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RESEARCH ARTICLE

STUDY ON RESIDUAL STRESS CHARACTERISTICS OF VERTICAL WELDED JOINTS

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ABSTRACT

With the acceleration of industrial process, the requirement of welding quality becomes higher, especially the residual stress. For vertical welded joints, a weld model is constructed in this paper, which includes four layers on the inside and outside. Eight different welding sequences are arranged and combined. Based on the finite element method of thermo-mechanical coupling, the variation rules of residual stress in vertical and horizontal directions are calculated. The results show that the maximum residual stress in the weld is distributed in the superheated zone, not in the weld zone. In addition, the mechanism of stress change and the method of improving welding quality are analyzed.

INTRODUCTION

Welding is one of the most important means in mechanical processing. According to statistics, more than 30% parts of construction machinery need welding technology. Welding is a typical hot working method. Thermal stress and thermal deformation are inevitable in the process. However, if the welding residual stress is studied by efficient and reasonable technical means and analyzed and predicted based on specific models, the performance and service life of the welded parts can be greatly improved. During the welding process, the thermal stress, phase transformation stress and processing stress exceed the yield limit, so that there are unresolved stresses in the welded parts after cooling. In this way, the residual stress in the element after cooling is called residual welding stress. The inhomogeneous temperature field in welding process and the local plastic deformation and different specific volume structure caused by it are the basic reasons for welding stress and deformation. Welding residual stress is the main cause of welding deformation and cracking. Welding deformation endangers shape and dimension tolerance, joint installation deviation and groove clearance in the manufacturing process, which makes the manufacturing process more difficult. The welding residual stress can make the weld, especially the positioning weld, partially or completely disconnected. At the same time, welding residual stress may cause brittle fracture of the structure, tensile residual stress will reduce the fatigue strength and corrosion resistance, and compressive residual stress will reduce the stability limit. Therefore, welding residual stress has always been one of the key issues in the field of welding. According to engineering experience, the welding quality of vertical joints can be effectively improved by technological sequence, that is, welding direction has a very important influence on residual stress. In this paper, the residual stresses of welded joints are analyzed based on vertical joints. At present, the commonly used welding method is to realize the welding of both ends of the work piece, and finally to complete the welding of the middle section. The welding sequence can effectively reduce the residual stress in a part of the weld. In this paper, a variety of welding sequence is set up, and the internal influence law of different process schemes on welding performance is compared and analyzed.

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Welding Technology and Analysis Scheme

Process plan design

In engineering, welding process often needs to combine manual operation with mechanical operation. For vertical welded joints, manual welding positioning and mechanical welding are generally used. For the convenience of analysis, there are four welds in this paper, including inner and outer welds. The groove of the weld is 45 degrees, as shown in Fig.1. In the formulation of welding sequence, the worker usually lacks theoretical guidance based on his years of work experience. If we do not pay attention to basic research for a long time, it is not conducive to the development of efficient production, and it is difficult to achieve process optimization.

Therefore, the welding direction of four layers is designed in this paper. The numbering of layer is shown in Fig.2. Four layer heat sources (Gu, 2014) include two inner layers and two outer layers. The inner layers are layer 1 and layer 2, and the outer layers are layer 3 and layer 4. By arranging and combining the welding directions of four beads of vertical joint, eight process schemes are finally obtained, as shown in Table 1. Among them, ⟶ is from left to right and ⟵ is from right to left.

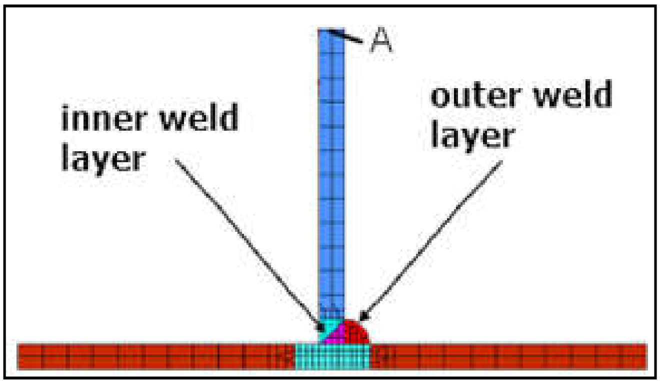

Fig.1. Schematic diagram of weld bead layer

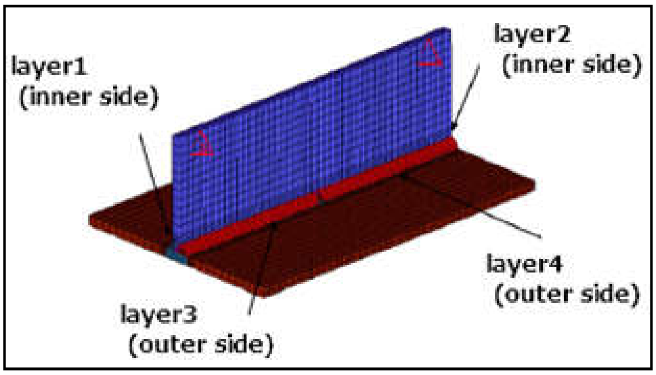

Fig. 2. Weld number

Table 1. Welding sequence combination scheme

combining number	weld direction			
	layer 1	layer 2	layer 3	layer 4
1	→	→	→	→
2	→	→	←	←
3	→	→	→	←
4	→	←	←	→
5	→	←	←	←
6	←	→	←	←
7	←	←	→	←
8	←	←	←	→

Analysis scheme design

Through the numerical simulation of the eight welding process schemes, the influence of welding process on residual thermal stress can be obtained, so as to improve the quality and performance of welded joint and provide the best welding direction. In this paper, the calculation of residual thermal stress is mainly based on thermo-mechanical coupling method, and the simulation method is finite element calculation (Li *et al*., 2016). In the finite element calculation, the quality of the mesh has an important influence on the accuracy of the results. Therefore, the hexahedral mesh with small size and low distortion should be adopted as far as possible. If the hexahedral mesh is partitioned forcibly, the mesh deformation will be serious, but the reliability of calculation will be reduced. Therefore, the mesh needs to be refined and optimized continuously. Hexahedron and tetrahedron can be used to complete the transition of the structure. Thermo-mechanical coupling mainly refers to the coupling of temperature field and displacement field, i.e. the interaction and influence between two physical fields are realized by coupling equation. Compared with independent field analysis, it is more in line with the real boundary conditions, so the calculation accuracy can be guaranteed.

Analysis of Residual Stress Characteristics

Trend analysis of stress change

The variation of the vertical and horizontal directions of residual stress is shown in Fig. 3-Fig.5. The position of point A is shown in Figure 1. As can be seen from the figure, the residual thermal stresses at different nodes show similar trends in vertical and horizontal directions, but there are significant differences in numerical values. In the eight process schemes, when the welding sequence from left to right is adopted for layer 1 and layer 3, smaller residual thermal stress can be obtained. Similarly, if layer 2 and layer 4 are in right-to-left order, smaller residual thermal stresses can also be obtained.

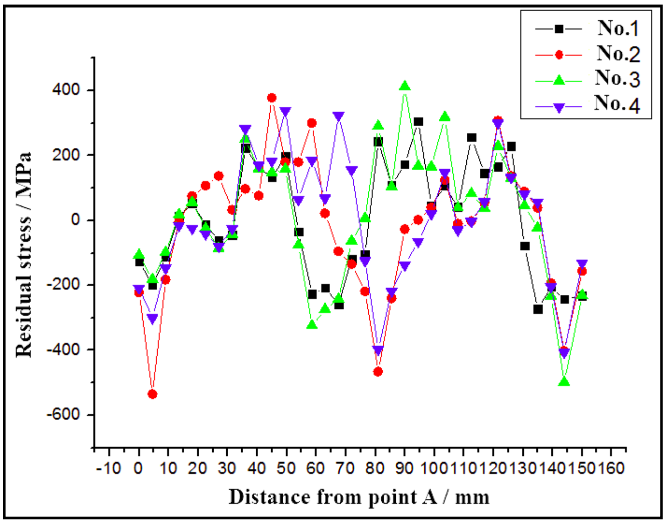

Fig.3. Variation of residual stress in vertical direction (No.1-No.4)

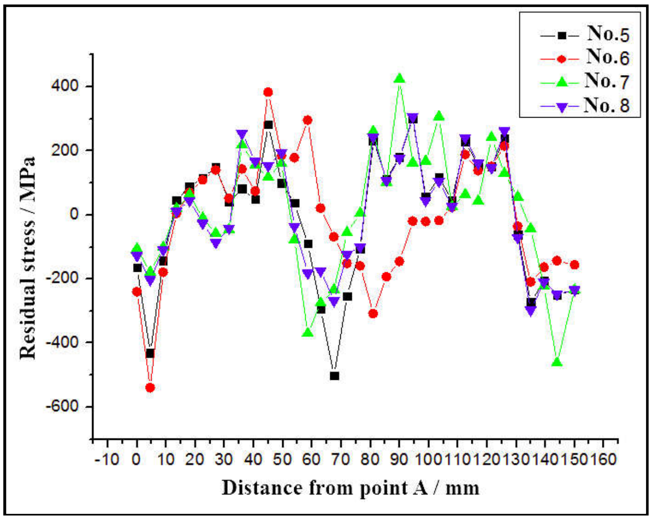

Fig.4. Variation of residual stress in vertical direction (No.5-No.8)

It can be seen from the analysis results that better residual stress can be obtained when the third welding scheme is adopted. In other words, the thermal deformation will be smaller and the strength and plasticity of the welded joint will be better. In order to further reduce the welding deformation (Cheng and Liao, 2015), the anti-deformation welding method can be used on the basis of scheme 3. Through simulation analysis, it is found that the welding deformation can be reduced by more than 10%.

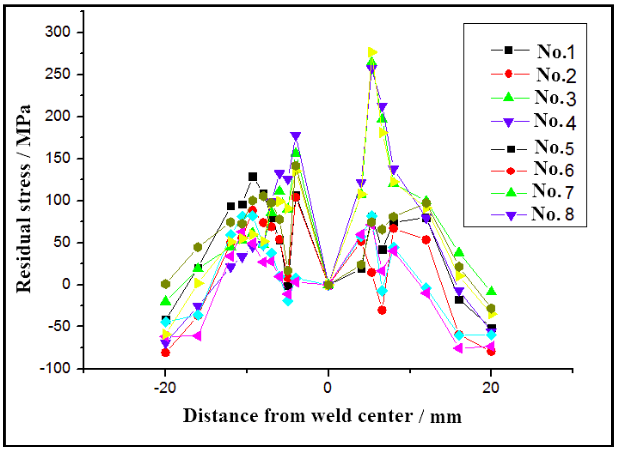

Fig. 5. Variation of residual stress in horizontal direction (No.1-No.8)

Causes of stress change

Welding is a fast heat transfer process. The change of residual stress in welded joint is not only affected by its physical properties, but also related to the type of welding heat source and welding method. It has complex and non-linear characteristics. In the vertical joint welding, the temperature field in the four beads is very uneven, and the internal stress exceeds the yield strength of the material itself, that is, the plastic deformation after welding (Fu and Bai, 2007). From the simulation results, it can be seen that the maximum residual thermal stress is not distributed with the weld center, but a certain distance from the center of the superheated zone (horizontal distance from the weld center (±10 mm), vertical distance from the weld center 40 mm). The reason is that because of the large temperature gradient and no recrystallization of liquid metals in this region, the grain size is large (Wang, 2015), and the internal stress caused by lattice distortion is large, which cannot be recovered in a short time. During welding, the welding area is heated and expanded locally. Because the restraint from the far part of the weld cannot extend freely, plastic deformation occurs in the weld area under compression. In subsequent cooling, the weld area shrinks shorter than other parts, and cannot be freely shortened under the constraints of the far part from the weld area, so the residual tension stress is generated under tension, while the other parts are subjected to residual compressive stress (Liu, 2014). In the absence of external constraints, welding residual stress is self-balanced.

Residual stress control scheme

Residual stress is one of the most important factors affecting the quality of welded joints, which cannot be ignored. Generally, there are two main ways to reduce the residual thermal stress of joints: joint structure optimization and welding process improvement. According to the analysis of vertical joint, good welding effect can be obtained by adjusting welding sequence and combining with reverse deformation method. According to the analysis results, pre-weld heat treatment and post-weld heat treatment are mainly applied to the places where the residual thermal stress is high. The method is low cost, simple and practical, and easy to operate. It has good application effect in actual production. If the material is brittle, it is impossible to homogenize the stress in the component with the increase of external force because the material cannot be plastic deformed. The peak stress will continue to increase until the yield limit of the material is reached, local failure will occur, and ultimately lead to the fracture of the whole component. The existence of residual stress in brittle materials will reduce the bearing capacity and lead to fracture. For plastic materials, the effect of three-dimensional tensile residual stress exists in low temperature environment, which will hinder the plastic deformation and greatly reduce the bearing capacity of components. For some closed welds and heavy work pieces, the method of reducing joint stiffness can be chosen. The purpose of reducing joint stiffness is to obtain enough free shrinkage of weld and reduce residual stress. Heating stress reduction zone is an effective method.

The heat in the heating zone drives the weld to produce deformation opposite to the contraction direction of the weld, and then to weld. When the weld is cooled, the shrinkage direction of the heating stress relief zone is the same as that of the weld, that is, the weld can obtain a certain degree of free shrinkage, resulting in the reduction of residual stress. This method can be used to weld some welding parts with larger rigidity. Tensile plastic deformation occurs in the tensile stress zone under the action of external load, which is opposite to the direction of compressive plastic deformation occurring during welding. Obviously, the higher the loading stress is, the more the compressive plastic deformation is offset and the more thoroughly the residual stress is eliminated. Elimination of residual stress by mechanical stretching is of special significance for welded products made of metal materials with good plasticity. Post weld heat treatment is to uniformly heat the whole or part of the welded component to a suitable temperature, at which a predetermined time is maintained, and then make it uniformly cooled to room temperature. In order to eliminate residual stress in heat treatment, the factors affecting residual stress are heat treatment temperature, holding time, heating and cooling speed, heating method and heating range. It is well known that the residual stress will be reduced to the yield stress at the heating temperature during the heating process. Therefore, the selection of the heating temperature is very important. The main reason for the decrease of residual stress is that the yield limit of metal materials decreases with the increase of temperature, and the stress relaxation occurs during heat preservation. However, in actual welded joints, due to the uneven distribution of residual stresses, more complex behavior is shown in the treatment process.

Conclusion

In this paper, the effect of welding sequence on residual thermal stress in welding process is studied. Through the analysis of phenomena and principle of residual thermal stress variation, it can be seen that smaller residual stress can be obtained by using right, right, right and left welding sequence. Under the same parameters, the improvement of welding process can get better welding quality. The maximum residual thermal stress is not the center of the weld, but the superheated zone at a certain distance from the weld, either vertically or horizontally. Reasonable pre-weld and post-weld heat treatment can effectively reduce the incidence of hot cracks and achieve good economic benefits.

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