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Effect of Welding Spot Spacing and Row Number on Fatigue Life of Corrugated Plate Component

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Abstract

Based on the equivalent stress， the fatigue life of corrugated plate component is simulated and its cost performance is calculated by using a simple model. Then,the research route is obtained, and the rationality of the structure parameters of the optimized welding joints is proved by physical test.It is found that the horizontal spacing between welding points has a significant effect on the fatigue life .As the horizontal spacing increases, the fatigue life decreases, and the trend is consistent with quadratic polynomial law. While,the row number of solder joints has no significant effect on the fatigue life for the upper and lower distance between the solder joints is too small. Considering the fatigue life and cost performance in a comprehensive way,it is a better welding spot structure parameter that the row number of solder joints is one,the left and right edge distance of welding points is 10 mm, the upper and lower edge distance is 4 mm, and the horizontal distance between welding points is 65.3 mm. At this point, the fatigue life simulation result is 2.06e6 times.Physical test shows that the actual fatigue life under this welding method is more than 2.0e7 times, which meets the requirement of working condition.

Keywords

Corrugated plate component; Equivalent stress; Fatigue life; Welding spot structure parameters; Physical test.

1. Introduction

The air preheater is mainly divided into heat pipe type, rotary type and various column pipe type[1].Sun jian et al.[2] expounded the hazards of air leakage in air preheater to its efficient and stable operation . At present, flexible sealing is one of the most advanced and effective sealing technologies [3],corrugated plate component is a good flexible sealing device for air preheater,which is subject to symmetric circulating load when working, and its fatigue performance has a direct effect on its sealing performance.The corrugated plate component adopts S316L non-extrusion forming, which requires combination connection, and S316L has good welding performance, which is suitable for spot welding.

Zhang yanhua [4] expounded three methods of strength analysis of welding parts, namely analytical method, numerical simulation method and engineering method. Among them, numerical simulation can obtain results which are difficult to obtain by experiment and theoretical analysis, and can effectively shorten the product development cycle, reduce cost, improve quality and production efficiency.R. KEIVANI [5] et al. used the finite element 3d model to study the thermal characteristics of copper C11000 in the process of FSW, and the temperature prediction results were in good agreement with the experimental results.Tao J F[6] et al. established the axisymmetric finite element numerical simulation model of thermoelectric coupling field based on the thermal effect zone and

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phase change principle of aluminum alloy spot welding, and revealed the mechanism of thermoelectric coupling transient and steady state difference.Ding-Fa FU[7]et al. established a three-dimensional finite element model by thermal-elastoplastic finite element method, studied the effect of different welding sequences on the residual stress of thin wall 6061 alloy welded parts after welding, and believed that choosing a reasonable welding sequence could effectively reduce the residual stress of octagonal pipe-plate joints.Therefore, it is feasible to stud-y the fatigue performance and other quality performance of mechanical parts by simulation.

The effect of soldering point factor on the fatigue performance of corrugated plate component is studied by simulation.The static strength of corrugated plate component is simulated under different welding joints spacing and row number, and the fatigue life is simulated by combining Fatigue Tool.On this basis,in order to obtain better welding spot structure parameters,the data analysis and processing are carried out.Finally, physical test is used to verify the rationality of the structure parameters of the optimized solder joint.

2. Research methods and model construction

2.1 Selection of welding spot structure parameter optimization method

There are two methods to estimate fatigue life, namely nominal stress method and local stress-strain method.The nominal stress method is applicable to high cyclic stress conditions with cycles of more than 1.0e4 times,while the local stress-strain method mainly combines the cyclic stress-strain curve of materials, and converts the nominal stress spectrum of components into the local stress-strain spectrum of dangerous parts through elastic-plastic finite element analysis or other calculation methods, and then estimates the service life according to the local stress and strain history of dangerous parts [8].The corrugated plate component needs to be replaced every 5 to 10 years, and the speed of the air preheater is 0.25 r/min and it 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 the median S-N curve, and the equation is shown in equation (1) [9]. Where S is the stress, m and C are the material constants determined by the test, and N is the life span.Take the logarithm of both sides of the equation and work out the formula (2).When N = 1.0e6, σ_{10^6} = δσ， according to the types of materials and heat treatment,and use“the table for the fatigue property estimation of commonly used domestic materials ”[9] to reasonably evaluate the advantage δ and b.Among them,a = Lg (c), δ = s, b =m .So we can determine the S-N curve of the material.

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

$$Lg\ N=a+b\ Lg(\sigma) \tag{2}$$

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

Spot diameter /mm	Spot pitch/mm					
	25		50		100	
	Equivalent stress/M Pa	Fatigue life/times	Equivalent stress/M Pa	Fatigue life/times	Equivalent stress/M Pa	Fatigue life/times
2	888.2	161.3	927.9	144.7	2533.3	14.5
4	888.8	161.0	928.4	144.6	2534.6	14.5
6	888.7	161.0	928.4	144.5	2534.6	14.5

The calculation accuracy is high and the effect of welding spot diameter can be analyzed when setting welding spot with beam element. However, if the number of welding points is large and the product

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structure is complex, the model establishment and fatigue life calculation take a long time.In order to select simple and reasonable solder joint model and simulation calculation method,and simplify the research process, two pieces of seal are used as the simple model pre-research .During the pre-research ,the beam element solder joint model with 2, 4, 6 mm diameter solder joint as an example is adopted ,which under the condition of 200 N load symmetry and the simulation of the static strength and fatigue life is carried out ,in order to determine the basic effect law of the spot size and spacing on the stress distribution and fatigue life .The simulation results are shown in table 1.

Under the three kinds diameters of solder joints, the equivalent stress of the simple model increases with the horizontal distance of solder joints, and the corresponding fatigue life decreases with the increase of equivalent stress.This may be due to the increase in horizontal distance between solder joints and the decrease in the number of solder joints, which result in the weakening of solder joints to the seals.The equivalent stress and fatigue life are similar under different diameters of solder joints.It can be seen that under working conditions, the change trend of fatigue life of the simple model is opposite to that of equivalent stress, that is, the smaller the equivalent stress is, the larger the fatigue life is.

It is generally believed that the maximum principal stress can explain the fatigue damage mechanism when studying fatigue life, that is ,the degree of the damage to which the isotropic probability of atomic escape can be represented .However, this theory is only applicable when one of the three maximum principal stresses occupies a dominant position [10].Sometimes, however, although the unidirectional load of structural component is very big ,but no damage ,this is because the tests of strength of materials are generally under unidirectional loading strength, and product structure has its complexity,the stress distribution under the condition and that of single tensile force of the structure will produce great differences, there may be no maximum principal stress in the dominant position .This is consistent with the rule reflected by the simulation results of some previous studies, that is, sometimes the maximum principal stress obtained from the simulation increases, and the corresponding fatigue life not only does not decrease, but also increases with it . 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 that results in material yield failure is distortion energy density, specific formula (3), which transformed the main stress（σ1、σ2、σ3）to equivalent stress（σs） to discuss [11].As a result, the fatigue life and equivalent stress of the simple model in table 1 are well correlated.

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

Taking the diameter of 6 mm as an example, the equivalent stress cloud diagram of the simple model is shown in Fig.1.When the welding spot horizontal spacing is 100 mm, there is no superposition of the stress concentration area around the welding spot.When the spacing is reduced to 50 mm, superposition begins to occur in the stress concentration impact zone, and becomes more obvious when the spacing is reduced to 25 mm.So,it can be seen that the horizontal spacing of the solder joint may significantly affect the superposition of the stress concentration area around the solder joint.When the welding spot diameter is 2 mm and 4 mm, the superposition of the stress concentration impact zone around the welding spot changes with the horizontal distance of the welding spot, which is similar to that when the diameter is 6 mm.

In order to improve the calculation efficiency, the effect of welding spot diameter and horizontal spacing on the stress and fatigue life under the simple model is integrated . In this paper, the effect of welding spot diameter will be ignored ,that is, the beam element is not used to build the soldering point model.According to the simulation accuracy and modeling efficiency of the model, combined with the welding principle and force characteristics of welding parts, Creat point command inside Desing Modeler module is selected to establish the welding spot unit.Software default welding spot

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as a particle, its essence is a binding contact, which will bound the separated parts together.Meanwhile, the welding joint structure parameters are optimized on the basis of the cost performance of the fatigue life of corrugated plate component ,and the flow chart is shown in Fig.2 .First, according to the actual working conditions, material characteristics and loading process of corrugated plate component, static strength simulation calculation is conducted in the Workbench, and then fatigue life calculation is conducted by combining with Fatigue Tool, and the cost performance of fatigue life is calculated to optimize the welding joint structure parameters.Finally, the rationality of the structure parameters of the solder joint after simulation optimization is verified by physical test .

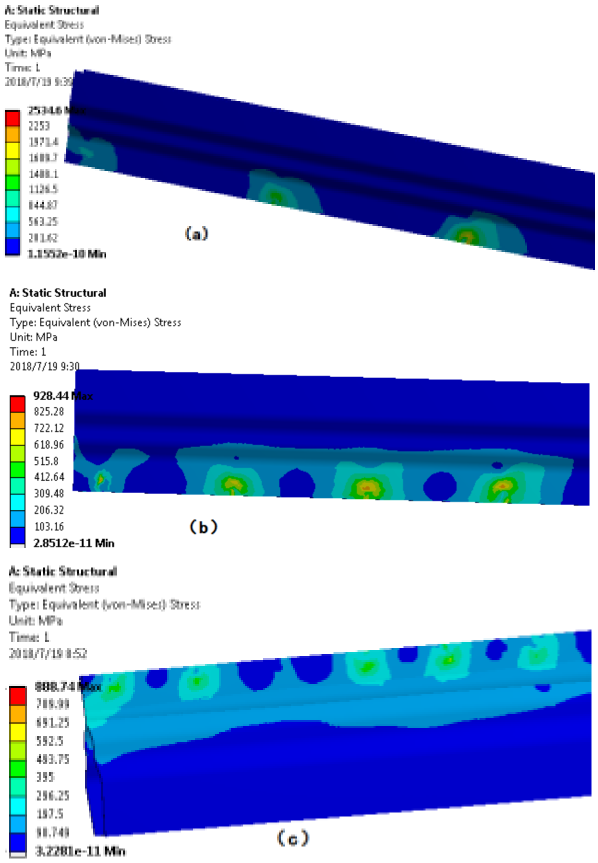

Fig.1 Equivalent stress cloud map of different solder joints in diameter of 6 mm
(a)100 mm; (b) 50 mm; (c) 25 mm;

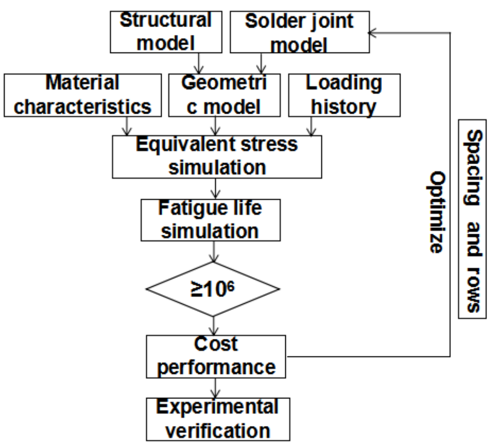

Fig. 2 Simulation process of fatigue life.

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2.2 Corrugated plate component model and loading method

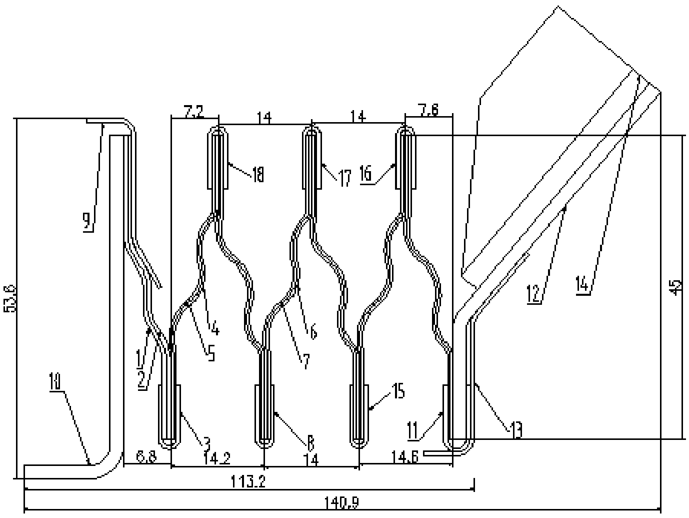

Fig.3 Corrugated plate component structure

The structure of corrugated plate component is shown in Fig.3, where parts 1 and 2 are 0.6 mm thick sealing sheet, parts 4 ~ 7 are 0.4 mm thick sealing sheet, parts 3, 8, 11, 15 ~ 18 are 0.6 mm thick u-plate, parts 9, 10, 13 and 14 are 0.6 mm thick folding plate, and parts 12 are 1.2 mm thick groove plate.The u-shaped plate is wrapped with 4 adjacent sealing sheets, which are fixedly connected through spot welding, and then connected with folding plate and groove plate respectively at both ends of corrugated plate component .10 ends of the folding plate are installed in the corresponding position of the air preheater, and 14 ends of the folding plate cooperate with other parts to drive the periodic compression and stretching of the corrugated plate component to play the role of circular sealing and air exchange.

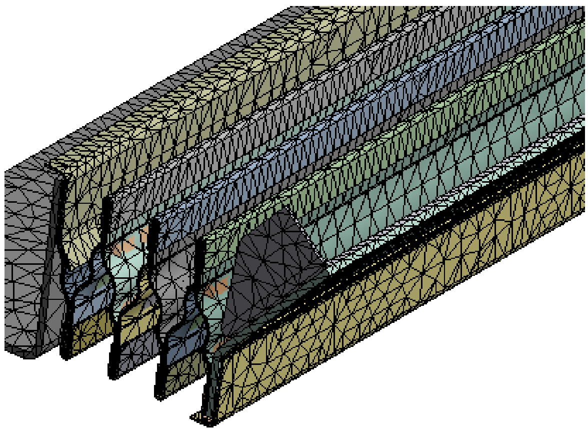

Fig. 4 Corrugated plate component grid model

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 unit size is set to 5 mm before optimization.The final model is shown in Fig.4. The total number of grids is 651485, and the total number of nodes is 1296158.

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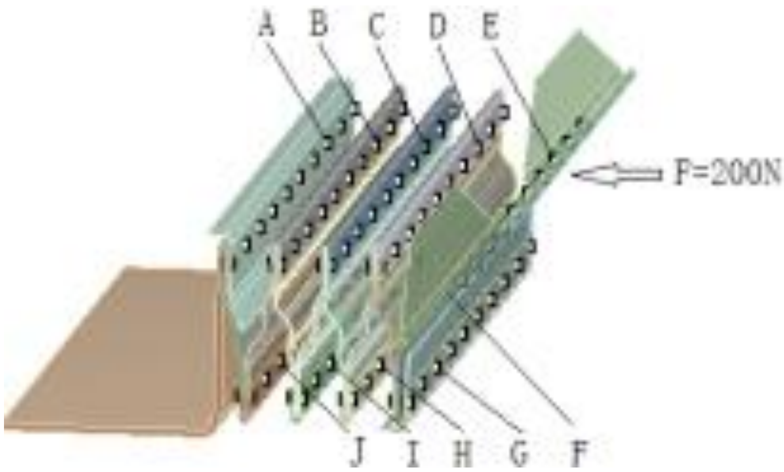

Fig.5 Position of spot weld and direction of the load

The spot-welding joint model and its loading mode is shown in Fig.5, where A ~ F is the welding spot.After determining the S-N curve of the material, the fatigue strength factor Kf is 0.8 and the stress ratio r is -1 (symmetric cyclic alternating stress) in the Fatigue Tool module, and 200 N is applied to groove plate 12 along the X (horizontal) direction.At the same time, a fixed constraint is applied to the folding plate 10.

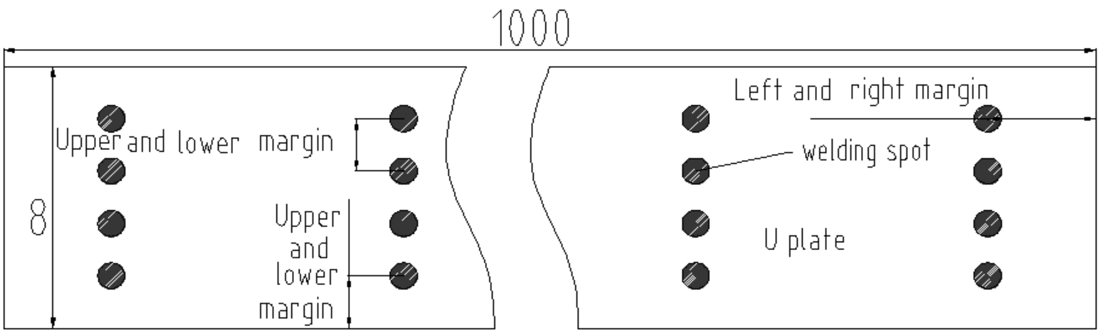

Fig. 6 Welding spot arrangement

The arrangement of welding spots is shown in Fig.6,according to the u-shaped plate width, equally arranged 1 ~ 4 row of solder joints, upper and lower side of the solder joints of u-shaped plate edge distance and the distance between the adjacent two rows of welding spots are equal, each row of solder joints along the u-shaped plate length direction parallel to decorate, 11 ~ 20 solder joints, uniform distribution and left and right side of the solder joint is apart from the U plate edge distance is fixed 10 mm.See table 2 for specific parameters of welding spot arrangement, a total of 40 layout methods.

Table 2 Welding spot layout of corrugated plate component

Solder joints row number	Left and right margin/mm	Upper and lower margin/mm	Horizontal spacing/mm
1		4	
2	10	2.7	98、89.1、81.7、75.4 70、65.3、 61.3、57.6、54.4、51.6
3		2	
4		1.6	

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3. Simulation results and discussion

It can be seen from table 3 that the equivalent stress of corrugated plate component is all less than 177 MPa under different welding spot spacing and row number connection, meeting the requirement of static strength of corrugated plate component .At the same horizontal spacing, the equivalent stress does not change significantly with the increase of the number of solder joint rows.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 [13], while the equivalent stress of the corrugated plate component is far less than the nominal yield limit, which satisfies the use condition of the linear accumulation rule of Miner.

Table 3 Equivalent stress simulation results in different quantities and rows of spot welds

Solder joints row number	Spot pitch/mm									
	98	89.1	81.7	75.4	70	65.3	61.3	57.6	54.4	51.6
	Equivalent stress / MPa									
1	79.56	78.98	63.13	58.47	61.13	48	51.6	50.33	45.80	46.65
2	86.52	79.97	64.49	60.97	54.37	54.41	48.05	48.76	46.73	43.47
3	90.31	72.31	66.82	64.99	65.69	51.14	49.38	52.31	43.12	46.34
4	88.63	67.61	70.80	61.50	63.81	52.49	56.36	53.11	47.70	46.02

In order to study whether the distance between solder joints and the number of rows has a significant impact on the equivalent stress of corrugated plate component, the variance analysis of double-factor non-repeat test was conducted on the data in table 3, and the analysis results are shown in table 4 .For a given significance level of 0.01, the F distribution table shows that F0.01 (9, 27) = 3.15 and F0.01 (3, 27) = 4.60 . FA is greater than or equal to 3.15, indicating that the change in the distance of solder has a significant effect on the equivalent stress when the number of solder joints remains unchanged.FB is less than or equal to 4.6, indicating that the change of the row number of welding spots has no significant effect on the equivalent stress when the distance between welding spots remains unchanged.

Table 4 Analysis of variance

Differences between the source	SS		df		$MS = SS/df$		$F = MS/MS_E$	
Factor A (pitch)	SS_A	6322.6	df_A	9	MS_A	702.5	F_A	54.46
Factor B (rows)	SS_B	40.4	df_B	3	MS_B	13.47	F_B	1.04
Error	SS_E	348.35	df_E	27	MS_E	12.9		
Sum	SS_T	6711.35	df_T	39				

(Note: SS_A、SS_B -the sum of squares of deviations caused by factor A and B ; SS_E-error squared sum; SS_T -total deviation squared sum ;df - squared sum of degrees of freedom ;MS_A、MS_B - factor A, B's group mean square; MS_E-error mean square ;F_A、F_B-factor A, B's f test. ）

The simulation results of fatigue life of corrugated plate component are shown in table 5. Under the arrangement mode of some welding spots, the fatigue life of corrugated plate component is less than 1.0e6 times of expected fatigue life (see underlined data).

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Table 5 Fatigue life simulation results in different quantities and rows of spot welds

Solder joints row number	Spot pitch/mm									
	98	89.1	81.7	75.4	70	65.3	61.3	57.6	54.4	51.6
	Fatigue life/times									
1	2.18e5	2.27e5	8.25e5	1.14e6	9.93e5	2.06e6	1.66e6	1.79e6	2.37e6	2.24e6
2	1.56e5	2.11e5	7.30e5	1.00e6	1.42e6	1.41e6	2.05e6	1.97e6	2.23e6	2.77e6
3	1.33e5	3.78e5	5.95e5	6.98e5	6.56e5	1.70e6	1.89e6	1.59e6	2.84e6	2.29e6
4	1.43e5	5.56e5	4.26e5	9.60e5	7.76e5	1.58e6	1.27e6	1.52e6	2.10e6	2.34e6

Fig.7 shows the effect of horizontal spacing on fatigue life. On the whole, the fatigue life decreases with the increase of horizontal distance between solder joints, which may be caused by the decrease of number of solder joints, the increase of spacing, and the weakening of connection effect of corrugated plate component.Under the parameter conditions in this paper, the variation trend of fatigue life with the horizontal spacing of solder joints is generally in accordance with formula (4). In each welding row, the fatigue life fluctuates up and down along the trend line as the spacing changes. On the one hand, it may be that the number of solder joints is different and the position of solder joints changes accordingly. In order to adapt to the solder joints model, the overall grid model of corrugated plate component is adjusted accordingly, resulting in certain calculation fluctuations. Second, a situation similar to that in fig.1, the welding spot spacing is small, resulting in the overlapping of the stress concentration area near the welding spot .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 [4]. 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 [9, 11]. On microscopic ,the escape isotropic of atoms or molecules is damaged in stress concentration area ,leading to the increases of probability of atoms or molecules in a certain direction to escape, which lead to the transient cavitation that caused by atoms or molecules escape can't be filled by atoms or molecules that escape elsewhere ,so the formation and accumulation of fatigue damage is greatly promoted.In addition, according to the Miner linear cumulative damage theory, the damage in the area of impact of stress concentration overlaps with each other, which also leads to the fluctuation of the fatigue life of corrugated plate component [10-12]. In actual welding, when the stress concentration area near the welding spot is superimposed on each other, the local stress of corrugated plate component will be uneven, and the slight deformation of the contour at the welding spot will make the stress distribution fluctuate. The simulation results are consistent with the actual situation.

$$y=ax^2+bx+c \quad (4)$$

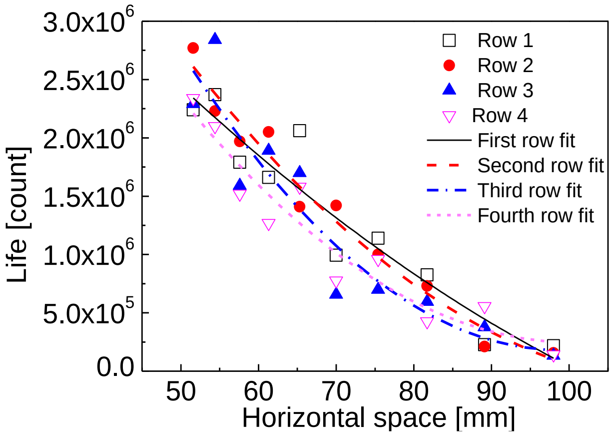

Fig. 7 Effect of solder joints spacing on fatigue life

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The effect of variation of upper and lower spacing on fatigue life of corrugated plate component at different horizontal spacing is shown in Fig.8.The fatigue life has no obvious change trend with the decrease of the upper and lower spacing of the solder joints, which is consistent with the analysis results of the significance of the effect of each factor on equivalent stress in table 4, that is, the number of solder joints has no significant effect on the equivalent stress of corrugated plate component.It is possible that the welding points along the width of u-shaped plate are relatively dense, causing the stress concentration areas near the welding points in the upper and lower directions to overlap with each other. Theoretically, the stress distribution caused by such superposition will be random, resulting in the overlapping of fatigue damage and randomness.

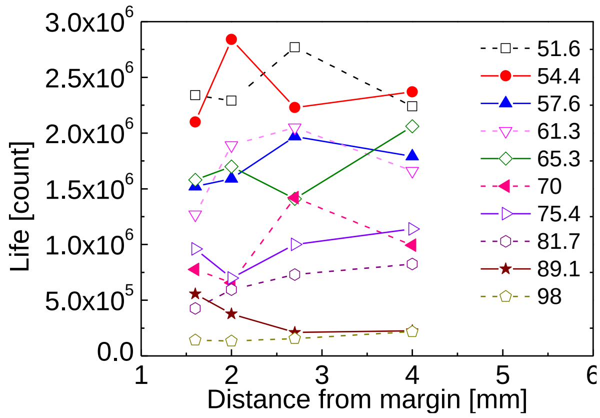

Fig. 8 Effect of upper and lower spacing on fatigue life

In order to select the welding spot arrangement mode with better performance and price, it is assumed that the cost of each welding spot is A yuan. The data with fatigue life over 1.0e6 times in table 4 are screened out for preliminary cost calculation, and the results are shown in table 6.Under the condition that the distance between solder joints remains unchanged, the cost performance of the fatigue life of corrugated plate components decreases with the increase of the row number of solder joints, among which the cost performance of corrugated plate is the highest when the row number of solder joints is 1 and the horizontal spacing is 65.3 mm.In this connection mode, the equivalent stress cloud diagram and fatigue life cloud diagram of corrugated plate component are respectively shown in Fig.9 and Fig.10

Table 6 Performance ratio of corrugated plate component fatigue life

Solder joints row number	Spot pitch/mm						
	75.4	70	65.3	61.3	57.6	54.4	51.6
	Cost performance						
1	81429/A	——	128750/A	97647/A	99444/A	124737/A	112000/A
2	29412/A	40571/A	39167/A	55405/A	51842/A	57180/A	69250/A
3	——	——	30357/A	33158/A	27413/A	48136/A	38167/A
4	——	——	20790/A	16494/A	19487/A	26582/A	29250/A

It can be seen from Fig.9 and Fig.10 that the equivalent stress of corrugated plate component is 48MPa and its fatigue life is 2.06e6.In general,when the left and right margin of solder joints is 10 mm ,single row spot-welding structure with horizontal spacing of 65.3 mm is adopted to connect corrugated plate

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component,fatigue strength can meet the operating condition requirements and is of good cost performance.

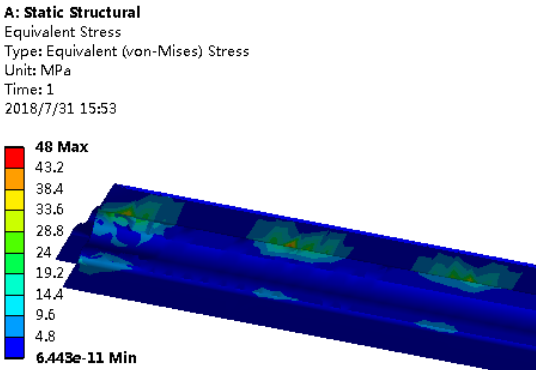

Fig.9 Equivalent stress cloud of corrugated plate component

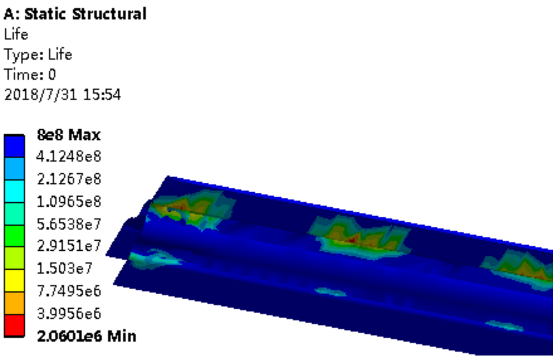

Fig. 10 Fatigue life of corrugated plate component

4. Experimental verification

In accordance with table 6 of the proceeds of the solder joint structure parameters processing three pieces of corrugated plate component,the linkage reciprocating motion of the test is shown in Fig.11.In the case of exceeding the operating load ,the eccentric wheel drive reciprocating motion mechanism by speed 20 r/s cyclic compression corrugated plate component,make its minimum of 8 mm, maximum of 15 mm periodic compression deformation . 3 corrugated plate components have no damage under repeated compression for 2.0e7 times.Which proves that the welding joint structure parameters resulted from simulation calculation and analysis and optimization are reliable and reasonable.

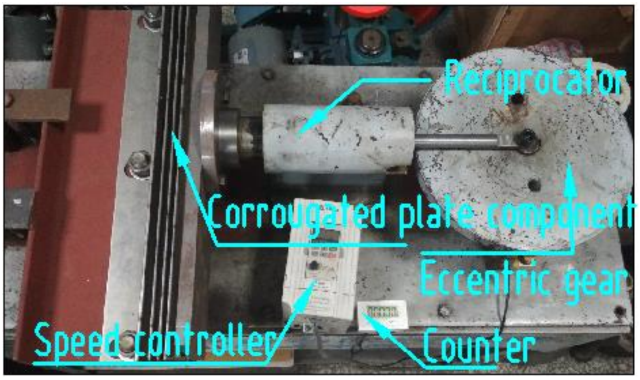

Fig.11 Fatigue test bench of corrugated plate

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5. Conclusion

(1) According to the structure and working condition of corrugated plate component, the fatigue life of corrugated plate component is studied on the basis of equivalent stress ,the simulation method is reasonable.The row number of welding spots (upper and lower spacing) has no significant effect on the equivalent stress and fatigue life of the corrugated plate component ,while the horizontal spacing of solder joints has significant effect on the equivalent stress and fatigue life of corrugated plate component .The fatigue life of corrugated plate component decreases with the increase of the horizontal spacing of solder joints, and its variation trend generally conforms to the law of quadratic polynomial.

(2) Considering the fatigue life and cost performance of corrugated plate component comprehensively, the fatigue simulation result of corrugated plate component is 2.06e6 times when the left and right margin of welding spots is 10 mm and the upper and lower margin is 4 mm, and the horizontal distance between welding spots is 65.3mm .Physical test shows that the actual fatigue life of corrugated plate component exceeds 2.0e7 times under the arrangement mode, which meets the requirements of working condition.

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