Structure Parameter Optimization of Welding Spot of Corrugated Plate Component

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Abstract. A simple model is used to determine the research route of corrugated plate component with good fatigue life based on equivalent stress, and the simulation results are proved to be reasonable by physical test. It is found that the equivalent stress of corrugated plate component increases with the increase of horizontal distance between welding points during single-row welding, after the analysis of the simulation results. In all the arrangement forms, the number of welding points arranged in triangle arrangement is large, which has good connection effect on corrugated plate component and good structural stability. Therefore, it is better to connect corrugated plate component in a way of welding in row 3, with a distance of 2 mm from top to bottom, a distance of 10 mm from left and right sides of row 1 and row 3, and a distance of 37.2 mm from left and right sides of row 2. The fatigue life simulation result of corrugated plate component under the structural parameters is 7.89e6 times, and the actual fatigue life of physical test exceeded 3.0e7 times, meeting the working condition requirements.

1. Introduction
The high-temperature flue gas from the boiler tail is used by air preheater, which is a kind of preheating equipment, to heat the air before entering the boiler to improve the boiler combustion efficiency and reduce the heat loss [1-2]. At present, there are three kinds of common air precast structures: including plate type, rotary type and tube type. The main advantages of rotary air precast mainly lie in simple structure, compact structure and light weight, so it has been continuously developed [3-5]. In the literature [6-8], Yu, L, Naphon, P. et al. expounded the harm of air leakage to its efficient and stable operation, and proposed corresponding improvement measures. For most of the current air preservers, there exist some problems such as wear resistance, weak corrosion resistance, and difficult dust cleaning [9-10]. In view of the above defects, a new type of sealing device called corrugated plate spring flexible contact seal is developed, which has the advantages of good sealing performance, good resilience, stiffness and automatic wear compensation, etc. Its advantage is that the sealing performance is good, and it also has good resilience and the rigidity and abrasion automatic compensation, etc, as well as a broad market prospect. At the present stage, flexible sealing technology is one of the most advanced and the best sealing technologies in the air preheater sealing technology [11-12]. The corrugated plate component studied in this paper is one of the many flexible sealing devices of air preservers. It has been widely used because of its strong sealing adaptive ability, simple structure and low cost. In actual work, the corrugated plate component of air preheater is subjected to a symmetrical cyclic load, and its fatigue performance directly affects the sealing performance. Therefore, it is necessary to study the fatigue performance of corrugated plate component. At present, welding technology has been widely applied in various fields of manufacturing industry, especially automobile manufacturing industry. Moreover, spot welding has the advantages of high automation
and easy operation. It is also famous for small deformation before and after welding [13-15]. While the corrugated plate component is formed by the overall rolling of S316L, which has a good welding performance. Therefore, spot welding is used to assemble and connect the corrugated plate component.

Yan-Hua, Z.[16] expounded three methods of strength analysis of welding parts, namely analytical method, numerical simulation method and engineering method. Among them, with a numerical simulation, the product development cycle can be shorten effectively, the cost can be reduced, and the quality and production can be also improved efficiently. Moreover, the results that are difficult to obtain with experiment and theoretical analysis can also be obtained with a numerical simulation. R. KEIVANI [17] et al. studied the thermal characteristics of copper C11000 in the FSW process by using a three-dimensional finite element model, and the predicted temperature was in good agreement with the experimental results. Jian-Feng,T[18] et al. established an axisymmetric finite element numerical simulation model of thermal-electric coupling field based on the thermal influence zone and phase transition principle of aluminum alloy spot welding, and revealed the mechanism of the difference between the transient state and the steady-state state of the process thermal-electric coupling. Ding -fa, F et al. [19] established a three-dimensional finite element model based on thermal-elastoplastic finite element method, studied the influence of different welding sequences on the residual stress after welding of thin-walled 6061 alloy welding pieces, and believed that choosing a reasonable welding sequence could effectively reduce the residual stress of the octagon tube-plate joint. Therefore, it is feasible to study welding fatigue performance and other quality performance of mechanical parts with simulation calculation.

In this paper, the effect of solder joint factors on fatigue performance of corrugated plate component is studied by simulation. Under spot welding with different spacing and arrangement, static strength simulation calculation is carried out. After data analysis and processing of simulation results, better welding joint structure parameters are obtained. On the basis, fatigue life simulation calculation was conducted with the fatigue tool, and then the optimum fatigue life was obtained. Finally, the physical test method was used to verify the optimized structure parameters of the welding spot. The research methods and ideas adopted in this paper can provide reference for other researchers or students who study the role of welding or component connection. In addition, the research results of this paper can also provide reference for industrial production and welding parts processing.

2. Research methods and model construction

2.1. Selection of welding joint structure parameter optimization method

The methods, which are used to estimate fatigue life, include nominal stress method and local stress-strain method. Nominal stress method is applicable to high cyclic variable stress conditions with cycle times above 1.0E4. The local stress-strain method is mainly combined with the cyclic stress-strain curve of the material. Through elastoplastic finite element analysis or other calculation methods, the nominal stress spectrum on the component is converted into the local stress-strain spectrum of the dangerous part, and then the life is estimated according to the local stress and strain history of the dangerous part [20]. The corrugated plate component needs to be replaced every 3 ~ 5 years, and the speed of air preheater is 1.0 r /min, in which the corrugated plate component works under the cyclic stress of about 200 N, and the expected life is about 1.0E6 times. Therefore, the nominal stress method is used to study the fatigue performance of corrugated plate component.

The fatigue life simulation is carried out on the basis of the S-N curve. The equation is shown in formula (1) [21]. In the formula, \( \sigma \) is stress, \( m \) and \( C \) are material constants determined by experiments, and \( N \) is life. Take the logarithm of both sides of the equation and arrange to get the formula (2).

\[
\sigma^m N = C
\]  
\[
mlg\sigma + lgN = lgC
\]
When \( N = 1.0 \times 10^6 \), \( \sigma = 10^6 \delta \sigma \). Based on the type of materials and heat treatment, and combined with the table for estimation of fatigue characteristics of commonly used domestic materials [21], the reasonable value of \( \sigma \) is obtained to determine the \( S-N \) curve of materials.

When using beam element to set the solder joint, the calculation accuracy is high and the effect of solder joint diameter can be analyzed. However, if the number of solder joints is large and the product structure is complex, the model establishment and fatigue life calculation will take a long time. In order to select a simple and reasonable solder joint model, simulation calculation method and simplify the research process, two pieces of sealing pieces were used as the preliminary study of the simple model. Under the condition of 200 \( N \) symmetrical load, the welding joint model of beam element was adopted to simulate the static strength and fatigue life of the welding joints with diameters of 2, 4 and 6 mm as an example, so as to judge the basic effect law of the welding joint diameter and spacing on the stress and fatigue life. The simulation results are shown in table 1.

Table 1. Simulation results of stress and fatigue life with different welding spot spacing and diameter

| Spot size/mm | Horizontal spacing of solder joints/ mm | Equivalent stress/MPa | Fatigue life/times | Equivalent stress/MPa | Fatigue life/times | Equivalent stress/MPa | Fatigue life/times |
|--------------|----------------------------------------|-----------------------|-------------------|-----------------------|-------------------|-----------------------|-------------------|
| 2            | 25                                     | 888.2                 | 161.3             | 927.9                 | 144.7             | 2533.3                | 14.5              |
| 2            | 50                                     | 888.8                 | 161.0             | 928.4                 | 144.6             | 2534.6                | 14.5              |
| 2            | 100                                    | 888.7                 | 161.0             | 928.4                 | 144.5             | 2534.6                | 14.5              |

In the three diameters of solder joints, the equivalent stress of the simple model increases with the increase of the horizontal distance between solder joints, and the corresponding fatigue life decreases with the increase of the equivalent stress. This may be due to the increase in solder joint horizontal spacing and the decrease in the number of solder joints, resulting in a weakened spot welding joint effect on the sealing sheet. The equivalent stress and fatigue life are equal under different welding joint diameters. It can be seen that under working conditions, the variation trend of fatigue life of the simple model is opposite to the equivalent stress of the simple model, that is, the smaller the equivalent stress is, the greater the fatigue life is.

It is generally believed that the maximum principal stress can be used to explain the fatigue damage mechanism, that is, the degree of damage to the isotropic probability of atomic escape can be represented. However, this theory only applies when one of the three maximum principal stresses dominates [22]. Sometimes, although unidirectional load of the structure is great, but no damage has been caused, for the reason that the tests of strength of materials are generally under unidirectional loading strength, however product structure has its complexity, so under the working condition, there is a big difference between the stress condition of the structural parts and that of the single tensile parts, therefore there may not exist the maximum principal stress that can be dominant. The above phenomenon is consistent with the law reflected in the simulation results of some previous studies, that is, sometimes the maximum principal stress obtained by simulation increases, however the corresponding fatigue life does not fall but rise. At this point, it is more reasonable to use the fourth strength theory (distortion theory) to analyze the yield damage, that is to say, no matter what the material stress state is, the main factor causing material yield failure is the distortion energy density, and the equation is shown in formula (3). In the formula, the main stress \((\sigma_1, \sigma_2, \sigma_3)\) is transformed to equivalent stress \((\sigma_s)\) [23]. The results of previous studies show that the simulation results of fatigue life have a good correspondence with the equivalent stress.

\[
\sigma_s = \frac{\sigma}{\sqrt{2}} \left( (\sigma_1 - \sigma_2)^2 + (\sigma_2 - \sigma_3)^2 + (\sigma_3 - \sigma_1)^2 \right) \leq [\sigma]
\]

Take the diameter of 6 mm as an example, the equivalent stress cloud diagram of the simple model is shown in figure 1. When the horizontal spacing of solder joints is 100 mm, there is no superposition of stress concentration influence zone around solder joints. When the spacing decreases to 50 mm, the superposition of the stress concentration affected area begins to occur, and when the spacing decreases
to 25 mm, the superposition becomes more obvious. It can be seen that the horizontal spacing of solder joints may significantly affect the superposition of stress concentration around solder joints. When the solder joint diameter is 2 mm and 4 mm, the superposition of the stress concentration influence zone around the solder joint varies with the horizontal spacing of the solder joint, which is similar to that when the diameter is 6 mm.

In order to improve the calculation efficiency, the effect of solder joint diameter and horizontal spacing on the stress and fatigue life under the simple model is integrated. So in this paper, the effect of solder joint diameter is ignored, that is, each solder joint model is not established by beam element alone. According to the simulation accuracy and modeling efficiency of the model, combined with the welding principle and the stress characteristics of welding parts, the Crea point command in Desing Modeler module was selected to establish the solder joint unit. The default solder joint of the software is a particle, which is essentially a binding contact, that is, the separated parts are bound together. At the same time, the equivalent stress is selected as the basis to optimize the welding joint structure parameters, and the flow is shown in figure 2. Firstly, according to the actual working condition, material characteristics and loading process of corrugated board component, static strength simulation calculation was carried out in Workbench, and data analysis and processing of simulation results were analysed and processed to obtain better welding joint structure parameters. Then fatigue life was calculated with fatigue tool to judge the Fatigue performance of corrugated plate component. Finally, it is verified by physical experiment.

**2.2. Corrugated plate component model and loading mode**

The structure of corrugated plate component is shown in figure 3, in which parts 1 and 2 are 0.6mm thick sealing plates, parts 4 ~ 7 are 0.4mm thick sealing plates, parts 3, 8, 11, 15 ~ 18 are 0.6mm thick U-shaped plates, parts 9, 10, 13 and 14 are 0.6mm thick folding plates, and parts 12 are 1.2mm thick grooved plates. U-shaped plate is wrapped with four adjacent sealing pieces, which are fixedly connected by spot welding. The folding plate and groove plate are connected by spot welding at both ends of corrugated plate component. One end of the folding plate is installed at the corresponding position of air preheater, and the other end of the folding plate is matched with other parts to drive the periodic compression and stretching of corrugated plate component, so as to play the role of circular sealing and air exchange. The corrugated plate component is made of S316L stainless steel. And the nominal yield limit of the material is equal to or greater than 177 MPa, the tensile strength is equal to
or greater than 480 MPa, the elongation is equal to or greater than 45%, the hardness is equal to or less than 200 HV, and the elastic modulus is about 200 GPa. In ANSYS Workbench, the corrugated plate component model was divided into grids. Considering the effect of grid quality and quantity on simulation accuracy and speed, the cell size was set to 5mm first, and then the mesh around the solder joint model was subdivided and optimized with the cell size of 0.5mm. The final model is shown in figure 4. The total number of grids is 651485, and the total number of nodes is 1296158.

The spot welding connection model and its loading mode are shown in figure 5, where A ~ J is the welding point. After determining the S-N curve of the material, fatigue strength factor $K_f$ was 0.8, stress ratio $r$ was -1 (i.e., symmetric cyclic alternating stress) in the fatigue tool module with a size of 200 N, which was applied along the X (horizontal) direction on the slot-plate 12. At the same time, a fixed constraint is applied to the folded plate 10.

3. Simulation results and discussion

3.1. Effect of horizontal spacing of solder joints on equivalent stress

Firstly, the effect of solder joint horizontal spacing on the equivalent stress of corrugated plate was studied when solder joints were soldered in a single row. The solder joint layout is shown in figure 6. It is can be seen that solder joints are arranged along the length of u-shaped plate, evenly distributed between 11 and 20 solder joints, and the distance between adjacent solder joints is called the horizontal distance. The distance from the solder joint to the upper and lower edge of the u-shaped plate is called the upper and lower edge distance, while the distance between the left and right solder joints and the edge of the u-shaped plate is called the left and right edge distance. Moreover, the specific parameters of solder joint layout can be seen in table 2.

| Solder joints row number | Left and right margin/mm | Upper and lower margin/mm | Horizontal spacing/mm |
|-------------------------|--------------------------|---------------------------|-----------------------|
| 1                       | 10                       | 4                         | 98, 89.1, 81.7, 75.4, 70, 65.3, 61.3, 57.6, 54.4, 51.6 |

As can be seen from table 3, the equivalent stresses of corrugated plate component corresponding to different horizontal spacing of solder joints are all less than 177 MPa, which meets the requirements of static strength of corrugated plate.

| Horizontal spacing/mm | Equivalent stress/MPa |
|-----------------------|------------------------|
| 98                    | 79.56                  |
| 89.1                  | 78.98                  |
| 81.7                  | 63.13                  |
| 75.4                  | 58.47                  |
| 70                    | 61.13                  |
| 65.3                  | 48                     |
| 61.3                  | 51.6                   |
| 57.6                  | 50.33                  |
| 54.4                  | 45.80                  |
| 51.6                  | 46.65                  |

The 9 groups of data with horizontal spacing of 54.4 ~ 98 mm were drawn as scatter plots, as shown in figure 7. In general, with the decrease in the number of solder joints and the increase in the horizontal spacing of solder joints, the joint effect of corrugated plate component is weakened, resulting in the gradual increase in the equivalent stress of corrugated plate components. After fitting, quadratic polynomial of fitting curve is obtained (4). When the horizontal spacing is 51.6 mm, the equivalent stress calculated according to formula (4) is 44.82 MPa, and the error between it and the simulation result 46.65 MPa is only 3.93%, indicating that the fitting formula has a good prediction.
effect on the equivalent stress. When the solder joint spacing is less than or equal to 75.4 mm, the equivalent stress fluctuates up and down with the change of horizontal spacing, which may be caused by two reasons: First, the number of solder joints is different, and the solder joint position changes accordingly. In order to adapt to the solder joint model, the overall grid model of corrugated plate component is adjusted accordingly, resulting in certain calculation fluctuations. On the other hand, it may be caused by the small solder joint spacing as shown in figure 1, which results in the superposition of stress concentration influence zones around solder joints. Macroscopically, the material's microstructure, mechanical inhomogeneity, fatigue resistance are random quantities, fatigue crack initiation and propagation rate and fatigue life will show statistical characteristics[16]. For welding parts, the contour parameters of the actual welding joints are also random along the direction of welding seam length, and the resulting stress concentration will also change randomly[22,24]. On microscopic, stress concentration place atoms or molecules escape isotropic damage, leading to the probability of atoms or molecules in a certain direction to escape increases, which caused by atoms or molecules escape transient cavitation can't being filled by a escape elsewhere to atoms or molecules, and that greatly promoted the formation and accumulation of fatigue damage. In actual welding, the superposition of the stress concentration effect areas near the solder joints will result in uneven local stress on corrugated plate components, as well as minor deformation of the solder joint contour, resulting in fluctuation of stress distribution. The simulation results are consistent with the actual situation.

In addition, according to Miner's linear cumulative damage theory, the damage in the stress concentration affected area overlaps with each other, which will also lead to the equivalent stress fluctuation of corrugated plate components[23-25]. When the solder joint spacing is greater than or equal to 75.4 mm, the solder joint horizontal spacing is larger, the spacing distance of the stress concentration effect region increases, and the superposition effect weakens, so the equivalent stress fluctuation decreases.

\[ Y = 0.00694x^2 - 0.25184x + 40.19361 \] (4)

Figure 6. Single row solder joint arrangement
Figure 7. Effect of solder joints spacing

3.2. Effect of solder joint number and solder joint arrangement mode on equivalent stress

When the solder joint spacing is 54.4 mm, the equivalent stress of corrugated plate component is the minimum, which achieves 45.80 MPa. Keep the solder joint spacing constant at 54.4 mm, and increase the number of solder joint rows. Each row of solder joints is evenly distributed along the width of u-shaped plate. Moreover the upper and lower solder joints are equal to the solder joint row spacing. The specific solder joint arrangement can be seen in figure 8 (a). At this time, four solder joints in any adjacent two rows constitute a rectangular structure, and the corresponding equivalent stress calculation results are shown in table 4. The minimum equivalent stress is 43.12 MPa when the spot welding is welded in three rows. However, as a whole, with the increase of solder joint rows, the equivalent stress of corrugated plate component has no obvious trend of change, which may also be caused by the small spacing between adjacent two rows of solder joints and the superposition of the affected areas of solder joint stress concentration. This also shows that under these solder joint arrangements, the joint effects of some adjacent solder joints on corrugated board component overlap with each other, resulting in that although the number of solder joint rows and the number of solder
joints increase, the joint effects on corrugated board component are not strengthened at the same level, so the solder joint arrangements can be further adjusted.

In order to reduce the interference of overlapping effect areas of stress concentration of solder joints in each row, the solder joints in the second row are reduced by 1, the left and right edge spacing is adjusted to 37.2 mm, and the horizontal spacing is unchanged. And the arrangement mode can be seen in figure 8. At this point, the minimum linear distance between any two adjacent solder joints of adjacent two rows increases from 2 mm to 27.3 mm, and the three adjacent solder joints constitute a stable isosceles triangle structure. At this time, the equivalent stress of corrugated plate component decreases to 24.95 MPa, which is more than 40% lower than the original 3-row rectangular structure. It can be seen that the minimum linear distance between adjacent two rows of solder joints significantly reduces the damage superposition in the affected area of stress concentration of solder joints.

| Arrangement | 1 Row | 2 Rows | 3 Rows | 4 Rows |
|-------------|-------|--------|--------|--------|
| Upper and lower margin/mm | 4     | 2.7    | 2      | 1.6    |
| Equivalent stress/MPa | 45.80 | 46.73  | 43.12  | 47.70  |

### 3.3. Simulation calculation of fatigue life

According to Miner fatigue damage theory, under cyclic load, the relationship between fatigue damage and load cycle number is linear, and fatigue damage can be accumulated linearly. When the cumulative damage reaches a certain value, fatigue damage will occur to the component, and its mathematical expression is shown in formula (5). Where D is the fatigue damage corresponding to each current load level, and N is the fatigue life corresponding to the current load level[25]. Generally, the smaller the load, the smaller the fatigue damage caused by each action. Miner's linear accumulation rule only applies to the linear part of the s-n curve, that is, the part within the elastic limit of the material[25], while the equivalent stress of corrugated plate component is far less than the nominal yield limit, which satisfies the service condition of Miner linear accumulation rule. In all the forms, when the horizontal spacing of solder joints is 54.4 mm, the solder joints are arranged in a single row, three rows of rectangular structure and triangular structure, and the equivalent stress of corrugated plate component is small. Therefore, the fatigue life simulation calculation of corrugated plate component with these three solder joint arrays was conducted, and the results are shown in table 5. The relationship between fatigue life and equivalent stress conforms to Miner linear accumulation rule.

\[ N = \frac{1}{D} \] (5)

| Arrangement | 1 Row | 3 Rows (rectangle structure) | 3 Rows (triangular structure) |
|-------------|-------|------------------------------|------------------------------|
| Equivalent stress/MPa | 45.80 | 43.12 | 24.95 |
| Fatigue life/times | 2.37e6 | 2.84e6 | 7.89e6 |

Compared with the case of single row welding, the number of solder joints increases significantly under the welding mode of triangular structure arrangement, and the connection of corrugated plate components is significantly strengthened. While compared with the welding mode of rectangular structure, the stability of triangular structure is higher than that of rectangular structure, and the minimum linear distance between adjacent solder joints is significantly increased, and the damage
superposition in the affected area of stress concentration of solder joints is significantly reduced. Therefore, the corrugated plate component has the best fatigue life when the solder joints are arranged in three rows of triangular structure. The fatigue life of the corrugated plate component reaches 7.89e6 times as shown in figure 9, which is significantly higher than the other two cases. The improvement degree exceeds 177% and even reaches 230%.

Figure 9 Fatigue life of corrugated plate component

4. Experimental verification

Process 3 corrugated plate components according to figure 8 (b) solder joint arrangement and the test is carried out on the reciprocating motion test bench of connecting rod as shown in figure 10. In the physical test, the eccentric wheel drives the reciprocating motion mechanism to compress the corrugated plate component in a cycle at a speed of 20 revolutions/second under the case of exceeding the working load, so that the minimum compression deformation of 8 mm and the maximum periodic compression deformation of 15 mm occur. The specific test conditions are shown in table 6.

Table 6. Test conditions

| Cycle index | Damaged condition |
|-------------|------------------|
| Sample 1    | 3.2e7 local damage |
| Sample 2    | 3.25e7 local damage |
| Sample 3    | 3.3e7 Edge damage |

The mean fatigue life of the three samples and the 95% confidence interval of the mean fatigue life were taken. According to the test, the minimum fatigue life of the sample is about 3.09E7 times. When the number of cycles is exceeded, microscopic cracks can be observed around the solder joint. It can be seen that the actual fatigue life of the corrugated plate component meets the design requirements. By applying pressure, the corrugated plate component is subjected to repeated shear pressure and tension pressure and will not undergo fatigue failure in the expected fatigue life, which proves the rationality and reliability of welding joint structure parameters.

5. Conclusion

(1) In single-row welding, the horizontal spacing of solder joint has a significant impact on the equivalent stress, and the equivalent stress increases with the increase of solder joint horizontal spacing, and the change trend generally conforms to the law of quadratic polynomials. As the equivalent stress of corrugated plate component decreases, the fatigue life increases correspondingly. Therefore, the equivalent stress can be used as the basis to optimize the welding joint structure parameters so as to obtain better fatigue life.

(2) The solder joints arranged in isosceles triangle can improve the stress of corrugated plate component. Physical test shows that the actual fatigue life of corrugated plate component reaches 3.0E7 times when 3 rows of welding are used. At the same time, the left and right edges of the 1st and 3rd rows of welding joints are 10 mm, the left and right edges of the 2nd row of welding joints are 37.2 mm, the top and bottom of the welding joints are 2 mm, and the horizontal distance of the welding joints is 54.4 mm, meeting the requirements of working conditions.
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