Effect of groove shape on welding stress and deformation

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Abstract. The thermal-elastic-plastic finite element method was used to simulate the stress field and deformation of the V-groove plate butt joint with 12 mm thickness. The residual stress of the V-groove Q235 butt plate was measured by borehole method. The accuracy of the numerical simulation results was verified by experimental method. The influence of groove shape on welding is deduced by simulation. Because the V-groove fills the most metal during welding, the deformation of V-groove is the largest, while the deformation of K-groove and X-groove is much smaller due to the symmetrical distribution of filling metal. Considering the actual welding process and simulation results, the X-groove should be opened as far as possible if the thick plate is welded. In order to simplify the process, a V-shaped groove should be made for 12 mm thick steel plate, and a 60 degree groove should be made as far as possible.

1. Simulation and experimental verification of stress field at 60°V groove
In this experiment, the borehole method with small destruction and high measurement accuracy was used to test [1] [2]. W. Soete and R. Vancornbrugge first proposed the resistance strain gauge to measure residual stress, namely Mathar-Soete method. Nawwaar and Ruud [3] [4] [5] studied the hole spacing and the radius of strain gauge. They thought that strain gauge and sensitive gate should not be too far away, and gave the appropriate spacing. The following figure is a schematic comparison between the simulation results and the experimental results.

![Comparison of simulated values and experimental values of v-shaped groove.](image-url)
The simulation results are compared with the experimental results, as shown in Table 1.

| Test method          | numerical simulation | absolute error | relative error |
|----------------------|----------------------|----------------|----------------|
| Average value of transverse residual stress | 85.14               | 96.48          | 11.34          | 13.32%        |
| Maximum Deformation in Y Direction | 3.13                | 2.81           | 0.32           | 11.39%        |

The accuracy of numerical simulation is verified by experiments, and the rules of other groove shapes can be deduced by numerical simulation.

2. Analysis of V-shaped grooves from other angles

In plate butting, generally speaking, the bigger the groove angle is, the shallower the unfused depth is, the greater the penetration depth is, and the better the welding effect is; the smaller the groove angle is, the deeper the unfused depth is, the smaller the penetration depth is, and the more the filling metal accumulates on the surface. However, the groove angle should not be too large, too large will cause the bottom of V-groove to be too thin, and welding defects such as burning through and undercut are easy to occur when heated and melted during welding. At present, butt-welded steel plate welding is a welding method requiring one-sided welding and two-sided forming, that is, welding on the side of the groove of the workpiece, the back can also be welded through, and forming a pattern. The process requirement determines that the current should not be too small to ensure enough filling metal. At the same time, the different groove angle will directly affect the amount of filling metal melt. The stress produced by the cooling of molten metal solution will lead to post-weld deformation. Therefore, the V-groove opening should not be too large, not exceeding 60 degrees. According to the welding manual, when the thickness of the plate is 7 ~ 26 mm, the V-groove angle is generally 40° ~60°. The same is V-shaped welding, different groove angle will lead to different deformation.

As we can see, the cross-sectional area formula of the 60 degree V groove heat source is as follows:

\[ A_1 = \frac{3.14 \times 4^2}{6} \]
\[ A_2 = \frac{3.14 \times (8^2 - 4^2)}{6} \]
\[ A_3 = \frac{3.14 \times (12^2 - 8^2)}{12} \]
\[ A_4 = \frac{3.14 \times (12^2 - 8^2)}{12} \]

As can be seen from the formula of A1, A1 represents 1/6 of the circular area with radius 4. So the two groove angles we chose for this time are 40 and 45. Both 40 and 45 degrees can be divided by 360 degrees, which can be used to calculate the heat source. By comparing three different groove angles, the deformation distribution can be better reflected. Welding deformations of 40, 45 and 60 degrees V grooves are shown in Fig. 2-4, respectively.
Fig 2. 40 ° V groove deformation figure

Fig 3. 45 ° V groove deformation figure

Fig 4. 60 ° V groove deformation figure
It can be seen from the figure that the deformation of V-shaped groove is 4.66 mm at 40 degree groove, 3.3 mm at 45 degree groove and 2.82 mm at 60 degree groove. Therefore, the deformation decreases gradually with the increase of angle and gets smaller value at 60 degree. Therefore, if the V-shaped groove is opened at 12 mm thick steel plate butt, the 60 degree groove should be opened as far as possible.

3. K-groove analysis
Residual total deformation of K-groove, as shown in Fig.5

The figure shows that the total residual deformation of K-groove is only 0.27mm, and the maximum deformation in X, Y and Z directions is 0.02mm, 0.1mm and 0.11mm, respectively. It shows that the residual deformation of K-groove is not large and the model does not produce obvious warp age. This is because K-groove has the properties of deformation and anti-deformation. The deformation caused by welding bottom groove will be offset by the deformation caused by welding top groove. Moreover, multi-pass welding technology is adopted to reduce the deformation obviously.

In this paper, the transverse and longitudinal residual stress curves of K-groove weld are directly adjusted. The transverse residual stress curves are shown in Fig 6 and the longitudinal residual stress curves are shown in Fig. 7.
From the transverse residual stress curve, it can be seen that the maximum stress in the weld zone is about 106 Mpa, the residual stress at the free end is only 11.2 Mpa, and the stress at the restraint end is 237 Mpa. The stress distribution is similar to that at the V-groove, but the residual stress value decreases obviously, which is consistent with the above analysis of deformation and anti-deformation. From the longitudinal residual stress curve, it can be seen that the majority of the residual stress at the longitudinal center of the weld is between 97.6 Mpa and 164 Mpa, which is better than the V-groove. The residual stress varies greatly at the beginning and end of the weld. The reason is similar to the V-groove and is no longer mentioned.

4. X-shaped groove analysis
The total residual deformation of the X-shaped groove is shown in Fig. 8.

The figure shows that the total residual deformation of the X-shaped groove is only 0.43 mm, and the maximum deformation in the X, Y and Z directions is 0.01 mm, 0.06 mm and 0.11 mm, respectively.
It shows that the residual deformation of the X-shaped groove is not large, and the model does not produce obvious warpage, which is consistent with the deformation of the K-shaped groove and the deformation trend is the same. This is due to the fact that the welding structures of X-groove and K-groove are not very different in nature, and both have the properties of deformation and anti-deformation.

In this paper, the horizontal and longitudinal residual stress curves of K-groove weld are directly adjusted, as shown in Fig. 9 and Fig. 10.

From the transverse residual stress curve, it can be seen that the maximum stress in the weld zone is about 181 Mpa, the residual stress at the free end is only 31.6 Mpa, and the stress at the restraint end can reach 225 Mpa. The stress distribution is similar to that of V and K grooves, but the residual stress value is obviously smaller than that of V grooves and slightly higher than that of K grooves. However, the actual output stability of welding equipment in the welding process should be taken into account, as well as the concrete problems. The simulation results of K-groove and X-groove are different, but from the qualitative analysis point of view, both of them have better weld ability and are stronger than V-
groove. From the curve of longitudinal residual stress, it can be seen that most of the residual stresses in the longitudinal center of the weld seam are between 162 Mpa and 189 Mpa, which is better than V-groove, but obviously higher than K-groove. Through the analysis of the process, it is found that the K-groove adopts 45 degree angle and the X-groove adopts 60 degree angle, that is to say, the X-groove weld in this paper and the experiment is larger than the K-groove. This can fully explain the reason why the residual stress of X-shaped groove is slightly larger than that of K-shaped groove.

5. Conclusion
1. The V-groove will produce large residual deformation at the far end and large residual stress around the weld. K-groove and X-groove have better weld ability than V-groove.
2. In view of the difference of K-groove and X-groove angles, the residual stresses of K-groove and X-groove are acceptable from the results of residual deformation and stress, but it is difficult to align the welding wires in the actual welding process of K-groove, which often results in uneven heat input between the two plates. Therefore, considering the welding process and simulation results, combined with experimental data analysis, this paper considers that the optimal shape of groove is X-shaped groove.
3. In order to simplify the process, a V-shaped groove should be made for 12 mm thick steel plate, and a 60 degree groove should be made as far as possible.

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