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CONTROL OF ROOT PASS STRESS BY TWO-SIDED ARC WELDING FOR THICK PLATE OF HIGH STRENGTH STEEL

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Abstract. For thick plate of high-strength steel, it is extremely important to control the residual stress. A new method for thick plate which does not require back gouging – two-sided arc welding – is adopted to control stress. Root pass adopts asymmetrical two-sided gas tungsten arc welding with wire feed in vertical up welding. The key of controlling stress for this method is to determine the arc distance and welding parameters of two-sided arcs. The effects of arc distance between fore and rear torches and heat inputs on the stress are investigated through experiments and numerical simulation. The calculated results are in a good agreement with the experimental results. The influence mechanism on welding stress of the arc distance and heat input is obtained. Research results show that selecting proper arc distance and regulating heat input of two arcs control effectively stresses.

1. INTRODUCTION

Welding structure of thick plate of high strength steel is widely used in high-pressure vessel, heavy machinery and so on. It is well known that if the thickness of the welding structure is thicker and the strength of it is higher, the residual stress will be higher and will be difficulty to control and reduce. So it is extremely important to control residual stress of the welding processes which directly influence the quality and productivity in manufacturing industry [1]. To reduce residual stress, many investigators in the world have deeply investigated on this. In 1994, Guan adopted heat sinking method to realize Low stress non-distortion in welding thin panels [2]. Dong found the residual stress during repair welding is reduced through presetting a proper temperature field on the plate [3]. Lin adopted the parallel heating welding to reduce residual stress in thin plate of stainless steel [4]. Zhang adopt DSAW to find the residual stresses lower than conventional method [5]. Above methods are applied in sheet plates. However, for large thick plate of high strength steel, to control stress has not reported at present.

For welding structure of thick plate of high strength steel, it is strict with welding heat input [6,7]. Two-sided TIG arc with wire feed in vertical position welding need keep a proper distance to control the temperature field under certain heat input. If arc distance and heat input are unsuitable, high stress will be generated. In this study, experiments are carried out to investigate the thermal character and the effects of arc distance on the stress. Meanwhile, numerical simulation is used to predict the transient temperature and welding stress with

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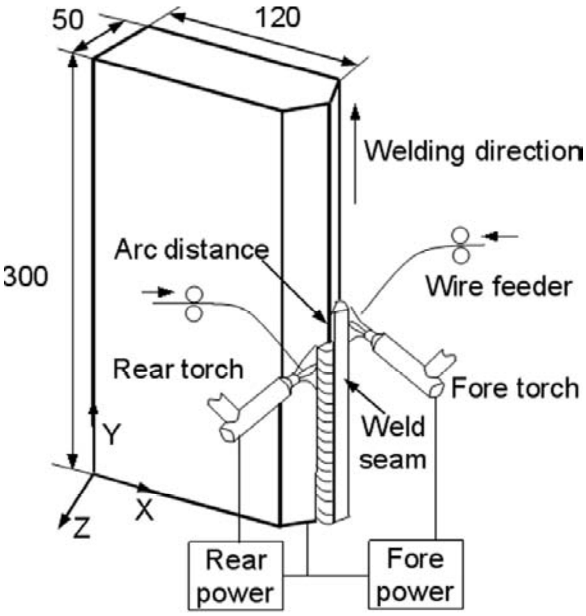

Fig. 1. Schematic diagram of asymmetric two-sided root pass welding.

different arc distance. The influence of heat input on the stress field is also investigated.

2. DSAW EXPERIMENTAL PROCEDURES

Backing run adopts two-sided tungsten inert gas arc welding (TIG) with wire feeder at vertical position as shown in Fig. 1. Two TIG torches are laid on the two sides of the plate and supplied by two powers individually. Fore and rear torches keep an arc distance in vertical up welding. Other passes adopt two-sided gas metal arc welding (GMAW). Two MAG torches are symmetrically laid on both sides of the plate and supplied by two powers individually [5]. The direction of *Y* is the welding direction, *Z* is the thickness direction, and *X* is perpendicular to the welding direction (width direction).

To verify the numerical results and understand the thermal characteristics, high strength steel plates 60° in butt groove angle, 3mm in root gap, 50 mm in thickness, 240 mm in width, and 300 mm in length as shown in Fig. 1, is welded at vertical position by using the asymmetric DSAW process at an arc distance 45 mm. Welding parameter *Q0* is shown in Table1 in the experiment. The magnitude of heat input is characterized by a welding speed 7.5 $cm \cdot min^{-1}$, welding voltage 14.2 V, welding current 155 A. The temperature is measured by the two platinum-rhodium thermo-couples which are distributed near fusion area on the two-sided surface of plate individually.

For double-sided arc multi-pass welding, the root pass stress is the highest among other passes [8]. The cold crack appears usually in root pass. Therefore, to control the stress of root pass welding is the key step. Because it is difficulty for the stress of root pass to measure, only the temperature fields are measured by thermocouples to verify the numerical model. The thermal cycles of two-sided arc welding in root pass are obtained through two platinum-rhodium thermocouples located near the fusion zone on both sides of the plates.

3. FINITE ELEMENT MODEL

Welding transient temperature and residual stress distribution is calculated by MSC.MARC finite element techniques. In this section, a thermal elastic plastic computational procedure is developed to calculate welding deformations of double-V joint. Understanding the mechanism of reducing welding distortion and stress is important in order to expand this method to many components. 3D finite element model is shown in Fig. 2b. The dimension of two pass bead is designed according to macrograph of two-sided root pass welding as shown in Fig. 2a, the lattices of each pass are divided into independent unit, and it is defined as dead unit before welding. The units in weld zone are activated one by one during welding process. The whole model is made up of 17460 elements and 21045 nodes. Fine mesh is used around weld. The element length around the weld region is 2 mm in the welding direction and in the thickness direction. The initial condition is preheating temperature 120 °C. The *X* axis is width

Table 1. Power of fore and rear arcs.

Serial code	Fore pass heat input, Q_f			Rear pass heat input, Q_r		
	Current (A)	Voltage (V)	Power (kW)	Current (A)	Voltage (V)	Power (kW)
Q0	155	14.2	2.2	155	14.2	2.2
Q1	175	14.9	2.6	155	14.2	2.2
Q2	155	14.2	2.2	135	13.4	1.8
Q3	165	14.6	2.4	145	13.8	2.0

direction of the plate, the *Y* axis is the welding direction, and the *Z* direction is thickness direction of the plate. The heat source model adopts double ellipsoid heat source model [9]. Since thermal elasto-plastic analysis is a non-linear problem, physical and mechanical properties are determined by considering the characteristics of temperature dependence. The low alloy high-tensile steel is adopted in this paper. Its carbon content is 0.1%. Under the condition of ambient temperature, the Poisson's ratio is 0.285, the density is 7.8 $kg{\cdot}m^{-3}$, the melting point is 1450 °C . Reference [10] shows the thermodynamic property of material as follows: the specific heat is $434 J{\cdot}kg^{-1}{\cdot}°C^{-1}$, yield strength is 850 MPa, heat conductivity is 30.7 $k{\cdot}°C\ W{\cdot}m^{-1}$, thermal expansion coefficient is $1.06{\times}10^{-5}\ °C^{-1}$, and Young's modulus is $2.08{\times}10^{5}$ MPa under room temperature. The heat analysis near the weld molten pool zone mainly appears heat radiation. However the farther place mainly appears surface heat exchanging. Considering the common effects of radiation and surface heat exchanging, a formula of compound heat conduction coefficient is adopted [11].

4. RESULTS AND DISCUSSIONS

4.1. Thermal analysis

To verify the numerical results and investigate the thermal characteristics, the transient temperature measured at arc distance 45 mm is presented in Fig. 3. The locations of thermo-couples (at $Y = 150$ mm) are shown in Fig. 2a. Calculated and experimental results show that the temperature appears two peaks. Although every peak temperature of measured curve is slightly lower than that of numerical curve because of thermal-couples position deviation, the whole evolution trend of calculated temperature agrees approximately with that of experimental temperature. The second heat cycle induced by rear pass can be regarded as a post heat action to the fore pass. Similarly, fore pass provides the rear pass with a preheat action. Rear TIG post-heating provides the fore pass with a second thermal cycle and reduces the temperature gradient [12]. The double-peak character of DSAW temperature will improve weld microstructure and alleviate the cold crack [5].

4.2. Effects of arc distance on stress

In order to investigate the effects of arc distance on the root pass stress, the stress distribution along the transverse direction at different arc distance is shown in Fig. 4. A stress acting parallel to the direction of the weld bead is known as a longitudinal stress, denoted by the term σ_y. Figs. 4b and 4d depicts the distributions of longitudinal residual stress along the *x* direction. A stress acting normal to the direction of the weld bead, is known as a transverse stress, denoted by the term σ_x. Fig. 4a and 4c illustrates the distributions of transverse residual stress σ_x along the *y* direction. The longitudinal stresses of fore and rear pass are high tensile stress. The transverse stresses are tensile stresses in the central areas and compressive in heat affected zone. All the peak stresses appear in the center of welding seam. But the peak stresses of fore and rear passes are different at different arc distance. Moreover, the stresses of fore and rear pass are different also.

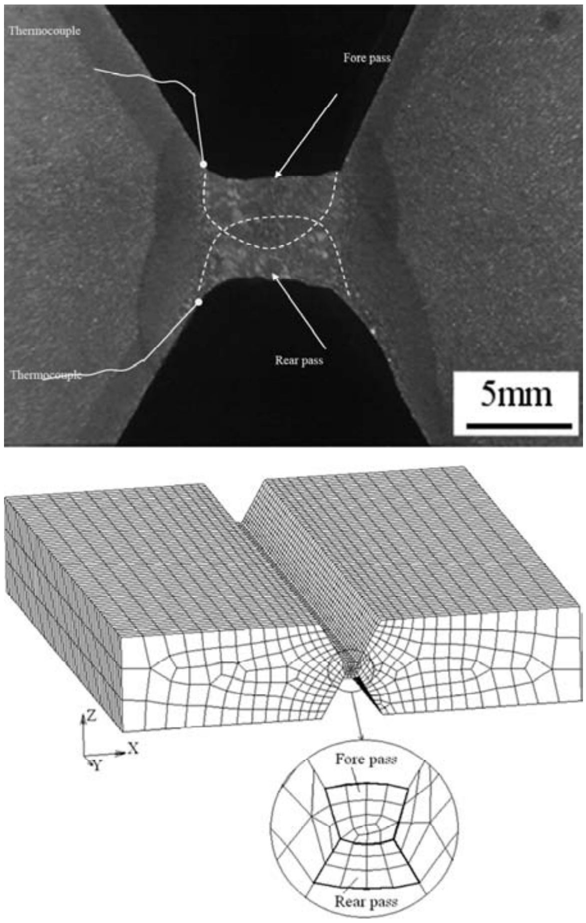

Fig. 2. Finite element model of two-sided root pass welding: (a) Macrograph, (b) 3D model.

Peak stresses of fore and rear pass are illustrated in Fig. 5. Theses curves show that the relationship between peak stresses and arc distance is nonlinear. Transverse and longitudinal stresses on both sides are first decreasing, then increasing with the increasing of arc distance. The transverse stresses of fore pass are larger than those of rear

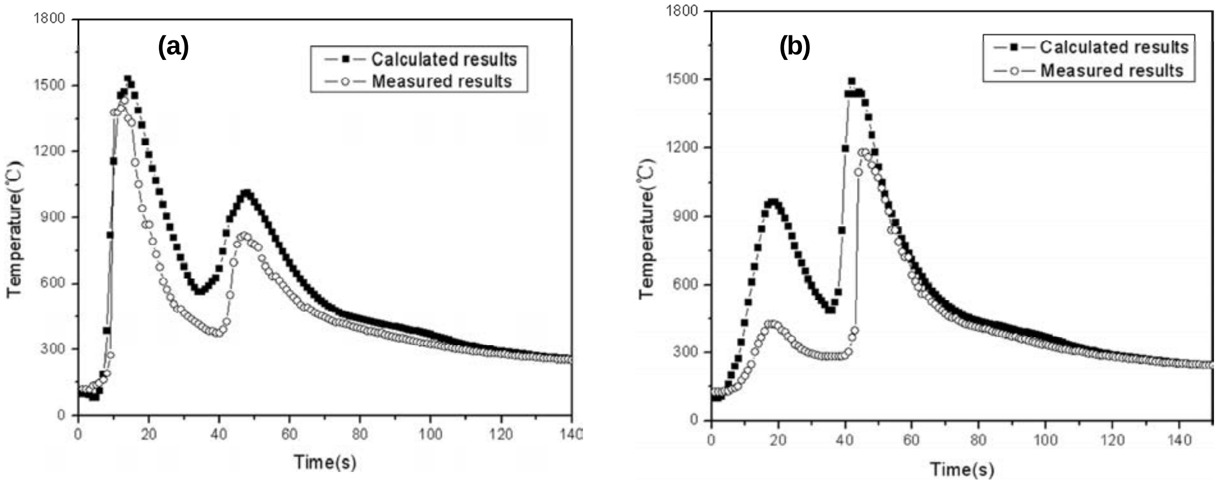

Fig. 3. Experimental and calculated results (at arc distance 45 mm): (a) Fore pass, (b) Rear pass.

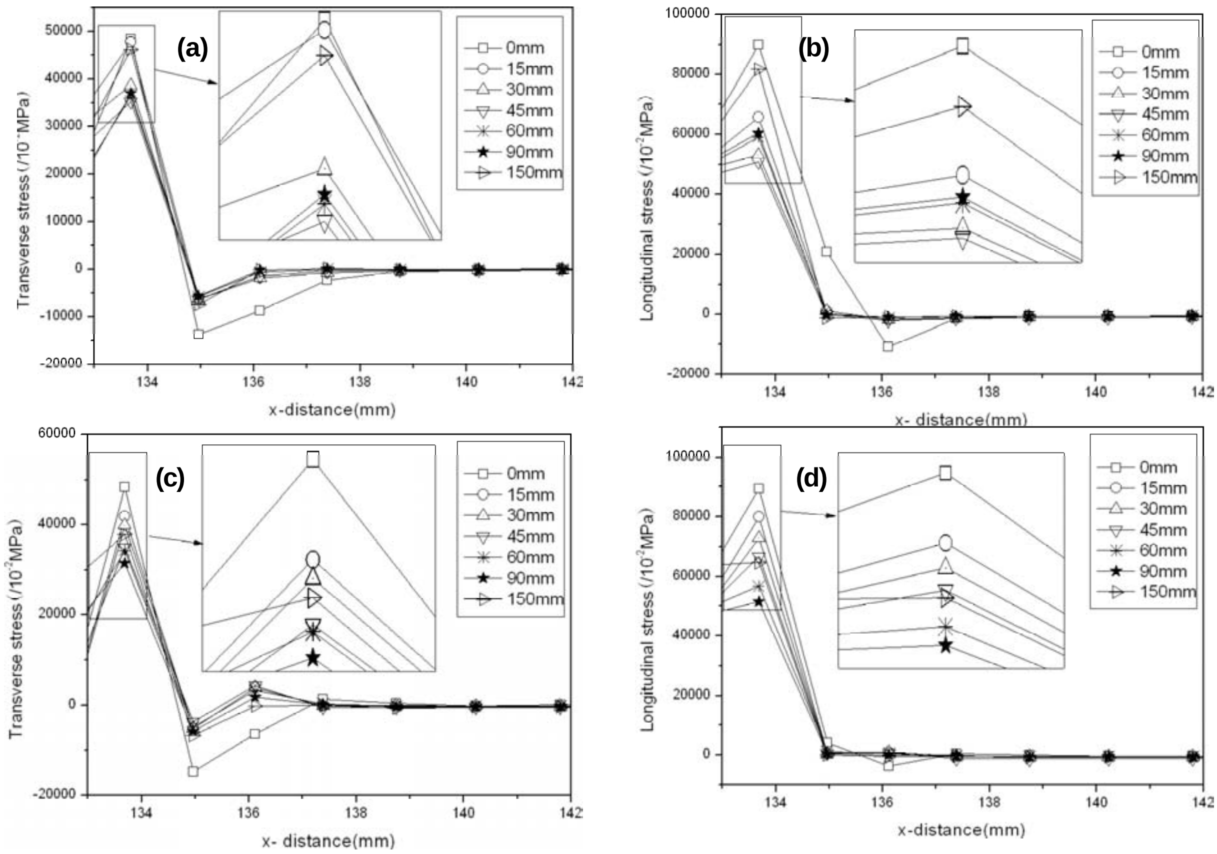

Fig. 4. Effect curves of arc distance on the stress: (a)Transverse stress of fore pass, (b) Longitudinal stress of fore pass, (c) Transverse stress of rear pass (d) Longitudinal stress of rear pass.

pass at all arc distances. For high strength steel of thick plate, the transverse crack is apt to induce due to high hydrogen content and high longitudinal stress [5]. In my paper, the longitudinal stress is the key to study. The longitudinal stresses of fore pass are larger than those of rear only at an arc distance more than ~60 mm. According to the above thermal analysis, the fore pass is provided with a post-heating treatment by the rear torch. But the post-heating temperature at a small arc distance is very high and can produce twice the thermal stress, which is mainly relative to the peak temperature of the rear pass. At small arc distance, the peak temperature of the rear pass is very high. So the longitudinal stresses of fore pass are very high too at small arc distance. But at a large arc distance the preheating stress will be decreased with the increasing of arc distance. If the post-heating temperature is lower than 700 °C, the action can be look upon as an annealing heat treatment to fore

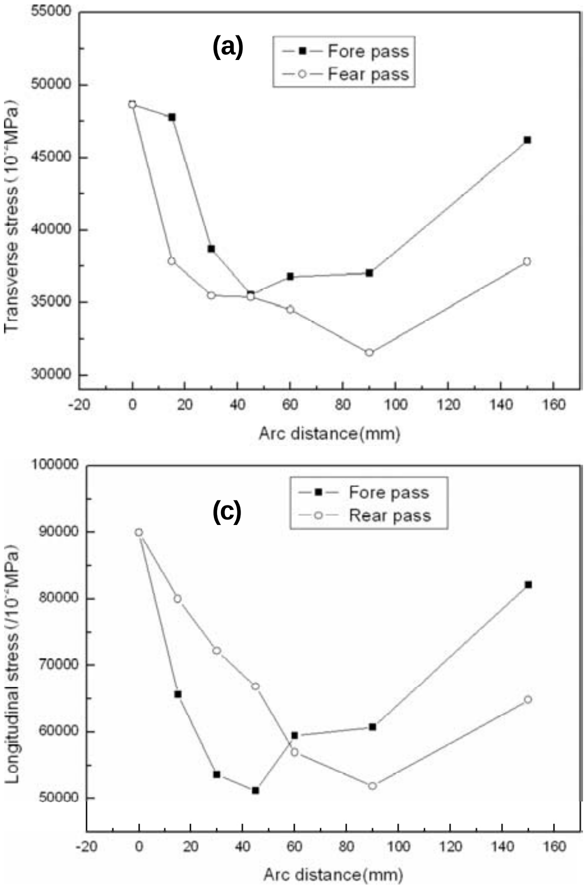

Fig. 5. Effect curves of arc distance on the stress: (a)Transverse stress, (b) Longitudinal stress.

pass [13]. Hence, the longitudinal stress of fore pass can decrease. This is the reason why the relationship between the stresses of both sides and arc distance is non-linear.

4.3. The relationship between stress and arc distance

Effect of arc distance on the peak stress is shown in Fig. 6. The evolution process of peak stresses with the increasing of arc distance can be divided into three stages as follows:

I: At very small arc distance (0 mm to 15 mm), the two-sided arc welding can be look on as a double arc single pass welding with double heat inputs, and more thermal plastic is produced. The stresses are mainly influenced by the heat input and restraint condition for this method. At small arc distance, the two passes shrink nearly simultaneously [14], the constraint force is very small and not considered in this paper. The heat input is decreasing with the increasing of arc distance. The peak stresses is decreasing at small arc distance.

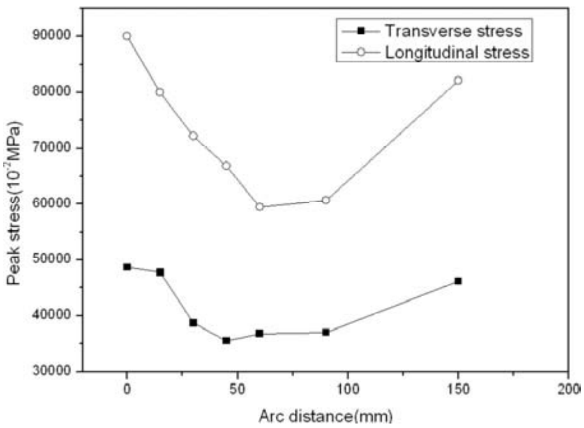

Fig. 6. Effect curves of arc distance on the peak stress.

II: At middle arc distance (45 mm to 75 mm), the two-sided arc welding can be seen as a kind of welding between double arc and single arc. The preheating and post-heating temperature provided by two arcs is neither too high nor too low. The proper preheating and post-heating temperature will lower the stress each other, the preheat effect provided by fore arc will lower the rear pass stress [15]. At

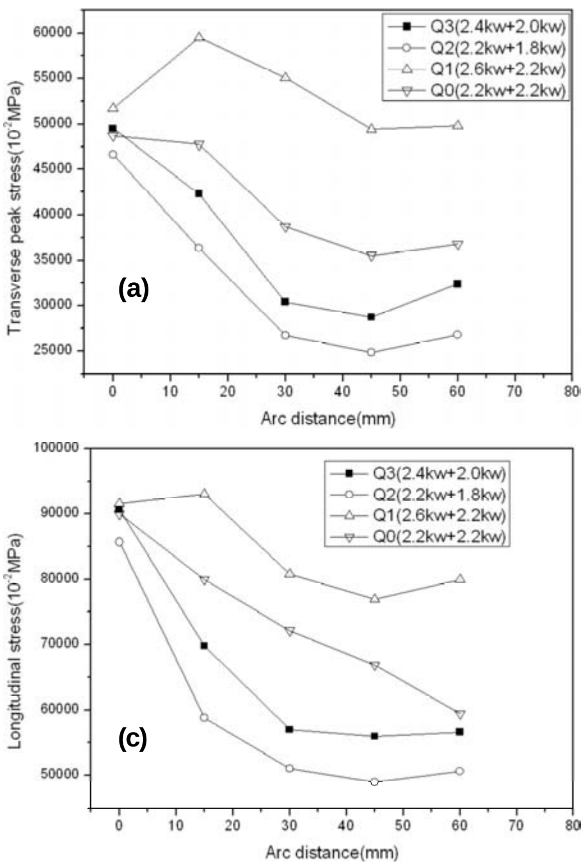

Fig. 7. Effect curves of heat input on the peak stresses: (a) Transverse stress, (b) Longitudinal stress.

the same time, the post-heat effect by rear arc will lower the fore pass stress too [16]. So the peak stresses are decreasing.

III: At large arc distance (>75 mm), it can be regarded as a single arc multipass welding. It is well known that the rear pass cannot shrink freely due to the existence of the constraint force induced by the fore pass during multipass welding. The mutual thermal effects are very low. The preheat and postheat temperatures are very low, so the stress is increasing.

At arc distance about 60 mm, the transverse and longitudinal peak stresses are the minimum. To select a proper arc distance is to control stress. But too large arc distance does not meet the requirement of no back gouging. Moreover cold crack is produced easily due to too high cooling speed. But too small arc distance will cause hot crack and bad weld shape. Lots of experiments show that at arc distance 20~30 mm will not cause hot crack and cold crack, and can not require back gouging [5]. But at arc distance 20~30 mm the stress are very big. It is very critical to obtain little stress at small arc distance. So effects of heat inputs on the stress are further investigated.

4.4. Effect of heat input on the stress

Under the condition of different heat inputs in Table 1, the transverse and longitudinal peak stresses are shown in Fig. 7. The transverse and longitudinal peak stresses adopted heat input $Q1$ are the highest among heat input $Q0$ to $Q3$. Those adopted heat input $Q2$ are the lowest. Increasing heat input of fore pass is to increase the transverse and longitudinal stresses. The stresses are decreasing through reducing the rear arc heat input $Q2$. At arc distance about 25 mm, the peak stresses are the minimum. To select proper arc distance and regulating heat input of rear arc effectively reduce the root pass welding stresses.

For vertical position welding, the too high or too lower heat inputs are all not so well for appearance of weld. In order to keep the total heat inputs 4.2 kW constant of $Q0$, the fore pass power increase to 2.3 kW, and at the same time the rear pass power decease to 1.9 kW. The stress of heat input $Q3$ is shown in Fig. 7. The curve is moving up as the total heat input deceasing when the different value of heat input between fore arc and rear arc is the same. Under total heat input constant, the power of fore arc should be increased and rear arc should be decreased. Not only the stresses are fatherly decreased but also the formation of weld meets production requirements.

5. CONCLUSIONS

Based on the above discussion, we can conclude the following.

1) The calculated thermal cycles are approximately in agreement with the experimental measurements. The thermal cycles of two-sided arc welding present double-peak features. The fore arc provides a preheat action to the rear pass, and the rear arc provides post-heat action to the fore pass.

2) The effect mechanisms of arc distance on the stresses on the both sides are analyzed. There are some factors such as the post-heating treatment provided by rear pass, the preheating treatment and restrain force induced by fore pass, which mainly influence the peak stresses with the changing of arc distance.

3) The effect of heat inputs on the stresses is investigated. Under total heat input constant, the power of fore arc should be increased and rear arc should be decreased at small arc distance. Not only the stresses are fatherly decreased but also the formation of weld meets production requirements.

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