Influence of welding groove on residual stress and distortion in T-joint weld

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Abstract. T-joint welding is the most common type used in heavy equipment industry. Localized heating and subsequent cooling induce residual stress in the weld process. Service loading overlapped with residual stress influences the strength of the welded structure and leads to premature failure of structure. In this study, finite element analysis is used to study the influence of welding groove on residual stress and distortion in T-joint welding. The simulation consists of sequentially coupled thermal and elastic-plastic analysis using an element birth and death method to model the addition of weld metal to the workpiece. The results of numerical simulation are verified by comparing with experiment from published literature. The results show that welding groove has a significant influence on welding residual stress.

1. Introduction
In heavy equipment industry, T-joint fillet weld is widely used in the manufacturing of complicated structures. Localized heating from welding and subsequent cooling process induce residual stress near the weld bead and produce distortion, both of them have negative effects on fatigue performance of welded structures [1]. Hence, the predication of residual stress and distortion in manufacturing process is of great importance.

Under the development of numerical simulation, finite element analysis validated with a few experiments has become a popular technique for the prediction of residual stress and distortion. In addition, finite element analysis is an effective tool to provide insight on welding residual stress that are difficult to measure experimentally.

A substantial number of numerical simulations and experimental works focusing on T-joint fillet weld with emphasis on predication of residual stress on flange plate is available in the literature. Gannon [2] studied the influence of welding sequences on residual stress and distortion in flat-bar stiffened plates by finite element analysis. The results show that welding sequence do not have a significant influence on the distribution pattern of the residual stress, however it affects the peak values. Fu [3] investigated the welding residual stress and distortion in T-joint weld under different mechanical boundary conditions. To improve the computational efficiency, a combined shell and solid FE model was proposed by Perić [4] to calculate
residual stress distribution. The FE simulation results have proved that the proposed shell and solid element technique is an effective method to predict welding distortions and residual stresses for large structures.

For the convenience of component assembly and welding penetration, the existence of groove is necessary in the component to be welded. Many researchers have developed numerical and experimental methods to investigate the effect of groove on welding residual stress.

Sattari-Far [5] used finite element techniques to study the effects of weld groove shape and weld pass number on welding residual stresses in butt-welded pipes. Akbari [6] investigated the effects of pipe wall-thickness, weld groove angle and root opening distance on welding residual stresses in dissimilar butt-welded pipe. Ye [7] discussed the influences of V, K and X groove joints on residual stress and angular distortion in a SUS304 butt-welded joint numerically and experimentally, the simulation results show that groove type has a significant influence on welding residual stress distribution, angular distortion and width of sensitization region. Teng [8] discussed the effects of welding penetration depth on residual stress and distortion.

Despite a number of researches focusing on prediction of residual stress in T-joint weld and effects of groove type in butt welded plate and pipe on residual stress, few researchers had paid attention to the counterpart in T-joint welds. The present study aims to figure out the effect of weld groove on welding residual stress and distortion in T-joint fillet weld. The welding simulation was carried out by a 3-D thermal elastic plastic finite element method and was validated with experimental measured data published by Fu [9] to prove the effectiveness of proposed computational approach. Welding residual stresses and distortions of welded plates with or without groove are discussed.

2. Finite element modelling

Thermal and structural finite element analysis were performed by using ANSYS parametric design language (APDL) code. For the weak structural to thermal field couplings, the problem is treated as a sequentially coupled thermal elastic-plastic analysis. The simulation consisted of two types of analysis. The first was a transient thermal analysis where the temperature distribution caused by a moving heat source was determined. Next, the thermal element was converted into structural element, the temperature distribution of all nodes from the thermal analysis were applied as loads in the structural analysis.

The same finite element is used in both thermal and mechanical analysis. In the thermal analysis, eight-node thermal brick element (SOLID70) is used, eight-node brick structural element (SOLID185) is used to proceed the elastic plastic analysis. A fine mesh is used in the vicinity of the welding seam and heat affected zone. The element size increases with the increase of distance from welding seam. The smallest element size is 2.5×1×1mm on the basic of mesh sensitivity analysis. The temperature dependent material property is taken from Wang [10] as shown in Fig. 1.

To take the influence of groove into account in numerical simulation, two different finite element models (i.e. without groove, or with two grooves in web plate) were prepared. The welding heat input is the same for the same welding velocity. A single-side metal gas (MIG) welding was employed. Welding sequence and direction are adopted from reference [9]. The geometry of plates to be welded is the same. The flange is 500mm×500mm, and the web is 500mm×300mm, thicknesses of both plates are 12mm. Fig.2 shows the finite element models with K groove and no groove.

2.1 Thermal analysis

Thermal analysis was carried out to determine the temperature distributions of welded plates. The governing equation of the transient heat transfer during welding is given by

\[
\rho c \frac{\partial T}{\partial t}(x,y,z,t) = -\nabla \cdot \vec{q}(x,y,z,t) + Q(x,y,z,t)
\]

(1)

where \( T \), \( t \), \( \vec{q} \) and \( Q \) are the temperature, time, the heat flux vector and internal heat generation rate respectively, \( \rho \) is the density, \( c \) is the specific heat capacity, \( \nabla \) is the spatial gradient operator and \( x \), \( y \) and \( z \) are coordinated in the reference system.
A double semi-ellipsoidal heat source proposed by Goldak [11] was used to model the volumetric heat distribution of the moving welding arc. A combined two half ellipsoidal heat source distribution was adopted to describe the heat distribution, which is expressed by the following equations:

\[
q_f(x, y, z) = \frac{6\sqrt{3}(f_f Q)}{abc_f \pi \sqrt{\pi}} \exp \left( -\frac{3x^2}{a^2} - \frac{3y^2}{b^2} - \frac{3z^2}{c_f^2} \right)
\]

\[
q_r(x, y, z) = \frac{6\sqrt{3}(f_r Q)}{abc_r \pi \sqrt{\pi}} \exp \left( -\frac{3x^2}{a^2} - \frac{3y^2}{b^2} - \frac{3z^2}{c_r^2} \right)
\]

These two equations represent the front part and the rear part of the heat source respectively. In these equations, x, y and z are the local coordinates of the heat source, \(f_f\) and \(f_r\) are the parameters which give the fraction of the heat deposited in the front and the rear parts. Q is the heat input given by \(Q = \eta VI\), where I is the current supplied, V is the voltage across the arc and \(\eta\) is the arc efficiency which is assumed to be 0.85. a, b, \(c_f\) and \(c_r\) refer to the geometry of heat source for the welding being modeled. The heat flux distribution and geometry of heat source is shown in Fig.3. This model suggested that the temperature gradient in the front of the heat source is steeper than the rear one according to experimental experience, an idealized welding pool consistent with experiment could be realized by adjusting the parameters in the equations.

For thermal boundary conditions, convective heat transfer with heat transfer coefficient of \(15 \times 10^{-6} W/ mm^2 \cdot ^\circ C\) and radiation heat transfer with emissivity of 0.51 are applied to all free surfaces. In order to account for heat transfer by convection due to fluid flow in the weld pool, an artificially increased thermal conductivity is assumed for temperature above the melting point [12]. The latent heat of fusion is considered due to the solidification of welding pool.

A conventional technique named element birth and death was used to model the addition of molten weld metal as the welding torch progressed along the workpiece. A full FE model was generated from the beginning, all elements representing filler metal were deactivated by assigning them extremely low stiffness. The deactivated elements were reactivated when they came under the influence of the welding torch.

### 2.2 Mechanical analysis

For the mechanical analysis, the finite element model used in thermal analysis was replaced by the mechanical one. The temperature history calculated in thermal analysis was imposed as a temperature load.
at each time step in the mechanical analysis, which caused the expansion and contraction of the material and plastic deformation occurred where the yield criterion was exceed. The mechanical boundary conditions of the finite element were just to prevent the rigid body motion as shown in Fig. 2.

Mechanical analysis was performed using thermo-elastic-plastic material model with Von Mises yielding criterion and bilinear hardening rule. The mechanical model is based on the solution of three governing partial differential equations of force equilibrium. In tensor notation, these are written as

$$\sigma_{ij,i} + p_j = 0$$  \hspace{1cm} (4)

where $p_j$ is the body force at any point within the volume, $\sigma_{ij}$ is stress tensor. The total strain increment at the integration point as a function of elastic, plastic strain and thermal strain is governed by

$$de = d\varepsilon^e + d\varepsilon^p + d\varepsilon^{th}$$  \hspace{1cm} (5)

where $d\varepsilon^e$, $d\varepsilon^p$ and $d\varepsilon^{th}$ are the elastic, plastic and thermal strain increments respectively.

A user-defined subroutine by using element birth and death technique was utilized to control non-convergence problem in the structural analysis. The temperature of every element in welding bead was checked, an element was deactivated if the temperature exceeded the melting point, it was reactivated in the subsequent cooling process.

3. Verification of the finite element model

The finite element model was validated by comparison of predicted residual stress with experimental results from Fu [9]. The measured points are alone path AB, which is the middle line in the flange and perpendicular with welding line as shown in Fig. 2. The comparison of results from finite element analysis and experiment are given in Fig.4, it can be seen that, for both longitudinal and transverse residual stresses, the finite element predictions show good agreements with experiment measurements. The welding effects on the finial residual stress becomes weaker as the distance to the welding line increases. In addition, it can be seen that the transverse residual stress on the right is higher than the left. This is due to that the right welding seam was welded earlier than left one. The temperature distribution of first welding seam has an effect of preheating on the later one. It functions as thermal tension to the later one to be welded and mitigates the transverse residual stress.

The results of numerical simulation show that an extremely large tensile residual stress occurs near the weld bead and it turns into compressive stress away from the welding bead in longitudinal stress. The maximum longitudinal residual stress reaches yield strength, and the distribution in the path AB shows a M pattern. The transverse residual stress is influenced by welding sequence, which conforms with the proposition of Fu and Teng [9, 13].

4. Results and discussion

![Figure 3: Double ellipsoid heat source model](image1)

![Figure 4: Results comparison of finite element analysis and experiment](image2)
4.1 Results of thermal analysis
The welding pool is the fusion zone where temperature exceeds 1450°C in the numerical simulation, the welding pool size from numerical simulation approach welding groove geometry size, which is the prerequisite to predict reasonable residual stresses and distortions. The welding pool of no groove and K groove are shown in Fig.5. The geometry size of welding pool without groove predicted matches with the experiment measured by Fu [9]. The fusion zone of K groove welding indicates that the welding penetration quality is guaranteed by enough penetration depth and overlap with groove shape.

4.2 Results of structural analysis
The distribution of longitudinal residual stress along path AB is shown in Fig.6, it can be seen that the tensile residual stress of K groove is larger than without groove welding. The tensile residual stress region for without groove is wider than that of K groove welding. However, the compressive residual stress for the case of without groove welding is larger.

Fig.7 shows the distribution of transverse residual stress along path AB for the different cases. It shows that both the magnitude and distribution pattern of transverse residual stress are more sensitive to the existence of groove than longitudinal residual stress. The width of high tensile transverse residual stress is opposite with counterpart in longitudinal residual stress, tensile residual stress region for without groove is narrower than K groove welding. Besides, the location of peak value in transverse residual stress is different from K groove.

The three-dimensional distribution of longitudinal residual stress on the right lower surface of the flange in K groove and without groove welding are shown in Fig.8. It can be seen that longitudinal residual stresses in K groove welding are larger and show less fluctuation, and tensile residual stresses are concentrated in welding bead. The residual stresses in no groove welding shows more volatility, and the change of residual stress from tensile to compressive is less sharp.

The existence of groove in welding influences the magnitude of heat input, the K groove welding represent larger penetration depth, which corresponds to a concentration in heat input or an increase of heat input in local zone. The consequences of heat input increase leads to the reduction of temperature variation of upper and lower surface of the flange, and the concentration of heat affected zone. Therefore, the K groove welding shows larger longitudinal tensile residual stress and narrower tensile stress zone. In addition, the concentration of heat input contributes to higher temperature zone, such as the heat input of the first welding seam strongly affects the second seam, which results in accumulation of temperature and larger transverse tensile residual stress.

The longitudinal and transverse residual stresses in web plate alone path CD are shown in Figs.9-10, it can be seen that longitudinal residual stress in the web is similar with the flange, the high tensile residual stress region is narrower in K groove welding. Both of K groove and no groove welding show compressive
transverse residual stress near the welding bead, the compressive residual stress is larger in K groove welding for more heat input on web plate.

**Figure.6** Longitudinal residual stress distribution for different groove

**Figure.7** Transverse residual stress distribution for different groove

**Figure.8** 3D longitudinal residual stress distribution

**Figure.9** Longitudinal residual stress in web

**Figure.10** Transverse residual stress in web

4.3 Effects of groove on distortion

Fig.11 compares the vertical deflection of the flange along path AB, the results of finite element analysis in no groove welding are compared with measured experiment results of literature [9], it shows that the simulated results match the corresponding experiment well. The discrepancy between K groove and no
groove welding is not significant, the vertical deflection of no groove is slightly larger than K groove welding, which comes from the different location of heat source on the flange.

**Figure 11** Comparison of vertical deflection of the flange

5. Conclusion

This research employs the finite element analysis to evaluate the effects of groove on residual stress and distortions in T-joint welding. Thermal elastic-plastic analysis to predict the temperature distribution, residual stress and vertical deflection distribution, the numerical results are in good agreement with experiment measurement results from published literature, which indicates that the current numerical method is suitable to the prediction of welding residual stress and distortion. The existence of groove in T-joint welding has a significant influence on residual stress and distortion. The peak value of longitudinal and transverse residual stress in K groove welding is higher than those in no groove welding, the higher region of residual stress is narrower in K groove welding. The influence of groove on vertical deflection in T-joint welding is not significant.

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