the difference between inside and outside the law is used[4]. Meanwhile, in order to simplify the calculation, the bead unit and the base
metal have the same thermophysical parameters. The variation of each parameter with temperature is shown in Table 1.

2.3. Boundary condition setting
When performing thermal-structural coupling analysis of the weld, it is generally necessary to define the structural constraints and the heat transfer boundary conditions[5]. The structural constraint is defined to prevent the workpiece from producing a rigid displacement during the analysis process, and at the same time, it cannot affect the stress release and free deformation during the welding process. Therefore, the joints at both ends of the alloy plate 5mm from the weld bead were restrained. The heat transfer boundary conditions generally include heat conduction, convection heat transfer and radiation heat transfer. Neglecting the contact heat transfer between the workpiece and the fixture, only considering the convective heat transfer and radiation heat transfer of the outer surface of the workpiece. Where, the convection heat transfer coefficient between the air and the workpiece is 15W/(m²·K), and the radiative heat transfer coefficient within each temperature range is calculated according to Newton's cooling formula, and is added with the convection heat transfer coefficient, which is combined to form the surface composite heat transfer coefficient.

Table 1. Thermodynamic parameters of welding materials

| Temperature (°C) | Density (kg/m³) | Thermal Conductivity (W/(m·K)) | Equivalent specific heat capacity (J/(kg·K)) | Elastic Modulus (GPa) | Poisson’s ratio | Linear expansion coefficient (10⁻⁶·K⁻¹) | Yield Strength (MPa) |
|-----------------|-----------------|-------------------------------|---------------------------------------------|----------------------|---------------|----------------------------------------|---------------------|
| 20              | 50.0            | 460                           | 205                                         | 0.28                 | 11.00         | 11.00                                  | 220                 |
| 100             | 49.0            | 468                           | 194                                         | 0.28                 | 11.40         | 11.40                                  | 202                 |
| 200             | 47.7            | 476                           | 183                                         | 0.29                 | 11.94         | 11.94                                  | 184                 |
| 400             | 42.8            | 550                           | 165                                         | 0.30                 | 13.22         | 13.22                                  | 148                 |
| 600             | 34.8            | 688                           | 118                                         | 0.32                 | 14.26         | 14.26                                  | 94                  |
| 700 7820        | 29.6            | 846                           | 86                                          | 0.34                 | 14.62         | 14.62                                  | 58                  |
| 750             | 27.0            | 1180                          | 70                                          | 0.35                 | 14.80         | 14.80                                  | 40                  |
| 800             | 27.6            | 814                           | 60                                          | 0.36                 | 14.62         | 14.62                                  | 37                  |
| 1000            | 30.0            | 720                           | 20                                          | 0.40                 | 13.40         | 13.40                                  | 25                  |
| 1200            | 32.0            | 666                           | 19.6                                        | 0.42                 | 13.36         | 13.36                                  | 15                  |
| 1600            | 330.0           | 1860                          | 19                                          | 0.45                 | 13.30         | 13.30                                  | 2                   |
| 2000            | 330.0           | 1860                          | 18                                          | 0.48                 | 13.20         | 13.20                                  | 1                   |

2.4. Multi-pass welding residual stress calculation scheme
The element life-and-death technique is used to simulate the sequential generation of weld bead elements and the movement of heat source. In the case that there is no highly nonlinear interaction, the indirect coupling method is more effective and convenient, because the two fields can be analyzed independently. Coupling is a cyclic process in which iterations are performed between two physics fields until the results converge to the required precision. The SOLID70 thermal analysis unit is adopted for welding temperature field analysis, which is then converted into structural analysis, and the results of temperature field are read step by step as thermal load to solve the stress field. The welding stress field analysis uses the SOLID185 structural analysis unit.

3. Design and simulation analysis of welding sequence
Numerical simulation of stress and deformation of four welding sequences of media box, the welding sequence is shown in Table 2. In the table, 1 to 10 indicate 10 weld beads from top to bottom of the alloy plate.
Table 2. Welding sequence table of dielectric box alloy plates

| The scheme | The welding sequence             |
|------------|----------------------------------|
| 1          | 1→10→5→2→9→6→3→8→4→7          |
| 2          | 1→6→2→7→3→8→4→9→5→10          |
| 3          | 1→2→3→4→5→6→7→8→9→10          |
| 4          | 1→10→2→9→3→8→4→7→5→6          |

ANSYS was used to simulate and analyze four welding schemes of alloy plate. In order to fully analyze the influence of different welding sequences on the welding deformation of alloy plate, the transverse deformation and longitudinal deformation of alloy plate under the four welding sequences were compared respectively. The simulation results are shown in Figure 3.

Figure 3. Maximum welding deformation of different welding sequences of alloy plates

The maximum transverse deformation of schemes 1 to 4 is 6.81mm, 6.80mm, 6.92mm and 6.86mm, respectively. It can be concluded that the maximum transverse deformation of scheme 3 is the largest, while the maximum transverse deformation of scheme 2 is the smallest, but the difference is small. Therefore, it can be concluded that different welding sequences have less influence on the transverse deformation of the alloy plate. The maximum longitudinal deformation of schemes 1 to 4 is 6.81mm, 6.80mm, 6.92mm and 6.86mm, respectively. It can be concluded that the maximum longitudinal deformation of scheme 3 is the largest, while the maximum longitudinal deformation of scheme 1 is the smallest. Therefore, it can be concluded that different welding sequences have a greater influence on the longitudinal deformation of the alloy plate.

4. Welding experiment and analysis
In order to test the simulation results of the four welding sequences of the alloy plates, 6 pieces of alloy plates of the same specification are welded in each welding sequence, and the maximum transverse deformation and maximum longitudinal deformation of alloy plates were measured. The measurement results are shown in Table 3.

The experimental results show that the average values of the maximum transverse deformation of the schemes 1 to 4 are 6.93 mm, 6.82 mm, 6.98 mm, 6.90 mm, and the average values of the maximum longitudinal deformation are 5.08 mm, 5.54 mm, 7.40 mm, 5.57 mm. Compared with the ANSYS simulation results, the actual welding deformation is slightly larger than the simulation results, but the difference is small. The solution with the smallest welding deformation is also scheme 1, which conforms to the simulation results.
Table 3. Alloy plate welding experiment results

| Schemes | Measurement type                  | Deformation amount (mm) | Mean values |
|---------|-----------------------------------|-------------------------|-------------|
|         | transverse deformation            |                         |             |
| Scheme1 | longitudinal deformation          | 7.03                    | 6.93        |
|         |                                   | 6.78                    |             |
|         |                                   | 6.89                    |             |
|         |                                   | 6.81                    |             |
|         |                                   | 6.98                    |             |
|         |                                   | 7.08                    |             |
|         |                                   | 6.93                    |             |
| Scheme2 | transverse deformation            | 5.03                    | 5.08        |
|         | longitudinal deformation          | 5.03                    | 5.06        |
|         |                                   | 5.10                    |             |
|         |                                   | 5.07                    |             |
|         |                                   | 5.12                    |             |
|         |                                   | 5.12                    |             |
| Scheme3 | transverse deformation            | 6.81                    | 6.82        |
|         | longitudinal deformation          | 6.80                    | 6.82        |
|         |                                   | 6.79                    |             |
|         |                                   | 6.89                    |             |
|         |                                   | 6.84                    |             |
|         |                                   | 6.81                    |             |
| Scheme4 | transverse deformation            | 5.48                    | 5.54        |
|         | longitudinal deformation          | 5.51                    | 5.54        |
|         |                                   | 5.60                    |             |
|         |                                   | 5.54                    |             |
|         |                                   | 5.56                    |             |
|         |                                   | 5.54                    |             |

5. Conclusion

The numerical simulation technology can predict the welding deformation during the welding process, and provide a theoretical basis for the analysis of multi-pass welding deformation of the alloy plate. The experimental results prove the correctness of the simulation results, which is of great significance for the selection of the optimal welding sequence for multi-pass welding.

Acknowledgment

This work is supported by the national natural science foundation project (the project number is 51875250).

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