Numerical Optimization of Groove Shape and Welding Sequence on T-joint Multi Passes Welding and Validation by Welding Test

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In case of welding of thick plates, it is necessary to apply appropriate groove shape for preventing welding distortion and defects. It is difficult to define an appropriate welding condition of inexperienced structure. In this study, the optimization method for welding condition on T-joint weld was investigated. The groove shape (groove angles and position of root edge) and a welding sequence were defined as design variables. The distortion was defined as the objective function and it was minimized. The response surface methodology was used for this optimization. For the purpose of confirming the validity of this optimization method, numerical analysis and actual weld experiment with optimized welding condition were performed. As a result of numerical analysis, the residual distortion was sufficiently small. Moreover, it was confirmed that the residual distortion of actual weld experiment was smaller than acceptable value.

Key Words: Non-linear FEM, Welding distortion, Groove shape, Optimization, Idealized explicit FEM

1. Introduction

In case of welding of thick plates, it is necessary to apply an appropriate groove shape for preventing welding distortion and defects. If the groove shape and the welding sequence are not appropriate for the material and welding thickness, a large distortion would occur. Once large welding distortion has occurred, it takes long time and needs costs for fixing it to correct the distortion. Therefore, it is useful for us to make a guideline of welding sequences and groove shapes for different thickness and materials by the numerical optimization.

Many researches have been done for an optimization of welding distortion. Some researches defined heat source parameters (such as voltage, current, weld speed, wire feed rate and so on) as design variables. Other researches defined welding sequence and welding direction as design variables. Those researches used process parameters as design variables. On the other hand, no research defined groove shape as design variable in our knowledge. The computational cost of groove welding of thick plate is very high. A large number of analyses are necessary for optimization. Therefore it is difficult to numerically optimize thick plate welding. However, the idealized explicit FEM which can compute welding much faster than general purpose software was developed recently. Consequently, it becomes possible to numerically optimize thick plate welding by using idealized explicit FEM. The optimization method for welding condition on T-joint welding was investigated in this study. The response surface methodology was used for the optimization. A groove shape (groove angles and a position of a root edge) and a welding sequence were defined as design variables. The welding distortion was defined as the objective function and it was minimized. In addition, for the purpose of confirming the validity of the proposed optimization method, actual welding test with optimal welding condition was performed.

2. Outline of Optimization Target

2.1 Target of Optimization

The welding conditions (the welding sequence and the groove shape) which restrain welding distortion on T-joint welding were investigated. Figure 1 shows the test piece of T-joint welding. The size of the plate is 500 mm in length, 300 mm in width and 30 mm in thickness. The material of the plate is SUS304. A welding groove is applied to vertical plate and the full penetration welding is performed. The number of total welding pass is about 20 and the number of welding layer is about 8. These values are changed a little by the groove shape.

Fig. 1 Test piece of T-joint welding
In this study, only the displacement of the vertical plate was optimized and the horizontal plate was fixed. Therefore for the purpose of eliminating the influence of angular distortion of horizontal plate, the horizontal plate was restrained by welding to the constrained plate.

### 2.2 Design variables and Objective functions

Figure 2 shows the design variables which include three size parameters that determine a groove shape. The parameter \( d \) represents a position of the groove edge and \( \theta_1 \) and \( \theta_2 \) represent left and right groove angle, respectively. There exist six welding blocks (A, B, C, D, E, F) and these blocks are welded sequentially from A to F. The number of layers in block A is fixed as one for preventing large distortion. The number of layers in block B, C and D are defined as design variables. The number of layers in block E and F are decided automatically when the number of layers in block A, B, C and D are defined. Therefore, six design variables exist. Table 1 shows the lower and upper limits of each design variables. Figure 3 illustrates the position of the objective functions. One of the functions is a residual horizontal displacement at the top of the vertical plate and the other function is a maximum horizontal displacement at the top of the vertical plate during the welding. The tolerances of the parameter \( d \) is 1 mm and the tolerances of \( \theta_1 \) and \( \theta_2 \) are 1 degree.

In the whole combination of each size parameter tolerance, the displacement must be smaller than acceptable value. Among the solutions which satisfy the above condition, the solution that has the smallest objective value is chosen as the optimal solution. The acceptable residual displacement is 2 mm (0.4 deg.) and the acceptable maximum displacement during welding is 25 mm (4.8 deg.). If the displacement during welding is increased more than 25 mm, the number of welding passes is changed. So, the actual pass number becomes different from the optimized pass number.

### 3. FEM Analysis

#### 3.1 Analysis Model

The thermal-elasto-plastic FEM analysis was conducted to compute the welding distortion. In this study, the idealized explicit FEM was used for the FEM analysis. Figure 4 shows the mesh of the FEM model. The FEM model consists of the vertical plate, the horizontal plate and the constrained plate. For thermal analysis, the horizontal plate and the constrained plate were completely contacted. So, there was no thermal contact resistance between both plates. The mesh of the welding area is 1 mm voxel mesh. Figure 5 shows the cross-section of the mesh and groups of welding passes. Even if the groove shape is changed, the same mesh can be used when the group of each pass is changed.
determined. Table 2 shows the values of each design variable of pre-welding test. Table 3 shows the welding conditions. In order to conduct full penetration welding certainly, the welding speed of the first pass was set slower than other passes. Table 4 shows the material data. Figure 6 shows the cross-sectional macrostructure of welding area. In this study, for the purpose of simplifying the welding phenomenon, the stringer welding was adopted. So, the bead shape was not smooth. According to the Fig. 6, the area of deposition of the first welding pass was 35 mm² and the average area of deposition of the other welding pass was 21 mm². Figure 7 shows the positions of thermocouples and Fig. 8 shows the temperature histories obtained by the FEM analysis and the pre-welding test during the third welding pass (the first welding pass of layer C). When the bead length is 16 mm and the thermal efficiency is 90%, the temperature obtained by the FEM analysis agrees with the temperature obtained by the pre-welding test. Figure 9 shows the individual displacement of each welding pass obtained by the FEM analysis and the pre-welding test. After the third welding pass, the displacement of the FEM analysis agreed with that of the pre-welding test. However, at the first and the second welding passes, the difference of the displacement between the FEM analysis and the pre-welding test was large. Therefore the FEM analysis results of the displacement of the first and the second welding pass was not used for this optimization. The displacement of the first and the second welding pass was fixed as the result of pre-welding test.

Table 2 Values of design variables of pre-welding test

| Variable | Value |
|----------|-------|
| \(d\)    | 15    |
| \(\theta_1\) | 45    |
| \(\theta_2\) | 45    |
| B        | 1     |
| C        | 2     |
| D        | 2     |

Table 3 Welding condition

| Weld Type | Current | Voltage | Weld Speed |
|-----------|---------|---------|------------|
| MAG weld  | 230 A   | 29 V    | 30 cm/min (first pass) |
|           |         |         | 50 cm/min (other pass)  |

Table 4 Material Data

| Temp (degC) | Thermal conductivity (W/mK) | Specific heat (J/kgK) | Density (kg/m³) | Young's modulus (GPa) | Poisson's ratio | Yield Strength (MPa) | Thermal expansion |
|-------------|------------------------------|-----------------------|----------------|-----------------------|----------------|----------------------|------------------|
| 20          | 14.6                         | 462                   | 7900           | 198.5                 | 0.29           | 238                  | 15.4 ± 6         |
| 400         | 23.0                         | 577                   | 7650           | 187.2                 | 0.32           | 192                  | 17.7 ± 6         |
| 600         | 23.8                         | 604                   | 7580           | 150.8                 | 0.33           | 178                  | 18.4 ± 6         |
| 800         | 23.8                         | 604                   | 7580           | 133.6                 | 0.34           | 100                  | 19.2 ± 6         |
| 1000        | 37.7                         | 644                   | 7470           | 85.4                  | 0.37           | 31                   | 19.5 ± 6         |
| 1200        | 35.2                         | 676                   | 7370           | -                     | 0.01           | 37                   | -                |
| 1400        | -                            | -                     | -              | -                     | -              | -                    | -                |

4. Optimization of Welding Condition on T-joint

4.1 Optimization Method

Figure 10 shows the procedure of the optimization method. At first, design variables are selected using the orthogonal array so that selected cases cover the whole design domain. Secondly, the welding distortion of each case is computed by the FEM analysis. Thirdly, a response surface is generated using results of the FEM analysis. The number of computed cases is not enough for the response surface to accurately approximate the welding distortion over the whole design domain, but this response surface is useful to estimate the optimal solution. Then, additional
cases which are considered as the optimal solution by the response surface are selected. Then, the welding distortions of the additional cases are computed. Then, the new response surface is generated using the all results of the FEM analysis. This new response surface is more accurate than the former one especially around the optimal solution. Finally, the optimal solution is selected using new response surface. Then the welding distortion of this optimal solution is computed by the FEM analysis. If the welding distortion is acceptable, it is confirmed that this is the optimal solution. Otherwise, we return to the fourth procedure and select additional sampling cases.

1. select sampling cases by orthogonal array
2. perform the FEM analyses at all sampling cases
3. generate response surface using the results of FEM analyses
4. select additional cases considered as optimal case
5. perform the FEM analysis at additional cases
6. generate response surface using all results of the FEM analyses
7. select optimal case and perform FEM analysis
   NG
   OK
   Optimal welding condition

Fig. 10 Procedure of optimization method

4.2 Optimization Result

Table 5 shows the 3 level 27 Latin square orthogonal array of this optimization case. 27 cases from this orthogonal array were selected at the first sampling step. And 40 cases from the first response surface which was generated by the first 27 cases were added at the second sampling step. Consequently, 67 cases of the FEM analyses were performed. Figure 11 shows the results of the FEM analyses. The welding distortions were acceptable in 8 cases. But when the size parameter tolerances of groove shape were considered, there was no case which the displacement in whole combination of size parameter tolerance (d: ±1mm, θ1, θ2: ±1degree) was acceptable. Then the response surface was re-generated using 67 cases. On the new response surface, the welding distortion was acceptable in 317 cases when each variable were defined as integer. When the size parameter tolerances of groove shape were considered, there were 5 cases which the displacement in whole combination of size parameter tolerance was acceptable. Then, one solution with the smallest value was selected as the optimal solution. Table 6 shows the design variables of the optimal solution. In order to confirm the value of the objective function of the optimal solution, the FEM analysis with the optimal welding condition was performed. As a result of the FEM analysis, the residual displacement at the top of the vertical plate was 0.13 mm and the maximum displacement during the welding was 14 mm and these values are almost same as the result of response surface.

Table 5 3 level 27 Latin square orthogonal array

| Case | d [mm] | θ1 [deg] | θ2 [deg] | B [-] | C [-] | D [-] |
|------|--------|-----------|-----------|-------|-------|-------|
| 1    | 11     | 40        | 45        | 1     | 1     | 1     |
| 2    | 11     | 40        | 55        | 2     | 2     | 2     |
| 3    | 11     | 40        | 60        | 3     | 3     | 1     |
| 4    | 11     | 45        | 45        | 2     | 2     | 2     |
| 5    | 11     | 45        | 55        | 3     | 3     | 1     |
| 6    | 11     | 45        | 60        | 1     | 1     | 2     |
| 7    | 11     | 50        | 45        | 3     | 3     | 1     |
| 8    | 11     | 50        | 55        | 1     | 1     | 2     |
| 9    | 11     | 50        | 60        | 2     | 2     | 1     |
| 10   | 14     | 45        | 45        | 2     | 2     | 1     |
| 11   | 14     | 45        | 46        | 3     | 3     | 2     |
| 12   | 14     | 45        | 53        | 1     | 2     | 1     |
| 13   | 14     | 49        | 45        | 2     | 1     | 1     |
| 14   | 14     | 49        | 49        | 2     | 1     | 2     |
| 15   | 14     | 49        | 53        | 2     | 3     | 2     |
| 16   | 14     | 53        | 45        | 1     | 2     | 3     |
| 17   | 14     | 53        | 49        | 2     | 3     | 3     |
| 18   | 14     | 53        | 53        | 3     | 3     | 1     |
| 19   | 17     | 45        | 40        | 3     | 2     | 0     |
| 20   | 17     | 45        | 45        | 1     | 3     | 1     |
| 21   | 17     | 45        | 50        | 2     | 1     | 1     |
| 22   | 17     | 45        | 55        | 4     | 1     | 3     |
| 23   | 17     | 55        | 45        | 2     | 2     | 1     |
| 24   | 17     | 55        | 50        | 3     | 2     | 0     |
| 25   | 17     | 60        | 40        | 3     | 1     | 1     |
| 26   | 17     | 60        | 45        | 3     | 2     | 0     |
| 27   | 17     | 60        | 50        | 1     | 3     | 2     |

Fig. 11 FEM analysis result of all sampling cases

Table 6 Value of optimal solution

| d [mm] | θ1 [deg] | θ2 [deg] | B [-] | C [-] | D [-] |
|--------|----------|----------|-------|-------|-------|
| 15     | 45       | 45       | 1     | 2     | 2     |
5. Welding Test

The welding test using the optimal welding condition was performed. Figure 12 shows the residual displacement of the welding test. The displacement with the optimal welding condition was 1.4 mm which was smaller than that of the pre-welding test and also it was smaller than acceptable value (2 mm). But the residual displacement of the welding test (1.4 mm) was not equal to the result of the FEM analysis (0.13 mm). Figure 13 shows the displacement after each welding pass of the FEM analysis and the welding test result of the optimal solution. The FEM analysis of the first and the second welding pass were not performed. Instead, the result of the pre-welding test was used. The displacement of the first and the second welding pass was different between the pre-welding test and the welding test with the optimal solution. And this difference remained until the end of the welding. If the accuracy of the FEM analysis at the first and the second welding pass is improved, it may be possible to consider the influence of the first and the second welding pass to this optimization and the accuracy of the optimization may be improved much more.

6. Conclusions

In this study, the optimization method for the welding condition on T-joint weld was investigated. The response surface was used for this optimization. The optimal solution was selected efficiently by updating the response surface. The tolerances of size parameters were considered. In the whole combination of each size parameter tolerance, the displacement must be smaller than acceptable value and it is minimized. Then this optimal solution has robustness to manufacturing tolerance. The welding test with the optimal welding condition was performed and the validity of this optimization method was confirmed.

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