Welding Deformation of Unequal Thickness Tailor Welded Blanks under Multiple Factors

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Abstract. With the popularity of lightweight requirements, the application of tailor welded blanks with unequal thickness is increasing gradually. The welding deformation of tailor welded blanks with unequal thickness inclined weld is affected by the external constraints and the internal structural parameters of the plates. In this paper, the effect of the external constraints and the internal structural parameters on the multi-layer and multi-pass welding deformation of unequal thickness inclined weld was investigated. The deformation distribution law of butt welding of unequal thickness inclined weld was obtained combined with simulation and experiment results. The results showed that the spring constraint method was similar to the actual welding condition, meanwhile, the control effect of spring constraint on the welding deformation was better. The welding gap had the greatest influence on the welding deformation, followed by the angle of inclined weld, thickness of thick plate and thickness of thin plate. When the thickness difference between two plates was kept at 50%, the control effect of welding deformation was the best.

1. Introduction
Welding deformation is usually caused by plastic deformation caused by uneven welding temperature field[1-3]. The research of welding process usually focuses on the analysis and prediction of welding temperature field and welding deformation, in order to control the welding deformation. In the process of welding, the inhomogeneity of the material, the temperature gradient of the thickness direction of the plate, the local non-conforming plastic strain of the material and the welding residual stress are all the important reasons for the welding deformation[4]. The application of butt welding technology of unequal thickness plate can not only meet the lightweight requirements, but also meet the strength requirements of components[5]. Thus, the external constraints and the internal plate structural parameters all have great influence on the prediction of welding deformation.

In the process of welding, the deformation of the plate has a great influence on the dimensional accuracy of the final structure. In the field of construction machinery simulation, it is usually affected by the factors such as large size of structural parts, complex working conditions and difficult quantitative analysis. The orthogonal experimental method is based on the Latin square theory and the group theory. For multivariable experiments, through a few representative experiments, weighing the influence of factors on the experiment results to obtain the best combination of parameters. In the optimization of the welding process, the orthogonal experimental method can be used to find out the best matching scheme of welding parameters accurately[6].
In this paper, based on the thermo elastoplastic finite element method and Marc finite element software, the orthogonal experimental design and experimental verification were carried out for the multi-layer and multi-pass welding of unequal thickness inclined weld to predict the welding deformation. Single factor orthogonal experimental design of external factor and four factors three levels orthogonal experimental design of internal factor of welding deformation were carried out respectively. Taking the welding deformation as evaluation index. According to the optimal welding parameters, experiments were carried out to verify the correctness of simulation results.

2. Establishment of finite element model

2.1. Welding Structure parameters
The experimental material was Q890 high strength steel plate. The inclined plate was welded by CO2 gas shielded welding and ER90-6φ1.2 welding wire. Table 1 showed the structure parameters of plates.

| Thickness of plate A (mm) | Thickness of plate B (mm) | The angle of inclined weld (°) | Welding gap (mm) |
|---------------------------|---------------------------|-----------------------------|-----------------|
| 6~10                      | 12~20                     | 45~75                       | 1~3             |

2.2. Mesh generation of finite element model
As for the thick plate in the butt welding process of unequal thickness inclined weld, 45° slope mouth was adopted for transition at the height equal to the thickness of the thin plate. It can effectively reduce the stress concentration effect, balance the distribution of welding stress and increase the joint strength, meanwhile, reduce the filling amount of the welding materials, as shown in figure 1.

In this paper, hexahedral solid element was used for mesh generation. Plate thickness of 8 mm and 20 mm, inclined weld of 45° and welding gap of 2mm were taken as an example. The total number of elements was 48750, and the total number of nodes was 60081. On the premise of ensuring the accuracy of simulation calculation, the transition mode of grid from dense to sparse was adopted to fine mesh the weld and heat affected zone, and the grid was sparse far away from the weld zone, so obtained the finite element model of unequal thickness inclined weld, the model was displayed in the figure 2.
2.3. Selection of welding heat source
The double ellipsoid heat source model which can accurately describe the CO$_2$ gas shielded welding was chosen as the heat source of welding simulation. The fixed temperature heat source loading mode was adopted, and the temperature was set as 1500℃. Due to the convective heat dissipation on the plate surface and surrounding environment in the actual welding work, the heat dissipation coefficient was set as 0.02, and the ambient temperature was 20 ℃.

3. Orthogonal experimental design

3.1. Single factor experimental design of external factors
In the welding simulation calculation, the matching degree of different constraint conditions and actual welding conditions was different. Consider not only to control the welding deformation, but also to meet the actual welding conditions as much as possible, full constraint, three point constraint, contact constraint and spring constraint were chosen as the experimental conditions.

Take plates thickness of 8 mm and 20 mm, inclined weld of 45 ° and welding gap of 2mm as an example, four constraint conditions were applied respectively. Full constraints at four ends of tailor welded blanks, as shown in figure 1(a). Apply three-way constraints to three ends of tailor welded plate, as shown in figure 1(b). Add contact constraint at the bottom of the TWB and apply displacement constraint in XY direction to the bottom of the weld, as shown in figure 1(c). Apply spring constraint in Z direction and displacement constraint in X direction directly below the weld, meanwhile apply Y direction displacement constraint at the middle position of both sides of TWB, as shown in figure 1(d). Constraint conditions and positions were illustrated in Figure 3.

![Figure 3. Constraint conditions and positions](image)

Single factor experimental design results of external factors were shown in table 2. Although the welding deformation of the plate was minimal under the condition of full constraints, the full constraints belonged to the rigid constraint on the end of the plate, which limited the thermal deformation process of the plate after welding seriously. It belonged to the category of over constraint. The spring constraint condition met the design requirements of butt welding of unequal thickness inclined weld and met the actual welding conditions.
Table 2. Results of single factor experimental design

| Number | Constraint type         | Welding deformation $\ell$(mm) |
|--------|-------------------------|-------------------------------|
| a      | full constraints        | 1.879                         |
| b      | three point constraints | 14.751                        |
| c      | contact constraint      | 12.062                        |
| d      | spring constraint       | 4.445                         |

3.2. Multi factors experimental design of internal factors

Thickness of plate A, thickness of plate B, the angle of inclined weld and welding gap were chosen to be factors. According to the $L9(3^4)$ orthogonal experimental table and four factors three levels orthogonal experimental design, 9 experiments obtained in total. Factors and levels of orthogonal experimental design were shown in table 3. Orthogonal experimental design scheme was illustrated in table 4.

Table 3. Factors and levels of structural parameters of unequal thickness inclined weld plate

| Levels | Factors                                                                 |
|--------|-------------------------------------------------------------------------|
|        | A Thickness of plate A $T_1$/mm                                         |
|        | B Thickness of plate B $T_2$/mm                                         |
|        | C The angle of inclined weld $\theta$/°                                 |
|        | D Welding gap L/mm                                                      |
| 1      | 6 12 45 1                                                               |
| 2      | 8 16 60 2                                                               |
| 3      | 10 20 75 3                                                              |

Table 4. Orthogonal experimental scheme of unequal thickness inclined weld

| Levels | Factors                                                                 |
|--------|-------------------------------------------------------------------------|
|        | A Thickness of plate A $T_1$/mm                                         |
|        | B Thickness of plate B $T_2$/mm                                         |
|        | C The angle of inclined weld $\theta$/°                                 |
|        | D Welding gap L/mm                                                      |
| 1      | 6 12 45 1                                                               |
| 2      | 6 16 60 2                                                               |
| 3      | 6 20 75 3                                                               |
| 4      | 8 12 60 3                                                               |
| 5      | 8 16 75 1                                                               |
| 6      | 8 20 45 2                                                               |
| 7      | 10 12 75 2                                                              |
| 8      | 10 16 45 3                                                              |
| 9      | 10 20 60 1                                                              |

4. Orthogonal experimental results and verification analysis

4.1. Principle of range analysis

Range analysis method is to use mathematical statistics method to calculate the $R$ value in the orthogonal table to determine the primary and secondary relationship of influencing factors, so as to find a better level combination.

$$K_i = \frac{T_{ij}}{r}$$

$$R_i = K_{i(max)} - K_{i(min)}$$

Among them: $i$ represents the amount of levels; $j$ represents the amount of columns; $r$ represents the total levels number of each factor; $K_i$ represents the average value of level $i$, column $j$; $T_{ij}$ represents the sum of the evaluation indexes of level $i$, column $j$; $K_{i(max)}$ represents the maximum
value of $K_{ij}$ in column $j$; $K_{ij(\text{min})}$ represents the minimum value of $K_{ij}$ in column $j$; $R_j$ represents the range value of column $j$.

4.2. Range analysis results

According to the principle of range analysis, table 5 showed that the range analysis results of butt welding procedure of unequal thickness inclined weld. According to the results of the range analysis, the primary and secondary relationship of the influence about the four factors on the welding deformation of tailor welded blanks was welding gap, the angle of inclined weld, thickness of plate B and thickness of plate A. The optimal combination of parameters combination was 2mm of welding gap, 60°of the angle of inclined weld, 16mm of thickness of plate B and 8mm of thickness of plate A.

Table 5. Table of range analysis

| A Levels | Factors | B | C | D Evaluating indicator |
|----------|---------|---|---|------------------------|
| Thickness of plate A | Thickness of plate B | The angle of inclined weld | Welding gap | Welding deformation |
| $T_1$/mm | $T_2$/mm | $\theta$/° | $L$/mm | $S$/mm |
| 1 | 6 | 12 | 45 | 1 | 3.828 |
| 2 | 6 | 16 | 60 | 2 | 5.303 |
| 3 | 6 | 20 | 75 | 3 | 3.673 |
| 4 | 8 | 12 | 60 | 3 | 3.847 |
| 5 | 8 | 16 | 75 | 1 | 5.032 |
| 6 | 8 | 20 | 45 | 2 | 4.445 |
| 7 | 10 | 12 | 75 | 2 | 4.635 |
| 8 | 10 | 16 | 45 | 3 | 3.277 |
| 9 | 10 | 20 | 60 | 1 | 4.388 |
| $T_{ij}$ | 12.804 | 12.311 | 11.551 | 13.248 |
| $T_2$ | 13.324 | 13.612 | 13.538 | 14.383 |
| $T_3$ | 12.301 | 12.506 | 13.341 | 10.797 |
| $K_{ij}$ | 4.268 | 4.103 | 3.852 | 4.416 |
| $K_2$ | 4.441 | 4.537 | 4.513 | 4.794 |
| $K_3$ | 4.101 | 4.022 | 4.447 | 3.599 |
| $R_j$ | 0.341 | 0.517 | 0.663 | 1.159 |

4.3. Simulation calculation of optimal welding parameters

For the optimal combination of welding parameters, finite element simulation calculation was completed, and the calculation result was illustrated in Figure 4. The maximum welding deformation in the thickness direction of tailor welded blank was 3.689mm, met the expectation of orthogonal experimental design.

Figure 4. simulation result of optimal parameters combination
4.4. Experimental verification
Combining the orthogonal experimental design with the simulation results of the optimal welding parameters, conducted the welding experiment to verify the optimal welding process of the unequal thickness inclined weld. Mertra SCAN three-dimensional laser scanner (measuring accuracy can reach 0.05mm) was utilized to scan and measure the welding deformation of plate which have been cooled to room temperature after welding. The welding deformation of tailor welded blanks completed under the condition of optimal welding parameters was 3.546mm, met the expectation of orthogonal experimental design. Figure 5 showed the plate after welding. Figure 6 displayed three dimensional laser scanner for experiment. Figure 7 showed the comparison of simulation results and experimental welding deformation distribution.

Figure 5. Experiment plate after welding
Figure 6. Three dimensional laser scanner
Figure 7. Comparison of welding deformation distribution between simulation and test
5. Conclusion
In this paper, the model of tailor welded blanks with unequal thickness inclined weld was established, compared the effect of internal and external factors on welding deformation of plate. The best combination of welding parameters of tailor welded blanks with unequal thickness inclined weld was obtained. Combined with the experimental verification, the conclusions are drawn as follows:

(1) Through the single factor orthogonal experimental design of the external factor of welding deformation, the influence of different constraints on the welding deformation of unequal thickness inclined weld was investigated. It was concluded that the spring constraint method was similar to the actual welding condition, and the effect of spring constraint on welding deformation was better.

(2) According to the internal structural parameters of the plates of welding deformation, L9(3^4) orthogonal experimental design scheme was selected, and the best welding structure combination of unequal thickness inclined weld was obtained by range analysis method. The welding gap has the greatest influence on the welding deformation, followed by the angle of inclined weld, the thickness of thick plate and the thickness of thin plate. The optimal combination of parameters combination was 2mm of welding gap, 60° of the angle of inclined weld, 16mm of thickness of plate B and 8mm of thickness of plate A.

(3) When the thickness difference between two plates was kept at 50%, the control effect of welding deformation was the best.

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