Effect of welding sequence on residual stress and deformation of Mg alloy fillet welds

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Abstract: In order to investigate the effect of welding sequence on stress distribution and deformation of Mg alloy fillet welds, DE-GMAW modified Gaussian heat source model established by MSC. Marc software was applied to the numerical simulation analysis of welding temperature field and stress field and proved by measurement of residual stress by blind hole method. The results indicated that the deformation and residual stress were lowest according to the sequence of welding fillet welds from the head of cylinder to the end on one side first and then welding in the opposite on the other side. The trend of residual stress measurement results was consistent with numerical simulation analysis results with 10% error, which provided theoretical support for stress distribution and deformation control of Mg alloy fillet welds.

1. INTRODUCTION

Welding residual stress was the major cause for fatigue fracture and stress corrosion cracking in welded joint, which partly reduced the bearing capacity, stability and service life of welded products\cite{1}. For thin-wall welded structure welding, the deformation induced by welding residual stress greatly effected the quality and reliability. Therefore, optimizing welding process has important practical significance for reducing the deformation and residual stress of thin-wall welded structure. Thin-wall welded structure of Mg alloy has been extensively applied in the field of space equipment, which was mainly carried out through physical experiments previously\cite{2}. With the development and application of numerical simulation technology in welding field, finite element simulation software has been widely applied in predicting deformation and optimizing welding process for thin-wall welded structure\cite{3}.

Amirreza khoshroyan\cite{4} studied the distribution of residual stress and deformation during the MIG welding of 6061-T6 aluminum alloy stiffener plate in two different orders by using a three-dimensional thermo mechanical coupled finite element model. The results show that the increase of welding speed can reduce the longitudinal deflection and transverse contraction of the plate, reduce the lateral deflection of the stiffener, but increase the maximum longitudinal tensile stress of the stiffener plate. The change of welding sequence changes the deformation distribution of the aluminum alloy stiffener plate, while the longitudinal residual stress distribution has no obvious change. Deng\cite{5} used numerical
simulation method to study the residual stress distribution characteristics of multi pass welding of stainless steel thick plate. The influence of welding sequence on the final residual stress was confirmed by numerical simulation. The welding sequence has a significant effect on the longitudinal and transverse residual stresses. The welding sequence not only has a significant effect on the magnitude of the peak stress, but also greatly changes the stress distribution. Li Can [6] establishes the finite element model based on the Thermoelastic-Plastic finite element method combined with the thermo mechanical coupling algorithm, and adopts ABAQUS software is used to simulate the welding of 6061-T6 aluminum alloy rectangular section. The influence of different welding sequence on the residual stress and welding deformation of aluminum alloy rectangular section is simulated. The results show that the maximum residual stress on the plane where the welding seam is located is tensile stress. Choosing symmetrical welding process can effectively reduce the residual stress after welding of aluminum alloy section and enhance the stability of weldment after welding, and the welding deformation can be reduced by starting from a long welding path.

The results mentioned above indicated that welding sequence have great effects on welding residual stress and deformation of joints. However most of the research focused on joint type and there are litter investigation on the stress and deformation mechanism of fillet welds especially for DE-GMAW (Double Electrode-Gas Metal Arc Welding) under high heat input conditions. The distribution of deformation and stress of fillet welds is more complicated than butt welds simulation. The DE-GMAW welding process of AZ31B Mg alloy fillet welds between wing plates and cylinder was simulated by MSC.Marc software investigated the distribution law of deformation and residual stress under different welding sequences after fillet welds welding, which provided theoretical support for fillet welds welding operation under high heat input.

2. ESTABLISHMENT OF WELDING FINITE ELEMENT MODEL

2.1 Experiments Materials and Welding Process

Table 1 lists the chemical composition of experimental base metal of AZ31B Mg alloy, the filler metal of φ1.2 mm has similar chemical composition with base metal. The shielding gas for both TIG and MIG was 100% Ar at a rate 10 mL/min and 16 mL/min of flow respectively. The thickness of wing plate is 3 mm, the thickness of cylinder is 6mm with φ200 mm diameter and the length of filler weld is 360 mm. Pin type link is used due to thin wing plate without finished groove. Single layer single pass fillet weld between wing plate and cylinder is welded by DE-GMAW process. Table 2 lists the welding parameters.

| TABLE I. CHEMICAL COMPOSITION OF AZ31B MAGNESIUM ALLOY (wt%, %) |
|-------------------|---|---|---|---|---|---|---|
| Al | Zn | Mn | Si | Cu | Ni | Fe | Mg |
| 3.20 | 0.86 | 0.36 | 0.021 | 0.0022 | 0.00056 | 0.0018 | balance |

| TABLE II. WELDING PARAMETERS |
|-----------------------------|
| Total current/A | Main circuit /A | Current bypass circuit/A | Main voltage /V | Current bypass voltage /V | Welding speed /(m·min⁻¹) |
| 200 | 115 | 85 | 26 | 15 | 2.56 |

2.2 Numerical Model

In order to ensure the accuracy of welding simulated results, finite model was established based on 1:1
ratio. Meshes were divided by transition having different distribution that the meshes were divided densely near the weld and HAZ to ensure the accuracy and the meshes were divided sparsely in other regions to reduce the amount of calculation. Thermal mechanical coupling calculation method was selected. According to statistical analysis, there are 13215 units and 18003 nodes with least units of 1.85 in side length. Fig.1 show the model and detail view.

Fig. 1 Model of finite element mesh

2.3 Material Properties
Materials properties are crucial to ensure the accuracy of welding simulated results. Fig.2 show the main thermal-physical properties of based metal AZ31B Mg alloy in this study including thermal conductivity, specific heat capacity, density, thermal expansion coefficient, elastic modulus, Poisson's ratio and shear modulus etc. The other properties select average constants.

Fig.2 Thermophysical properties of AZ31B magnesium alloy

2.4 Heat Source Model
Welding heat source models mainly include point heat source model, line heat source model, surface heat source model, Gauss heat source model and double ellipsoid heat source model. The welding heat source model in this study is modified Gauss heat source model after adjustment of action form due to the difference between DE-GMAW and traditional welding process. The total current I for DE-GMAW process includes main current I1 and loop current I2, namely I=I1+I2. I1 acts directly on base metal, while I2 melts wires. Therefore, welding heat source model for DE-GMAW can be divided into three regions based on the heat distribution as shown in Fig.3. Region 1 represents the arcing area of TIG and Region 3 represents the arcing area of MIG, while Region 2 represents the area under the action of superpose by TIG and MIG. The thermal efficiency of loop arc is designed as 1.5K. The expression for heat distribution was established as equation 1 based on the reasons mentioned above.
Fig. 3 Model of heat source

\[ q = \frac{3Q_1}{\pi R_1^2} \exp \left(-\frac{3r_1^2}{R_1^2}\right) + \frac{3Q_2}{\pi R_2^2} \exp \left(-\frac{3r_2^2}{R_2^2}\right) \]  

(1)

In the formula:
- \( R_1 \) and \( R_2 \) represent the heating radius of TIG and MIG heat source respectively;
- \( r_1 \) and \( r_2 \) represents the distance from the center of TIG and MIG heat source respectively;
- \( Q_1 \) and \( Q_2 \) represent the actual power of TIG and MIG respectively.

Effective heating radius of arc was set to 5mm and 6mm respectively in simulation. \( Q_1 \) and \( Q_2 \) can be expressed as equation 2:

\[ Q_1 = \eta_1 U_1 I_1 \quad Q_2 = \eta_2 U_2 I_2 \]  

(2)

In the formula:
- \( \eta_1 \) and \( \eta_2 \) represent the thermal efficiency of thermal efficiency TIG and MIG, which was 0.7 in this study.
- \( U_1 \) and \( U_2 \) represent the voltage of main circuit and bypass arc respectively;
- \( I_1 \) and \( I_2 \) represent the current of main circuit and bypass arc respectively.

Welding Path and Sequence

Fig. 4 show the welding path based on comprehensive consideration about the simulation feasibility and the proximity of simulation process to actual welding operations. Only two fillet welds for fixing and joining wing plate and cylinder was investigated for the uniform distribution of 4 wing plate surrounding the cylinder and was marked as “weld ① and weld ②” respectively.

Fig. 4 Path layout diagram

4 wing uniformly with size of 360 mm×200 mm×3 mm distributed along the circumferential direction of cylinder. In order to clearly demonstrate the welding sequence, provisions made as following: “+” represents the direction from the head to the end of cylinder, “-” represents the direction...
from the end to the head of cylinder. Point A, B, C and D at 1mm from fusion line were analyzed. Point A is 120mm distant from the end of cylinder and point B is 120mm distant from A. The distance from point C to D is the length of wing plate about 360mm. Fig. 5 shows the welding path and the location of selected points.

Four welding sequences were simulated:
Sequence 1 is +①+②: simultaneously weld two sides fillet welds according to “+” direction;
Sequence 2 is +①→+②: Firstly weld one side welds according to “+” direction, then weld the other side welds according to “+” direction;
Sequence 3 is +①→-②: simultaneously weld two sides fillet welds of one wing plate according to “+” and “-” direction
Sequence 4 is +①→-②: Firstly weld one side welds according to “+” direction, then weld the other side welds according to “-” direction;

2.5 Initial and Boundary Conditions
In the welding process, the heat loss is mainly caused by convection and radiation, and the radiation heat loss is larger than convection. The higher the temperature is, the stronger the radiation heat transfer effect is, and the more obvious the heat loss is. The heat loss can expressed as:

\[ q_a = a \left( T_a - T_s \right) \]  
(3)

In the formula:
Ta and Ts represents the temperature of the weldment surface and surrounding medium respectively; 
a is surface heat transfer coefficient, \( a = a_c + a_r \); \( a_c \) is convective heat transfer coefficient; \( a_r \) is radiation heat transfer coefficient;
The initial temperature of the whole model is specified as 20 °C. In order to simulate the stress and strain during the actual welding, x-constraint is applied on both sides of the weldment according to the use of the fixture, and fixed constraint is applied at the beginning of the fillet weld to simulate the constraint effect between the weldments. In this way, the loading boundary conditions can not only ensure the rigid displacement of the model but also prevent the free release and deformation of the stress during the welding process.

3. ANALYSIS OF SIMULATION RESULTS OF TEMPERATURE FIELD AND STRESS FIELD

3.1 Analysis of temperature field results
Fig. 6 shows the thermal cycle curve of point A and B under 4 welding sequences. When welding according sequence 2 and 4, point A and B experienced heat source action two times, so the curve has two peaks, one of which is higher than the other. This is due to the high peak temperature caused by the
direct action of heat source on the joint when welding the side fillet weld. When welding the fillet weld on the other side, the temperature of the joint is the heat conduction effect of the welding heat source on that side. Because the welding sequence 1 is that two welding heat sources move in the same direction at the same time, which is equivalent to that observation points a and B experience two heat sources, and the heat input is large, so its peak temperature is the highest. Because the heat source acts on point a later than point B, its temperature rise is slow, and the cooling speed is low. In welding sequence 3, the movement process of the two welding heat sources is the same, so the thermal cycle curve is also the same.

(a)

(b)

(c)
3.2 Simulation and Analysis of Stress and Deformation

Welding strain field are calculated coupled with the temperature field simulation results. Fig. 7 shows the thermal deformation after the deformation area is enlarged 15 times. Under the high temperature action of welding arc, the unmelted base metal at room temperature will restrain the melted metal in the welding joint area, and the resulting compressive stress will lead to plastic deformation. It can be indicated from Fig. 7 that although the four welding sequences are different, the deformation trend is all that the flange shrinks along the z-axis direction and offsets along the y-axis direction. The residual deformation of welding sequence 1 is 3.221 mm, and sequence 2 is 2.610 mm. The maximum residual deformation according to welding sequence 3 is 3.573 mm. This is due to the large heat input, the large amount of deformation on both sides, and the large rigidity of the weld formed by cooling when welding along the "-" and "+" directions at the same time, which results in the small amount of deformation on both sides offset each other to a certain extent, so the large amount of shrinkage deformation is generated when using the sequential welding flange.
The residual deformation according to the fourth welding sequence is the smallest, only 2.423 mm. This is due to the relatively small welding heat input and short residence time above the high temperature according to "+" and "-" directions to weld the fillet welds on both sides of the wing plate. When one side fillet weld is welded, the expansion and distortion of the flange are small. In addition,
when the other side of the fillet weld is welded, the deformation generated by the fillet weld is offset with the existing residual deformation to a certain extent.

3.3 Residual Stress Analysis

Because the deformation of the flange and the cylinder is mainly the stay of the cylinder and the contraction of the flange, the distribution of the transverse residual stress near the fillet weld is analyzed. The analysis path in Fig. 8 is on the straight line where points A and B are located. It can be seen that the residual stress of the weld and its adjacent area is mainly tensile stress. The residual stress at the starting point of welding is the largest, which is due to the bending effect of the weldment, the smaller constraint of the first fillet weld and the larger influence of welding deformation. The welding sequence 2 and 4 are welding the welds on both sides of the wing plate respectively, and the change trend of the transverse residual stress curve of the two sequences is similar. This is because the welding process of the first fillet weld in the two welding sequences has a pre-stretching and heat treatment effect on the second fillet weld, which reduces the compression plastic deformation and transverse residual stress of the second weld metal. Because the welding sequence 1 and 3 are to weld the fillet welds on both sides of the wing plate at the same time, the heat input is large, resulting in uniform distribution of the transverse residual stress.

![Fig.8 Transverse residual stress](image)

From the perspective of softening effect, due to the constraint of the welding direction of fillet weld, the transverse residual stress often reaches or exceeds the yield strength. When considering the material softening effect, the yield strength of the material decreases during the welding process, and the corresponding longitudinal residual stress also decreases. On the other hand, for the longitudinal residual stress, the yield strength is not the main dominant factor. Therefore, in the process of simulation calculation, the longitudinal residual stress is not sensitive to the softening effect.

4. EXPERIMENTAL VERIFICATION

Blind hole method is used to verify the simulation results. Strain gauge is used to test the residual stress of fillet weld obtained from welding sequence 1, and the welding slag and spatter on the surface of fillet weld are cleaned to make it clear that it is clean and flat to ensure that strain gauge can be effectively attached to the surface of fillet weld. The distance between the measuring points is 20 mm, 19 test points are selected, as shown in Fig. 9. At the same time, the data of transverse residual stress of the same path are collected for the simulation results. The test value is compared with the simulation value, and the results are shown in Fig. 10. It can be seen from the figure that the peak of residual stress occurs at the starting point of welding. In the process of simulation, it is found that: in the actual welding operation, because the TIG arc, MIG arc and their composite parts are inclined and move along the welding direction, the heat flow of the arc is asymmetric distribution, and the heating area is not a circle symmetrical about the arc centerline, but an ellipse, and before and after the arc The ellipse of AZ31B
magnesium alloy plate is also different, so the use of heat source needs to be further studied. At the same time, the thin mesh division of AZ31B magnesium alloy plate is not small enough, and the physical model established needs to be further improved. The above factors are the main reasons for the deviation between the actual welding operation and simulation.

![Fig.9 Test point location](image)

![Fig.10 Sequence 3 comparison between simulated value and measure value](image)

5. CONCLUSIONS

a). Because the welding sequence 1 is that two welding heat sources move in the same direction at the same time and the heat input is large, its peak temperature is the highest. Because the heat source acts on point a later than point B, its temperature rises slowly and its cooling speed is low. In welding sequence 3, the movement process of the two welding heat sources is the same, so the thermal cycle curve is also the same.

b). The simulation results of fillet weld strain show that the maximum residual deformation of welding sequence 3 is 3.573 mm, and the minimum residual deformation of welding sequence 4 is 2.423 mm.

c). The simulation results of residual stress show that the transverse residual stress at the starting point of the four welding sequences is relatively large, while the welding sequences 1 and 3 are simultaneous welding of the fillet welds on both sides of the wing plate, so the residual stress is relatively large. The fourth welding sequence has the least residual stress, which is the most advantageous for controlling the residual stress in the welding process of AZ31B magnesium alloy fillet weld.

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