# Effect of Welding Spot Diameter and Arrangement on Fatigue Life of Corrugated Plate Component

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***Abstract*—In this paper, the effect of the diameter, arrangement and spacing of solder joints on the fatigue performance of corrugated plate component was simulated, and the structure parameters of solder joints were optimized. First, the static strength simulation of corrugated plate component was carried out in Workbench, and then Fatigue numerical simulation was carried out by combining with Fatigue Tool. Finally, the data analysis and processing of the simulation results were carried out to obtain reasonable welding joint structure parameters. Considering fatigue life and cost performance of the corrugated plate component, it is the better welding spot structure parameters that the left and right margin of the first welding spot is 10 mm, 6 in number, and the center of the welding spot is 3.5 mm away from the upper boundary, while the left and right margin of the second welding spot is 108 mm, 5 in number, and the center of the welding spot is 4.5 mm from the upper boundary, and the diameter of the two rows of solder joints is 2 mm and the horizontal spacing between them is 196 mm. Under this parameter, the fatigue life simulation result of corrugated plate component is 1.56e6 times, and the actual fatigue life of physical test is more than 2.0e7 times, meeting the requirements of working condition.**

***Keywords—corrugated plate component; welding spot; fatigue life; simulated analysis; physical test***

## I. INTRODUCTION

Air preheater is a kind of preheating equipment which uses the high-temperature flue gas from the boiler tail to heat the air before entering the boiler to improve the boiler combustion efficiency and reduce the heat loss [1]. At present, air preheater is mainly divided into heat pipe type, rotary type and various tube type [2]. Li yu et al. [3] expounded the harm of air leakage to its efficient and stable operation, and put forward corresponding improvement measures. At the present stage, flexible sealing technology is one of the most advanced and effective technologies in the air preheater sealing technology [4]. The corrugated plate component studied in this paper is one of the many flexible sealing devices for air preservers. It has been widely used because of its strong sealing adaptive ability, simple structure and low cost. In practice, the corrugated plate component of air preheater is subjected to symmetrical cyclic loading, and its fatigue property can directly affect the sealing performance. At present, welding technology is widely applied in various fields of manufacturing industry, especially automobile manufacturing industry, and spot welding has the advantages of high automation, small deformation before and after welding and easy operation [5-8]. The corrugated panel component is formed by the overall rolling of S316L, and S316L has good welding performance. Therefore, it is assembled and connected by spot welding.

The corrugated panel component is composed of S316L rolled forming assembly welding joint, and S316L has good welding performance. Therefore, spot welding is adopted for assembling connection.

In the finite element simulation of spot welding connector, dai jiangliang [9] et al. studied four models, including ACM2 model, solid model, CWELD model, RBE2 rigid beam model, to replace spot diameter and summarized their advantages and disadvantages. Li xiaofeng [10] et al. used finite element method, based on equivalent structural stress, to calculate the fatigue life of welding seams relatively accurately, and solved the deficiencies of existing analysis methods.Weiguo et al. [11] analyzed the local stress state of the welded toe using finite element analysis, and estimated the fatigue life of the cross welded joint under cyclic tensile load. Le jingxia [12] et al. used finite element method to model and analyze the structure of welding deformation of superstructure deck of luxury cruise ships, and obtained the distribution of fatigue hot spot stress around the welding seam, and discussed the effect of welding deformation on the stress distribution of fatigue hot spot. Therefore, it is feasible to study welding fatigue performance and other quality performance of mechanical parts by simulation calculation.

Considering modeling simulation accuracy and efficiency, combining with the characteristics of welding principle and the stress of the welding parts. In this paper, the Imprint Faces function of the Design Modeler module in the finite element software Workbench was used to mark the circular seal surface, which was used to set up the finite element model of welding spot, and combination function (Bonded) of Contact module was used to bound together the corresponding circular seal surface of the adjacent two pieces of seal corrugated plate components, so the circular spot welding connection problem can be converted to the Contact problem of the seal surface. In this paper, the effect of welding spot diameter and arrangement mode on the stress and fatigue performance of corrugated plate component was studied emphatically, and the structure parameters of spot welding were optimized according to the cost performance of its fatigue life. Finally, the rationality and reliability of the optimized structure parameters of welding spot were verified by physical test.

## II. RESEARCH METHODS AND MODEL CONSTRUCTION

### *A. Fatigue Analysis and Solder Joint Structure Parameter Optimization Methods*

At present, there are two methods for estimating fatigue life: nominal stress method and local stress-strain method. Nominal stress method is mainly based on the stress-life curve of materials and is used for parts with cycle times above 1.0e4 under high cyclic variable stress. 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 and strain spectrum of the dangerous part, and then the life is estimated according to the local stress and strain history of the dangerous part [13]. The corrugated plate component needs to be replaced every 3 ~ 5 years, and the speed of air prepper 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 fatigue performance of corrugated plate component is studied by nominal stress method. The fatigue life simulation is carried out on the basis of *S-N* curve. The equation is shown in formula (1) [14]. 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).

$$\sigma^m N=C \tag{1}$$

$$m\lg\sigma+\lg N=\lg C \tag{2}$$

When N = 1.0e6, $\sigma_{10}{}^{6} = \delta\sigma$. Based on the type of materials and heat treatment, and combined with the table for estimation of fatigue characteristics of commonly used domestic materials [14], reasonable value of σ is obtained to determine the S-N curve of materials.

When studying fatigue life, 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, but this theory only applies when one of the three maximum principal stresses dominates [15]. Sometimes, however, although unidirectional load of the structure is very big, but no damage has been happened, this is because the tests of strength of materials are generally under unidirectional loading strength, and product structure has its complexity, under the working condition, there is a big difference between the stress of the structural parts and that of the single tensile parts, there may not be the maximum principal stress of dominant. This 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, and the corresponding fatigue life not only does not decrease, but also increases. At this point, it is more reasonable to use the fourth strength theory (distortion theory) to analyze the yield damage, that no matter what the material stress state is, the main factor causing material yield failure is distortion energy density, specific formula (3), where ,the main stress ($\sigma_1$, $\sigma_2$, $\sigma_3$) is transformed to equivalent stress ($\sigma_s$ ) [16]. The results of previous studies show that the simulation results of fatigue life have a good correspondence with the equivalent stress.

$$\sigma_s=\{[(\sigma_1-\sigma_2)^2+(\sigma_1-\sigma_3)^2+(\sigma_2-\sigma_3)^2]/2\}^{1/2}\leq[\sigma] \tag{3}$$

In order to improve the calculation efficiency, the circular seal surface is used to replace the diameter of the welding spot in this paper. Based on the equivalent stress, the fatigue life of the corrugated plate component of the spot welding structure is simulated by the finite element method of stress analysis and calculation, and the structure parameters of welding spot are optimized by combining the cost performance of welding production. Finally, it is verified through physical experiments, and the specific research process is shown in fig. 1.

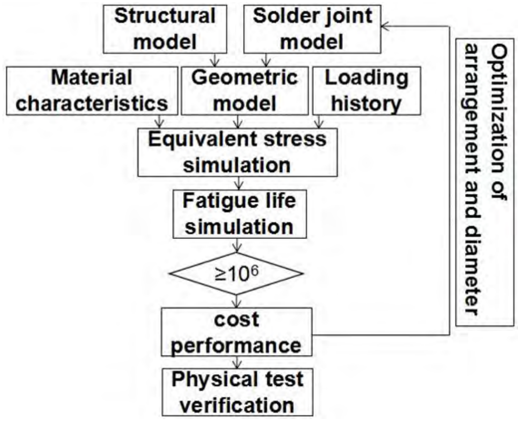


FIGURE I. OPTIMIZATION PROCESS OF WELD SPOT STRUCTURE PARAMETERS

### *B. Welding Model and Loading Method of Corrugated Plate Component*

The corrugated plate component is S316L stainless steel as a whole, the nominal yield limit of the material is greater than or equal to 177 MPa, the tensile strength is greater than or equal to 480 MPa, the elongation is greater than or equal to 45%, the hardness is less than or equal to HV 200, and the elastic modulus is about 200 GPa. In the ANSYS Workbench, the corrugated plate component model is divided into grids. Considering the effect of grid quality and quantity on simulation accuracy and speed, the grid cell size is set to 5 mm, and then the grid around the welding spot model is subdivided and optimized with the cell size of 0.5 mm. The final grid model is shown in fig. 2. The total number of grids is 651485, and the total number of nodes is 1296158.

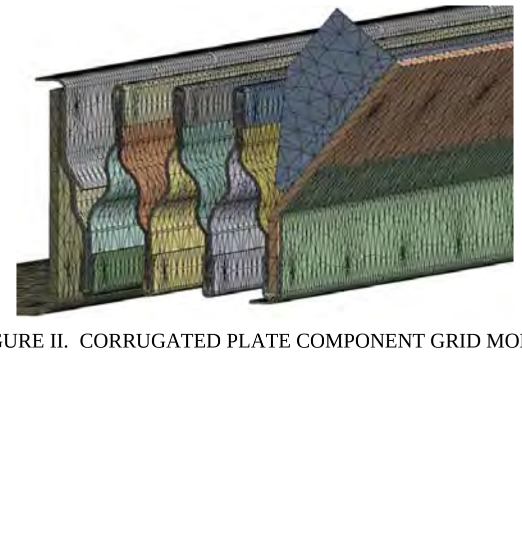

FIGURE II. CORRUGATED PLATE COMPONENT GRID MODEL

The spot-welding joint model and its loading mode is shown in fig.3, where A ~ I is the welding spot. Parts 1 and 2 are 0.6 mm thick corrugated plate sealing sheets, parts 4~ 7 are 0.4 mm thick corrugated plate sealing sheets, parts 3, 8, 9, 10, 14 ~ 16 are 0.6 mm thick u-type joint plates, parts 11, 13, 17 and 18 are 0.6 mm thick folding plates, part 12 is 1.2 mm thick groove friction sealing plates. The u-shaped plate is wrapped with 4 adjacent corrugated plate sealing plates, which are fixedly connected through spot welding. The folding plates and grooved friction sealing plates are then spot-welded on both ends of the corrugated plate components. The end of the folding plate 18 is installed at the corresponding position of the air preheater, and the end of the folding plate 13 is combined with other parts to drive the periodic compression and stretching of corrugated plate component, which plays the role of circular elastic sliding seal. After determining the *S*-*N* curve of the material, the Fatigue strength factor $K_f$ is set to 0.8 and the stress ratio r is set to -1 (i.e., symmetric cyclic alternating stress) in the Fatigue Tool module. Surface load is applied to groove friction seal plate 12 along the X (horizontal) direction, and its size is 200 N. At the same time, a fixed constraint is applied to the folding plate 18.

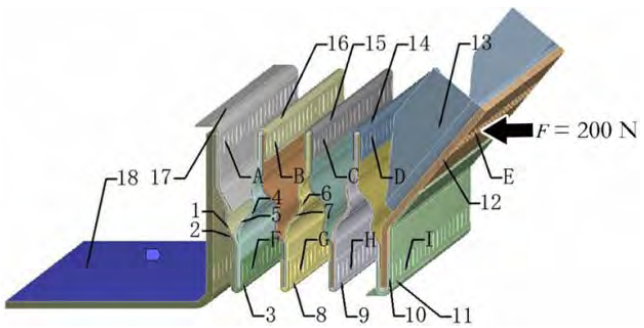


FIGURE III. POSITION OF SPOT WELD AND DIRECTION OF THE LOAD

## III. SIMULATION RESULTS AND DISCUSSION

### A. *Single Row Welding Method*

According to the previous research, in the case of single-row welding, the left and right edge distance of the welding spot is 10 mm, the upper and lower edge distance is 4 mm, and the horizontal distance is 70 mm, the change of the welding spot diameter has a significant impact on the stress of the corrugated plate component, and the corrugated plate component has a better stress condition. At the same time, the arrangement of solder joints is shown in fig.4.

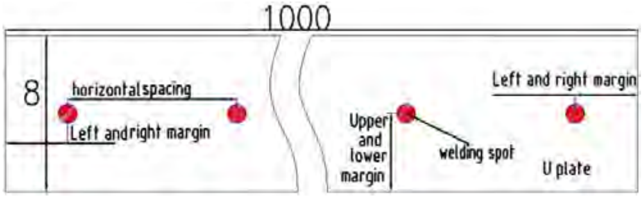


FIGURE IV. SINGLE ROW SOLDER JOINT ARRANGEMENT

### B. *Arrangement Mode of Triangular Welding*

The simulation of corrugated plate component must be based on the analysis of static strength. First of all, there is limited space for the u-shaped plate to be used for spot welding connections. The welding points are arranged in a rectangular area of 1000 mm long and 8 mm wide. In consideration of the welding spot diameter, the integral value between 2 and 7 mm is selected for the welding spot diameter, and the maximum number of welding spot rows is 2 (R is for the row number of welding spot, N is for the number of the first row welding spot, and D is for the diameter of welding spot). When two rows of welding are used, the center of the first row welding spot is 3.5 mm away from the upper boundary, and the left and right edge distance of the welding spot is 10 mm, and the welding spot is uniformly distributed. The center of the second row welding spot is 4.5 mm away from the upper boundary, and the welding spot is located on the center line of any two adjacent welding points in the first row. Thus, the second row of solder joints is one less than that of the first and any adjacent 3 solder joints form an isosceles triangle. Horizontal spacing refers to the distance between two adjacent solder joints in the horizontal direction. At this point, the specific arrangement of welding spots is shown in fig. 5.

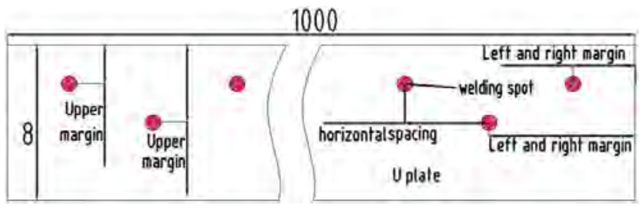


FIGURE V. SPOT TRIANGULAR ARRANGEMENT

In the above solder joint arrangement mode, the simulation results of equivalent stress and fatigue life of corrugated plate components are shown in table 1 through corresponding solution Settings. Under the arrangement mode of some solder joints, the fatigue life of corrugated plate components are less than 1.0e6 times of expected life (see the underlined data in the table).

TABLE I. SIMULATION RESULTS OF EQUIVALENT STRESS AND FATIGUE LIFE UNDER DIFFERENT WELDING SPOT DIAMETERS AND ARRANGEMENT MODES (STRESS [M PA], FATIGUE LIFE [TIMES])

| Arrangement mode | Diameter of welding spot | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | 2 mm | | 3 mm | | 4 mm | | 5 mm | | 6 mm | | 7 mm | |
| | Stress | Life | Stress | Life | Stress | Life | Stress | Life | Stress | Life | Stress | Life |
| R1N15 | 114.0 | 7.44e4 | 82.17 | 2.75e5 | 58.9 | 1.39e6 | 44.03 | 3.17e6 | 44.31 | 3.14e6 | 43.77 | 3.20e6 |
| R2N15 | 66.34 | 9.44e5 | 64.54 | 1.05e6 | 66.34 | 9.44e5 | 66.79 | 9.08e5 | 67.8 | 8.32e5 | 71.51 | 6.13e5 |
| R2N10 | 98.3 | 1.28e5 | 72.43 | 5.70e5 | 61.87 | 1.20e6 | 63.86 | 1.09e6 | 63.41 | 1.11e6 | 66.26 | 9.51e5 |
| R2N9 | 67.3 | 8.69e5 | 64.02 | 1.08e6 | 64.34 | 1.06e6 | 64.04 | 1.08e6 | 65.4 | 1.01e6 | 67.36 | 8.64e5 |
| R2N8 | 66.2 | 9.55e5 | 65.88 | 9.82e5 | 65.73 | 9.95e5 | 61.86 | 1.20e6 | 67.3 | 8.69e5 | 68.04 | 8.16e5 |
| R2N7 | 56.58 | 1.57e6 | 62.91 | 1.14e6 | 56.3 | 1.59e6 | 55.65 | 1.64e6 | 58.46 | 1.42e6 | 63.19 | 1.12e6 |
| R2N6 | 56.6 | 1.56e6 | 61.91 | 1.19e6 | 56.24 | 1.59e6 | 57.94 | 1.46e6 | 59.5 | 1.34e6 | 56.06 | 1.61e6 |

It can be seen from table 1 that the equivalent stress of corrugated plate components are all less than 177 MPa, meeting the requirements of static strength. The linear accumulation rule of Miner only applies to the linear part of *S-N* curve, that is, the part within the elastic limit range of the material [17], while the equivalent stress of the corrugated plate module is far less than the nominal yield limit, which satisfies the use condition of the linear accumulation rule of Miner. In order to study whether the welding spot diameter and horizontal spacing have a significant effect on the stress status of corrugated plate component, the equivalent stress of corrugated plate component in the triangular arrangement mode in table 1 is analyzed by means of variance without repeated two-factor test. The results are shown in table 2. For a given significance level of 0.01, the *F* distribution table shows that $F_{0.01}$ (5, 25) = 3.85. $F_A$ is less than or equal to 3.85, indicating that when the horizontal spacing between welding is kept unchanged, there is no significant effect on the equivalent effect force of welding spot diameter change. $F_B$ is greater than or equal to 3.85, which indicates that the change of the horizontal distance of the welding spot has a significant effect on the change of the equal effect force when the diameter of the welding spot remains unchanged. However, in the early stage of single-row welding, the variance analysis of two-factor unrepeated test on the welding spot diameter and horizontal spacing of the equivalent stress of corrugated plate component showed that both the welding spot diameter and horizontal spacing had no significant effect on the stress of corrugated plate component. The results of two variance analysis show that the triangulation of welding spot can change the force condition of corrugated plate component.

TABLE II. ANALYSIS OF VARIANCE

| Differences between the source | *SS* | | *d f* | | *MS = SS/d f* | | *F = MS/MS*$_E$ | |
|---|---|---|---|---|---|---|---|---|
| Factor A (diameter) | $SS_A$ | 201.98 | $d f_A$ | 5 | $MS_A$ | 40.4 | $F_A$ | 1.11 |
| Factor B (pitch) | $SS_B$ | 756.74 | $d f_B$ | 5 | $MS_B$ | 151.35 | $F_B$ | 4.17 |
| Error | $SS_E$ | 906.45 | $d f_E$ | 25 | $MS_E$ | 36.26 | | |
| Sum | $SS_T$ | 1865.17 | $d f_T$ | 35 | | | | |

(note: *SSA*, *SSB* -- sum of squares of deviation caused by factor *A* and factor *B*;*SSE* - sum of squared error;*SST* - sum of total deviation squared;$d_f$ - degrees of freedom for each sum of squares;$MS_A$, $MS_B$ -- the mean square between the groups of factor *A* and factor *B*, and $MS_E$ -- error mean square;$F_A$, $F_B$ -- *F* test of factor *A* and factor *B*)

On the macro level, the material's microstructure, mechanical nonuniformity, fatigue resistance are random, fatigue crack initiation and propagation rate and fatigue life show statistical characteristics [18]. For welding parts, the contour parameters at the actual welding joint are also random along the weld length direction, and the resulting stress concentration will also change randomly [14, 16]. 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, which greatly promoted the formation and accumulation of fatigue damage. In addition, according to the Miner linear cumulative damage theory, the damage in the stress concentration affected zone overlaps with each other, resulting in a fluctuation in the fatigue life of the corrugated plate component [16,19,20].

Fig. 6 shows the effect of welding spot diameter on the fatigue life of corrugated plate component under each arrangement mode. It can be seen from fig. 6 that the fatigue life of corrugated plate component changes significantly with the change of welding spot diameter during single-row welding, which is consistent with the previous study - the change of welding spot diameter has a significant effect on the stress situation of corrugated plate component when single-row welding and horizontal spacing is 70 mm. While in the triangular arrangement, the fatigue life of corrugated plate component does not change significantly with the change of welding spot diameter, and there are slight fluctuations. This is consistent with the result of variance analysis in table 2, that is, the change of welding spot diameter has no significant effect on the equivalent effect force. The fluctuation may be caused by the increase of weld diameter, the increase of micro defects of materials, and the random superposition of damage in the area affected by stress concentration.

Fig. 7 shows the effect of horizontal spacing on the fatigue life of corrugated plate component in the triangular arrangement of solder joints. Locally, the fatigue life of the corrugated plate component varies slightly with the horizontal spacing of the solder joints. As a whole, the fatigue life of corrugated plate component increases with the increase of horizontal distance between solder joints. In the triangular arrangement mode, when the horizontal spacing changes in a small range, the stress concentration area of the corrugated plate component is randomly superimposed, resulting in small fluctuations. However, when the horizontal spacing changes greatly, the stress of corrugated plate component changes greatly, and the joint effect of welding spot on the corrugated plate component and the random superposition effect on the stress concentration area around the welding spot intersects with each other, resulting in a large change in the fatigue life of the corrugated plate component. This is consistent with the results of variance analysis in table 2, in which the change of the horizontal spacing of the solder has a significant effect on the change of the equivalent force while the diameter of the solder remains unchanged.

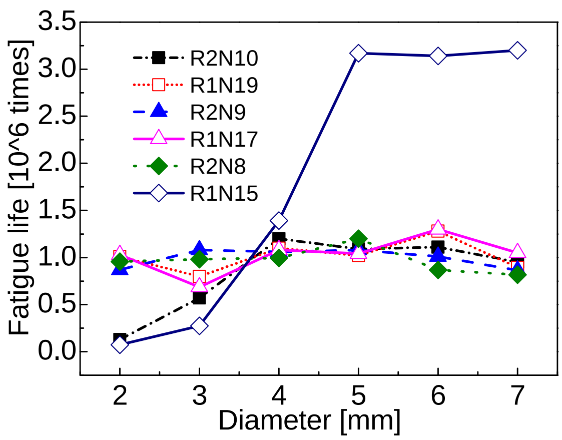


FIGURE VI. EFFECT OF WELDING SPOT DIAMETER ON FATIGUE LIFE

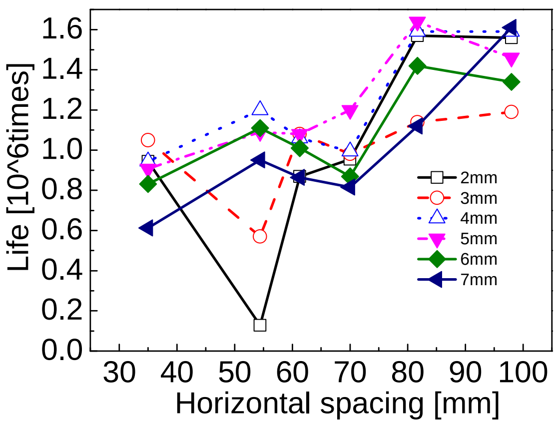


FIGURE VII. EFFECT OF HORIZONTAL SPACING OF SOLDER JOINTS ON FATIGUE LIFE

In order to select a method of welding spot arrangement with good performance ratio, it is assumed that the cost of each welding spot with a diameter of 2 mm is A yuan, and the cost of welding spot is proportional to the diameter of welding spot. Data of fatigue life over 1.0e6 times in table 1 are screened out for preliminary cost calculation, and the results are shown in table 3. Among them, corrugated plate component has the most cost-effective during the R2N6D2 arrangement mode. At this point, the equivalent stress cloud diagram and fatigue life cloud diagram of the corrugated plate component are respectively shown in fig. 8 and fig. 9.

TABLE III. PERFORMANCE RATIO OF CORRUGATED PLATE COMPONENT FATIGUE LIFE

| Arrangement mode | Diameter of welding spot | | | | | |
|---|---|---|---|---|---|---|
| | 2 mm | 3 mm | 4 mm | 5 mm | 6 mm | 7 mm |
| | Cost performance | | | | | |
| R1N15 | —— | —— | 46333/A | 84533/A | 69778/A | 60952/A |
| R2N15 | —— | 24138/A | —— | —— | —— | —— |
| R2N10 | —— | —— | 31579/A | 22947/A | 19474/A | —— |
| R2N9 | —— | 42353/A | 31176/A | 25411/A | 19084/A | —— |
| R2N8 | —— | —— | —— | 32000/A | —— | —— |
| R2N7 | 120769/A | 58462/A | 61154/A | 50462/A | 36410/A | 24615/A |
| R2N6 | 141818/A | 72121/A | 72273/A | 53091/A | 40606/A | 41818/A |

It can be seen from fig. 8 and fig. 9 that the equivalent stress of corrugated plate component is 56.6 MPa and its fatigue life is 1.56e6. In general, under the arrangement mode, the fatigue strength of corrugated plate component meets the requirements of working condition and has a good performance ratio.

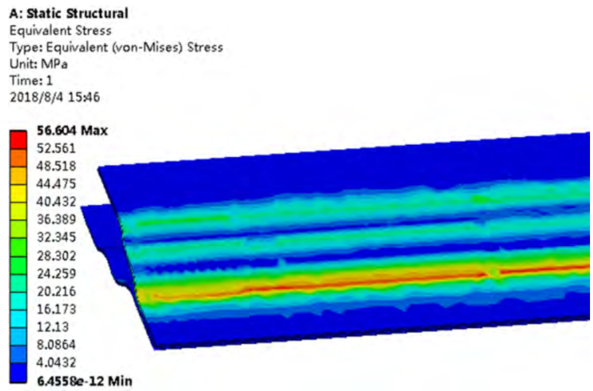


FIGURE VIII. EQUIVALENT STRESS CLOUD OF CORRUGATED PLATE COMPONENT

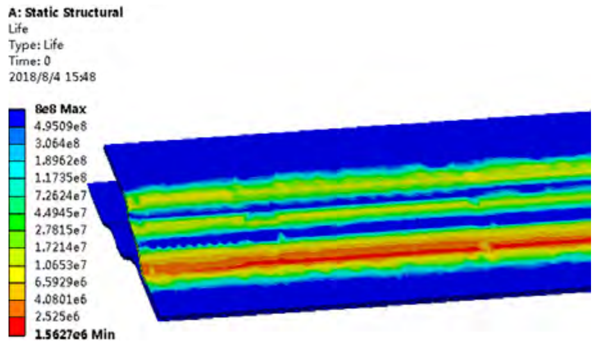


FIGURE IX. FATIGUE LIFE CLOUD DIAGRAM OF CORRUGATED PLATE COMPONENT

## IV. EXPERIMENTAL VERIFICATION

According to table 3 of the proceeds of the structural parameters of solder joint processing three pieces of corrugated plate component, shown in figure 10 linkage reciprocating motion of the test, at more than the physical test load conditions, the eccentric wheel drive reciprocating motion mechanism by speed 20 r/s cyclic tensile compression corrugated plate component, the minimum of 8 mm, maximum of 15 mm cyclical tensile compression deformation. 3 corrugated plate components have no damage under repeated compression for 2.0e7 times. Their fatigue life is far beyond the requirements of operating conditions, which proves that the welding joint structure parameters after simulation calculation and analysis and optimization are reliable and reasonable.

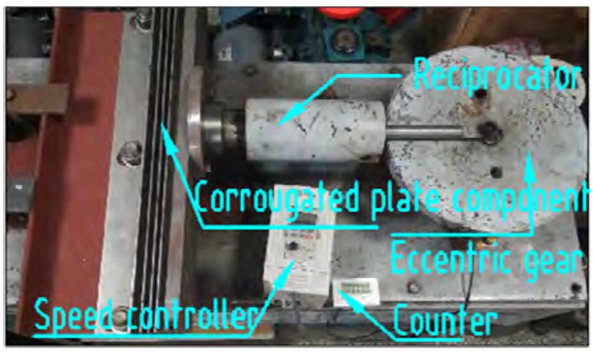


FIGURE X. FATIGUE TEST BENCH OF CORRUGATED PLATE COMPONENT

## V. CONCLUSION

(1) When the welding spot is arranged in triangular mode, the change of welding spot diameter has no significant effect on the equivalent stress of corrugated plate component, while the change of welding spot horizontal spacing has significant effect on the equivalent stress of corrugated plate component.

(2) Considering fatigue life and price ratio of the corrugated plate component, the solder joint structure parameters which should be choosed are as follows: The left and right margin of the welding spot in the first row is 10 mm, the number of welding spot is 6, and the center of the welding spot is 3.5 mm away from the upper boundary, while the left and right margin of the second welding spot is 108 mm, the number of welding spot is 5, and the center of the welding spot is 4.5 mm away from the upper boundary. The diameter of the two welding spots is 2 mm and the horizontal spacing is 196 mm. Under this arrangement mode, the fatigue life of corrugated plate component has reached 1.56e6 times. And under physical test, the actual fatigue life of corrugated plate component has exceeded 2.0e7 times, meeting the requirements of working condition.

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