Influences of fine pitch solder joint shape parameters on fatigue life under thermal cycle[①]

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Abstract: The solder joint reliability of a 0.5 mm lead pitch, 240-pin quad flat package(QFP) was studied by nonlinear finite element analysis(FEA). The stress/strain distributions within the solder joints and the maximum plastic strain range of the solder joints were determined. Based on the calculated maximum plastic strain range the thermal fatigue life of the solder joints was calculated using Coffin-Manson equation. The influences of shape parameters including volume of solder joint, pad size and stand-off on the thermal fatigue life of the solder joints were also studied. The results show that the stress and strain distribution in the solder joint are not uniform; the interface between the lead and the solder joint is the high stress and strain region; the maximum stress and stain occur at the topmost point where the solder joint intersects with the inner side of the lead. The solder joint cracks should occur firstly at this point and propagate along the interface between the solder and the lead. The solder joint with the pad size of 1.25 mm × 0.35 mm, the stand-off of 0.02 mm and the solder volume of 0.026 mm^3 has longer fatigue life than that of any others. These optimal parameters have been applied in practice to assemble the 240-pin, 0.5 mm pitch QFP.

Key words: fine pitch; solder joint shape; nonlinear finite element analysis; thermal fatigue life

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1 INTRODUCTION

The electronicer industry is driven mainly by the demand for "smaller, faster, higher complexity, lower power consumption and cheaper"[1]. To meet these needs, the demand for smaller size, higher density and higher heat dissipation integrated circuit (IC) chips is on the rise. With the requirements of high performance and small package size, the design of IC chips is headed toward higher pin count, smaller pad size and fine pitch; consequently, the fine pitch technology is a key to electronic industry. When the lead pitch of a surface mount component is equal to or less than 0.65 mm, then it is called a fine-pitch surface mount component(SMC)[2]. As a typical model of fine-pitch SMC, the lead pitch of quad flat package (QFP) has been developed from early 0.8 mm pitch to 0.65 mm and 0.5 mm pitch in dominant as yet, the 376-pin, 0.35 mm pitch QFP has also been applied[3], but 0.2 mm pitch QFP is very rare[4]. With the same size of 32 mm × 32 mm, 0.8 mm pitch QFP contains 120 pins, and 0.5 mm pitch, 0.3 mm pitch QFP contains 208 pins,

328 pins, respectively. The increase in number of leads results in the difficulty of assembling, and some problems, such as bridge, occur during the reflow process[5]. QFP solder joints provide both a mechanical support and an electrical connection between the package and PCB. The reliability of solder joints is directly affected by the shape parameter[6, 7], therefore, the design of parameters for the solder joints shape before assembling will be very important for the quality of solder joints[8, 9]. In this work, a 240 pins, 0.5 mm pitch QFP, whose type is XC4028EXHQ240, will be considered. The ultimate goal of the present study was to perform a QPF solder joint reliability analysis under thermal cycling, which consisted of three different steps: 1) finite element analysis modeling of QFP; 2) nonlinear finite element analysis of QFP solder joint to determine the stress/stain distribution within the joint and failure life of QFP solder joint predicting under thermal cycling condition; 3) influence of some shape parameters on the thermal fatigue life of QFP solder joints analysis.

2 FINITE ELEMENT ANALYSIS AND FATIGUE LIFE PREDICTION OF SOLDER JOINT OF QFP UNDER THERMAL CYCLING CONDI-TION

2. 1 Finite element analysis model of QFP

The 240-pin QFP is made of plastic, which is shown in Fig. 1. It has gull-wing shaped leads that are spaced on 0. 5 mm pitch with 0. 6 mm foot in length. For the QFP solder joints under tempera-ture cycle, a mismatch of the coefficients of ther-mal expansion(CTE) between the plastic package, solder joints and the FR-4 PCB can induce repeated straining, which will result in fatigue damage accu-mulation in the solders[10, 11]. In the present study, by means of nonlinear finite element method, the thermal stress/strain analysis of QFP solder joints was performed, and the key solder joint that was subjected to the most thermal stresses/strains could be determined and the maximal plastic strain was calculated. Based on the Coffin-Manson equa-tion and plastic strain calculated, the fatigue life of the QFP solder was also estimated.
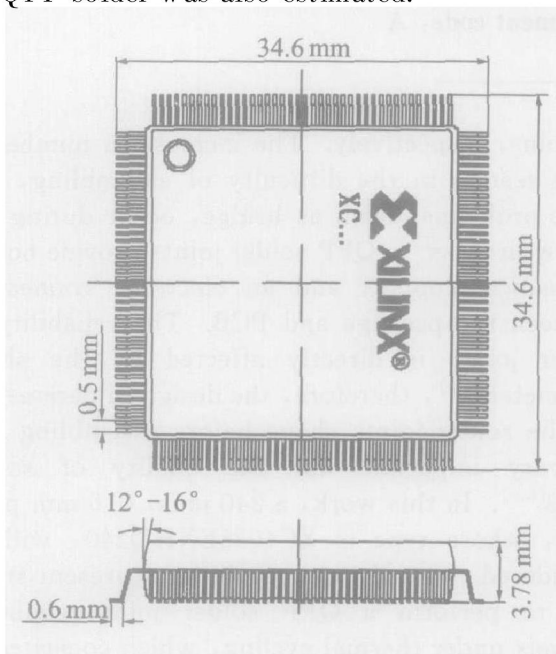

Fig. 1 Schematic of 240 pin QFP

The two-dimensional finite element method (FEM) analysis model is given in Fig. 2, where the size of pad is 1. 6 mm × 0. 35 mm and the volume of the 63% Sn-37% Pb solder joint is 0. 02 mm³. The stand-off is 0. 012 7 mm. The finite element model consists of 745 elements with 2 490 nodes. The solder joint was modeled as visco-plastic material whereas all other materials were modeled as linear elastic material. Material properties of the QFP package are listed in Table 1. The temperature cy-cling profile is shown in Fig. 3. The imposed dis-placement boundary conditions are: 1) at the

Table 1 Material properties of QFP package

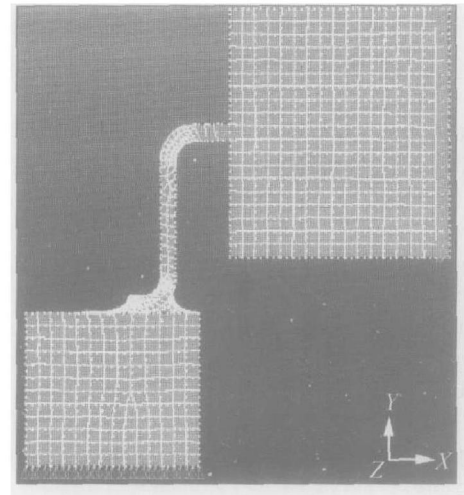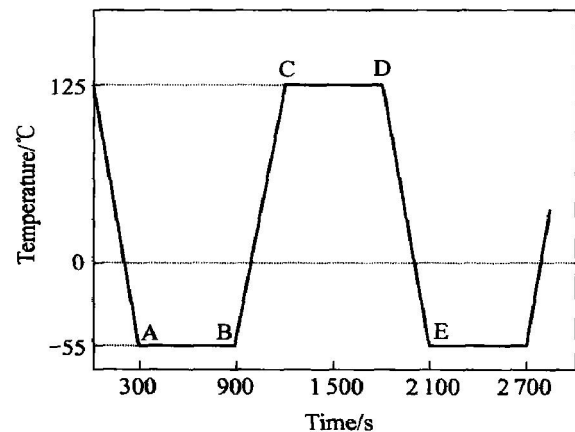| Material	Elastic modulus/ MPa	Poisson ratio	CTE/ (10^{-6} · $℃^{-1}$)
Plastic	$1.4 × 10^4$	0. 3	22
PCB	$1.1 × 10^4$	0. 28	15
Solder	$1.0 × 10^4$	0. 4	21

Fig. 2 Finite element model of QFP

Fig. 3 Temperature cycling profile
(A to B: 10 min; B to C: 5 min;
C to D: 10 min; D to E: 5 min)

bottom of PCB all points cannot move in the x di-rection and y direction; 2) at the upper end of chip all points cannot move in the x direction.

2. 2 Finite element analysis and results

The FEM analysis result of the typical QFP solder joint is shown in Fig. 4, which shows the stress distribution within the whole QFP assembly at the third cycle. Fig. 5 shows the stress distribu-tion just within the solder joint and Fig. 6 shows the strain distribution within the same solder joint at the same cycle. Some stress/strain data on sev-eral nodes of the solder joint are given as examples in Tables 2-5.
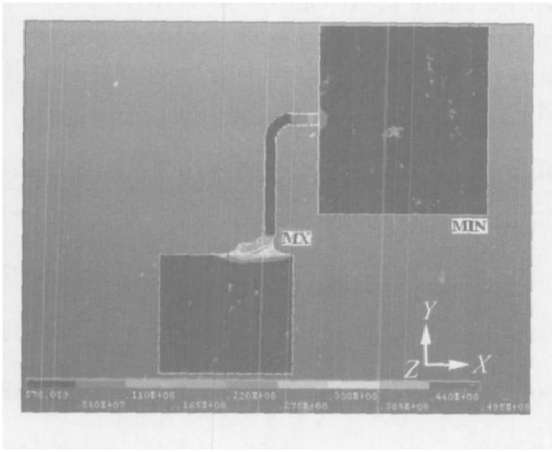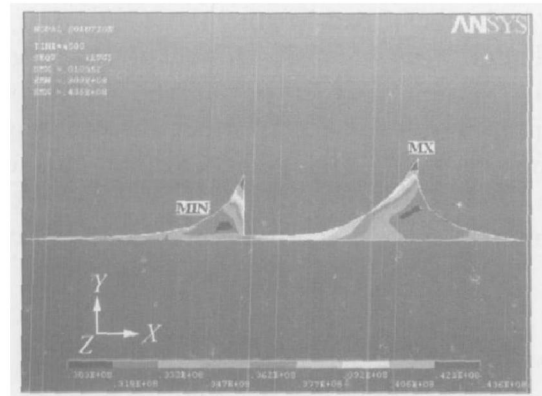
Fig. 4 QFP finite element analysis result

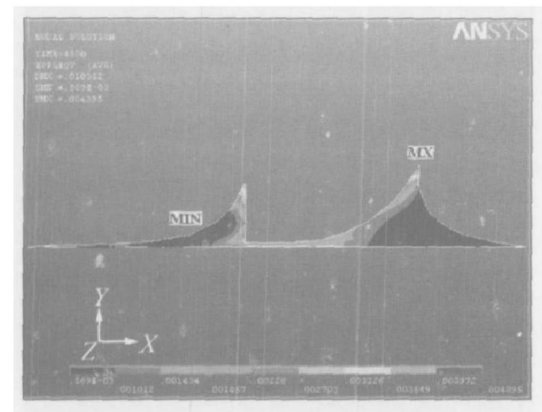**Fig. 5** Stress distribution just within QFP solder joint

Fig. 6 Strain distribution just within QFP solder joint

Table 2 Stress on nodes of QFP solder joint

Node	Principal stress/MPa			Stress intensity/ MPa	Equivalent stress/ MPa
	σ_1	σ_2	σ_3		
1	40.917	26.648	– 0.039 095	40.956	36.008
17	38.955	19.163	0.159 85	38.795	33.6

As indicated in Fig. 4, the maximum stresses of the whole QFP assembly occur mainly at the interface between the pin foot and the solder joint. And it also can be seen from Figs. 5 and 6 that: 1) the stress and strain distribution in the solder joint

Table 3 Maximum stress on nodes of QFP solder joint

Principal stress/MPa			Stress intensity/ MPa	Equivalent stress/ MPa
σ_1	σ_2	σ_3		
1 580	2 212	2 247	1 583	1 583
46.259	41.714	8.187	46.146	45.563

Table 4 Strain on nodes of QFP solder joint

Node	Principal plastic strain/ 10^{-3}			Plastic strain intensity/ 10^{-3}	Equivalent plastic strain/ 10^{-3}
	ε_1	ε_2	ε_3		
1	0.759 83	0.180 05	– 0.977 08	1.736 9	1.021 1
17	0.664 55	0.066 551	– 0.772 91	1.437 5	0.835 16

Table 5 Maximum plastic strain on nodes of QFP solder joint

Principal plastic strain/ 10^{-3}			Plastic strain intensity/ 10^{-3}	Equivalent plastic strain/ 10^{-3}
ε_1	ε_2	ε_3		
1 583	1 583	2 150	1 583	1 583
2.81	1.602 9	– 0.315 04	7.112	4.394 5

are not uniform; 2) the interface between the pin foot and solder is the high stress/strain region, the maximum stress/stain occurs at the topmost point that the solder joint intersects with the inner side of the lead. The maximum stress/stain are 43.563 MPa and 4.394 5 × 10^{-3} respectively according to Table 3 and Table 5. Thus, the solder joint cracks should occur firstly at the topmost point of the solder joint and propagate along the interface between the solder and the lead and through the whole interface finally, as a result, the solder joint is disabled.

2.3 Thermal fatigue life of QFP solder joint

The thermal fatigue life of the QFP solder joint can be estimated based on the calculated maximum plastic strain and Coffin-Manson equation[12, 13]:

$$N_f = \theta (\Delta \gamma_p)^\eta \qquad (1)$$

where N_f is mean cycles to failure, $\Delta \gamma_p$ is maximum plastic strain which can be calculated by FEA, θ and η are material constants. For 63% Sn-37% Pb solder joints, the values of θ and η are 1.292 8 and – 1.96 respectively[14, 15]. In this case, the maximum plastic strain of 0.004 394 5 can be obtained from Fig. 6, consequently the solder joint of QFP should have the fatigue life of 53880 cycles according to Eqn. 1. Following Ref. [13], a safe factor of 4 was used, as the result, it is safely predicted that the solder joint will

have the life of 13 470 cycles.

3　INFLUENCE OF SHAPE PARAMETERS ON FATIGUE LIFE OF QFP SOLDER JOINT

3.1　Influence of volume of solder joint

The influence of the variation of volume on the distribution of stress within the solder joint is shown in Figs. 7 and 8, in which the volumes are 0.024 mm^3 and 0.032 mm^3 respectively, but the pad size is fixed at 1.25 mm in length and 0.35 mm in width, and the stand-off is 0.012 7 mm.
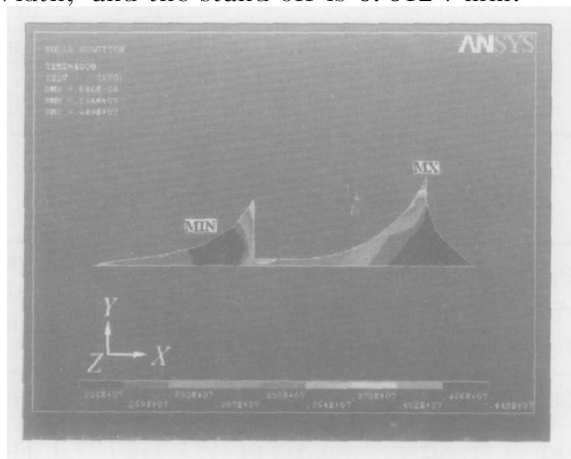

Fig. 7　Stress distribution just within QFP solder joint(V= 0.024 mm^3)

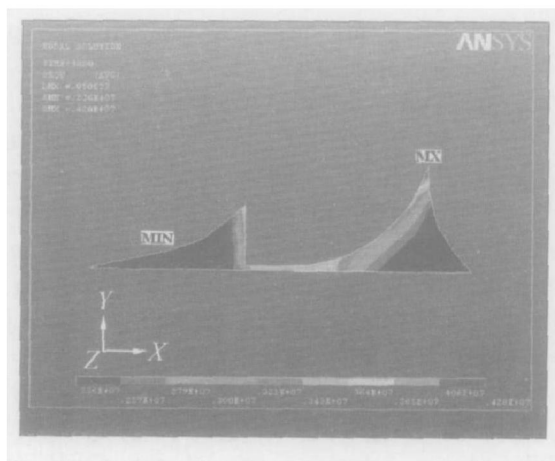**Fig. 8**　Stress distribution just within QFP solder joint(V= 0.032 mm^3)

Figs. 7 and 8 show that: 1) the distribution of stress within the solder joint varies with the volume, and different volumes have different stress distributions within the solder joint; 2) although the stress distribution within the solder joint is influenced by the volume, the high stress/strain region is still fixed at the interface between the pin foot and solder, and the maximum stress/stain also occurs at the topmost point of the solder joint intersected with the inner side of the lead. When other conditions keep constant, the fatigue life of solder joint with different volumes was calculated,

shown in Table 6. It can be seen from Table 6 that the fatigue life varies with the solder volume, compared with the others, the longer fatigue life is found in the volume of 0.026 mm^3.

Table 6　Variation of fatigue life with volume

Volume/mm^3	Strain range/10^{-3}	Fatigue life
0.024	4.39	13 497
0.026	3.68	19 073
0.029	4.82	11 238
0.032	6.56	6 142

3.2　Influence of pad length

The influence of the variation of pad length on the distribution of stress within the solder joint is shown in Figs. 9 and 10, in which the pad length is 1.0 mm and 1.6 mm respectively, but the pad width, the stand-off and the volume are fixed at 0.35 mm, 0.02 mm and 0.026 mm^3, respectively.
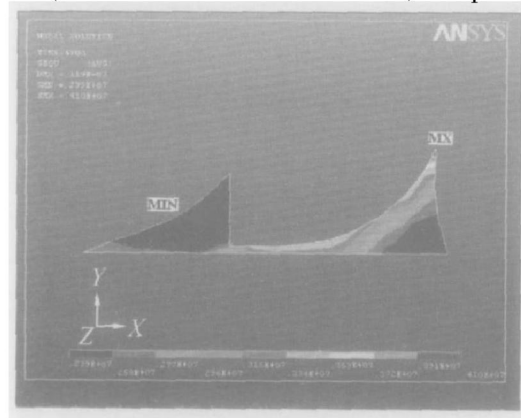

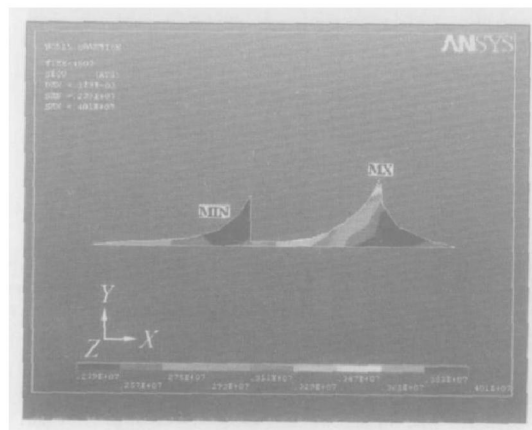**Fig. 9**　Stress distribution just within QFP solder joint(L= 1.0 mm)

Fig. 10　Stress distribution just within QFP solder joint(L= 1.6 mm)

Figs. 9 and 10 show that: 1) the distribution of stress within the solder joint varies with the pad length, and different pad lengths have different stress distributions within the solder joint; 2) al-

though the stress distribution within the solder joint is influenced by the pad length, the high stress/ strain region is still fixed at the interface between the pin foot and solder, and the maximum stress/ stain also occurs at the topmost point of the solder joint intersected with the inner side of the lead.

When other conditions keep constant, the fatigue life of solder joint with different pad lengths was calculated, shown in Table 7. It can be seen that the fatigue life varies with the pad length, and the pad length of 1. 25 mm has longer fatigue life than those of the others.

Table 7 Variation of fatigue life with pad length

Pad length/ mm	Strain range/ 10^{-3}	Fatigue life
1. 0	3. 57	20 242
1. 25	1. 85	73 420
1. 4	3. 31	23 475
1. 6	3. 34	23 064

3. 3 Influence of stand-off

The stand-off is defined as the height measured from the lowest point on the lead of QFP to PCB. The influence of the variation of stand-off on the distribution of stress within the solder joint is shown in Figs. 11 and 12, in which the stand-off is 0. 020 3 mm and 0. 025 4 mm, respectively, but the pad length, the width and the volume are fixed at 1. 6 mm, 0. 35 mm and 0. 02 mm^3, respectively.
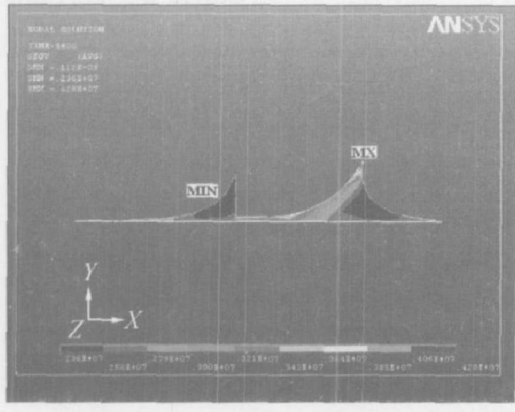

Fig. 11 Stress distribution just within QFP solder joint($H =$ 0. 020 3 nm)

Figs. 11 and 12 show that the distribution of stress within the solder joint varies with the stand-off, however the high stress/ strain region is still fixed at the interface between the pin foot and the solder, and the maximum stress/ stain also occurs at the topmost point of the solder joint intersected with the inner side of the lead.

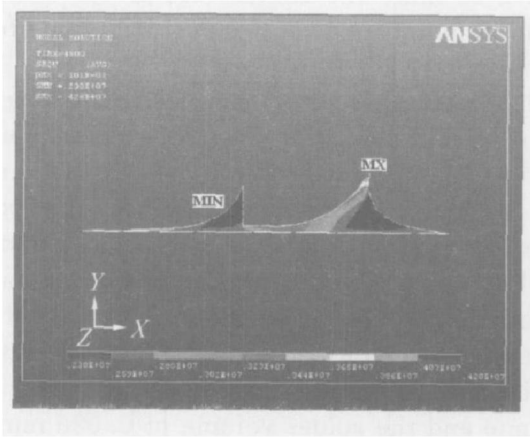When the other conditions keep constant, the fatigue life of solder joint with different stand-offs

Fig. 12 Stress distribution just within QFP solder joint($H =$ 0. 025 4 nm)

was calculated, shown in Table 8. It can be seen that the fatigue life varies with the stand-off; while at the stand-off of 0. 005 1 mm the solder joint has longer fatigue life than in any other cases.

Table 8 Variation of fatigue life with stand-off

Stand-off/ (10^{-2} mm)	Strain range/ 10^{-3}	Fatigue life
0. 51	2. 45	42 336
1. 27	4. 4	13 470
2. 03	4. 16	14 999
2. 54	4. 19	14 789

By comparing Tables 6 - 8, it can be seen that the solder joint with the pad size of 1. 25 × 0. 35 mm, the stand-off of 0. 02 mm and the solder volume of 0. 026 mm^3 has the longest fatigue life than any other cases. These optimal parameters have been applied in practice to assemble the 240-pin, 0. 5 mm pitch QFP, whose type is XC4028EXHQ240.

4 CONCLUSIONS

1) The stress/ strain distribution in the solder joint is not uniform, and the interface between the lead and the solder is the high stress/ strain region. The maximum stress/ stain occurs at the topmost point where the solder joint intersects with the inner side of the lead. The solder joint cracks should occur firstly at this point and propagate along the interface between the solder and the lead and through the whole interface finally.

2) The plastic strain in the solder joint was calculated. Based on the calculated plastic strain and Coffin-Manson's equation, the thermal fatigue life of the 0. 5 mm pitch, 240-pin QFP solder joint was estimated. In the case of the pad size of 1. 6

mm × 0. 35 mm, the solder volume of 0. 02 mm³ and the stand-off of 0. 0127 mm the fatigue life was estimated to be 13 470 cycles.

3) The fatigue life is sensitive to the shape parameters. Although the stress distribution within the solder joint is influenced by the shape parameters, the high stress/strain region is still fixed at the interface between the pin foot and the solder, and the maximum stress/stain also occurs at the topmost point of the solder joint intersected with the inner side of the lead. The solder joint with the pad size of 1. 25 mm × 0. 35 mm, the stand-off of 0. 02 mm and the solder volume of 0. 026 mm³ has the longest fatigue life than other cases. These optimal parameters have been applied in practice to assemble the 240-pin, 0. 5 mm pitch QFP.

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