Derivation of Equation on Thermal Life Prediction of Plated Through Hole for Printed Wiring Board

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Abstract
Printed wiring boards(PWBs) have recently been experiencing higher thermal stress in car electronics and high current equipment, etc. In this study, the effects of structural factors and material properties on thermal fatigue life of plated through hole (PTH) in multilayer PWB have been investigated by finite element method (FEM) based on Box-Behnken experimental design. This methodology showed the effects of single factor and interactions of multiple factors of PWB on the strain causing an occurrence of cracks in copper (Cu) plating of PTH. The simulation was conducted with obtained properties of thin Cu plating in previous research and a model of a simplified glass cloth equivalent to a cross section of a PWB. It became clear that the effects of Cu plating thickness of PTH, CTE (coefficient of thermal expansion) and elastic modulus of PWB material were significant on inelastic strain range ($\Delta\varepsilon_{in}$) in PTH during thermal fatigue. PTH pitch, though, did not have a measurable impact. The influence of PWB material Tg was found to be so overwhelmingly strong in the experimental design that behaviours of other factors became too muted to be analysed, which means Tmax should be below Tg. A formula of the $\Delta\varepsilon_{in}$, in consideration of the significant factors and its temperature-scaling factor related to ΔT, was proposed. In addition, the $\Delta\varepsilon_{in}$ became large in accordance with shape and size of roughness of PTH. When the Cu plating of PTH obeys Manson-Coffin rule, the thermal fatigue life of PTH in consideration of the structural and material factors, can be predicted by the proposed formula on $\Delta\varepsilon_{in}$ and the low-cycle fatigue life prediction law of Cu plating obtained by previous research. The acceleration factor (AF) equation was established and validated by test data using various PWBs and temperature conditions in temperature cycling test (TCT). The calculated AF roughly agreed with the ratios of Weibull average of TCT results.

1. Background

The lifetime of the PWB in electrical products is very dependent on how long the PTH will last. The PTH reliability is dependent on several variables such as the thickness of the PWB, the quality and plating in the PTH, the thickness of the Cu plating as well as connection interface between the inner layer and the PTH.

The conventional approach to predict PTH lifetime is to perform an accelerated TCT which is very time consuming. For a solder joint, the modified Coffin-Manson equation has been established to predict its lifetime. For PTH, there is currently no such accelerated equation. Leveraging on results obtained from earlier study, this study aims to establish a popular equation to predict PTH lifetime, focusing on PWB used in the telecommunication equipment, computers and servers.

By using the equation, PTH life and dominant factors of PWB and PTH from thermal cycling (TC), in both field and test, can be predicted with faster computation. Critical design factors of PWB/PTH can be found at an early product design stage, allowing necessary design improvements to be made to enhance product life and reduce product warranty costs. If a failure happens, the best parameter that should be changed and the best value that would be suitable for the parameter can be speculated on.

2. Experimental plan

PWB factors were simulated at three levels using Box-Behnken design applied as an efficient experimental plan used for tremendous combinations of multiple factors, cutting redundancy. The first investigation with 2 sets of 62 runs analysed the effects of factors, PTH length, Cu plating thickness of PTH, PTH diameter, PTH pitch, PWB material CTE, PWB material Young's Modulus, and PWB material Tg, and the various interactions between 2 factors. Using the data analysed in the 1st investigation with 3 levels of 7 factors, the 2nd investigation with 3 levels of 5 refined the factors for a further 41 FEM simulation runs to better understand the effects and the interactions of the factors. The relationships of these factors were then established and subsequently optimized to derive the equation for TC. Concretely speaking, after these FEM simulations, from the result of Box-Behnken design, N, the number of cycles to failure, was established, followed by AF, acceleration factor.

No	PTH length	Cu plating thickness of PTH	PTH diameter	PTH pitch	PWB material CTE	PWB Material Young's modulus	PWB material T_g (TMA)
1	0	0	1	-1	0	0	-1
2	0	0	1	-1	0	0	1
3	-1	0	1	0	1	0	0
4	-1	0	1	0	-1	0	0
5	0	0	0	1	1	-1	0
6	0	0	0	1	-1	-1	0
7	0	1	1	0	0	1	0
8	0	-1	1	0	0	1	0
9	-1	-1	0	1	0	0	0
10	1	-1	0	1	0	0	0
11	0	1	1	0	0	-1	0
⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮
60	1	0	0	0	0	1	-1
61	0	1	0	0	-1	0	1
62	1	0	-1	0	1	0	0

Figure 1 – Box-Behnken design showing 62 simulation runs with 3 levels of 7 factors

3. FEM simulation

This study used FEM to simulate the behaviour and strain on several PWB models, under various operating environments and TCT temperature conditions.

3.1 Simulation model of PWB materials

Instead of wave-shaped glass cloth model similar to real glass cloth, a straight-shaped glass cloth model was used to simplify the material model, as the number of FEM simulations to run was high. Prepreg and laminate of the simulation model of PWB were composed of a resin part and a composite part which comprised glass cloth and resin. Thus the composite part of the structure was simplified from wave to straight without losing calculation accuracy.

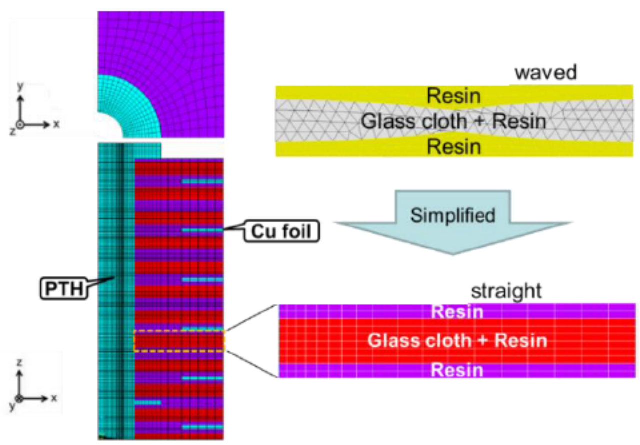


Figure 2 – Simplified model of PWB material

3.2 Simulation model of PWB

3 different thicknesses of conventional type of PWB with 0.1mm prepreg / laminates and 18 microns copper (Cu) foil were designed and fabricated. Solder mask was omitted. Symmetric one-eighth model was used to save time for the FEM simulations.

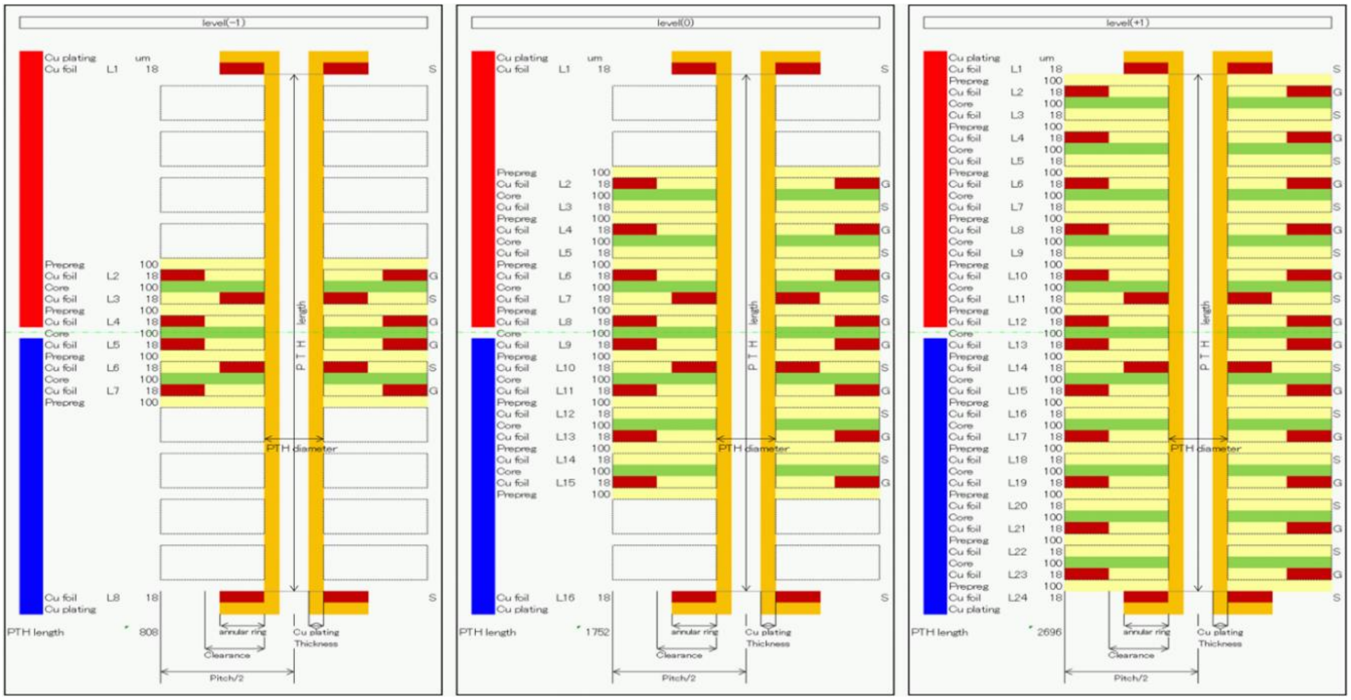
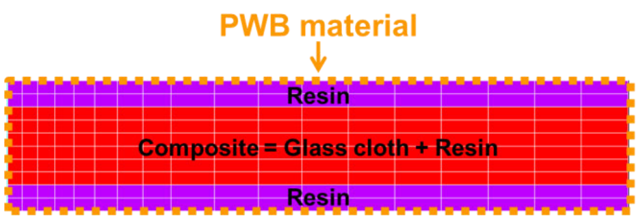


Figure 3 – 3 simulation models of PWB

3.3 PWB materials Young's Modulus

Young Modulus of the PWB material was not a property of resin alone nor glass cloth alone. The bending elastic modulus of the PWB material, at three levels, were computed from the values of the elastic modulus of composite and instantaneous elastic modulus of resin, and used in the simulation.



Factor	Elastic modulus of Composite	Instantaneous elastic modulus of Resin	Bending elastic modulus of PWB material
Level(-1)	36	0.9	14.6
Level(0)	48	2.7	23.0
Level(+1)	60	8.1	33.2

Figure 4 – Composite PWB material Young Modulus

3.4 PWB materials CTE and Tg

3 levels each of CTE and Tg produces 9 levels of these two combined parameters.

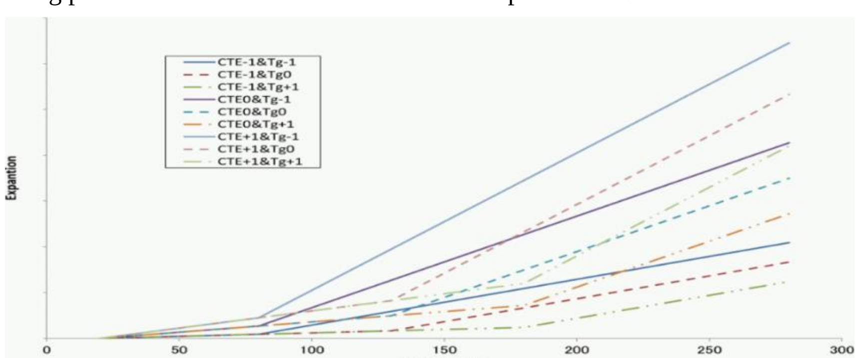


Figure 5 – 9 levels of PWB material CTE and Tg

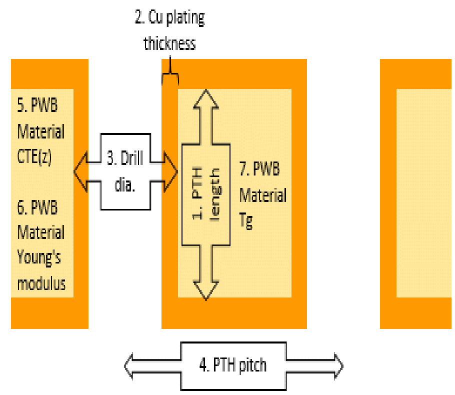
4. First Investigation

4. 1 First investigation parameters and conditions

As simulation parameters, 7 basic factors of the PWB and PTH, comprised of 4 dimensional factors and 3 material property factors were given commonly used values at three levels for simulation, as shown in Table 1 below. Level(-1) and level(+1) were set widely to see the effect of these factors clearly.

Table1 – 1st investigation simulation parameters

Factors		level(-1)	level(0)	level(+1)
1. PTH length		0.81mm	1.75mm	2.70mm
2. Cu plating thickness of PTH		15um	35um	55um
3. Drill diameter		ϕ0.15mm	ϕ0.25mm	ϕ0.35mm
4. PTH pitch		0.8mm	1.0mm	1.2mm
5. PWB Material CTE	a1	14.8ppm/C	44.8ppm/C	75.4ppm/C
	a2	100ppm/C	200ppm/C	300ppm/C
6. PWB Material Young’s modulus		14.6GPa	23.0GPa	33.2GPa
7. PWB Material Tg		80C	130C	180C



Two kinds of temperature profiles for the simulations were used, as shown in Figure 6 below.

- Temperature condition 1: ⊿T=215 deg C (-65 deg C to 150 deg C) (following IPC-TM-650 2.6.7.2 E)
- Temperature condition 2: ⊿T=165 deg C (-40 deg C to 125 deg C)

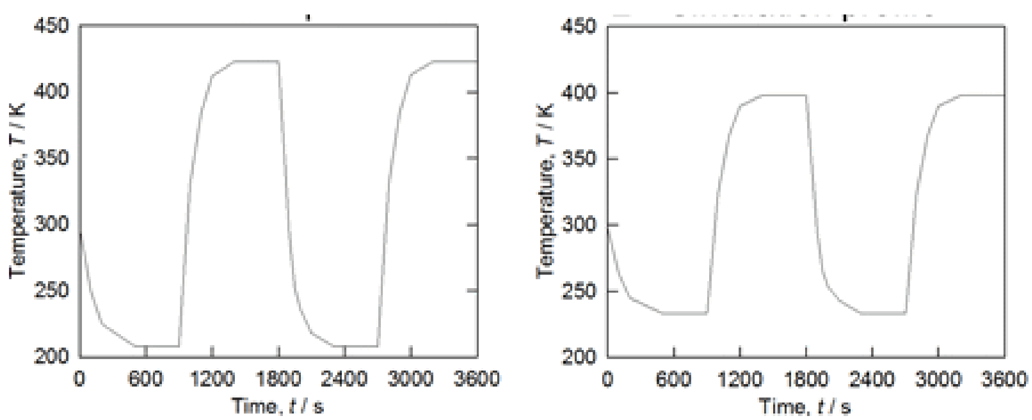


Figure 6 – 1st investigation simulation conditions

4.2 Simulation result (Center-point model) – 1st investigation

The graph below shows simulation results of the center-point model having all level (0) of factors. The rising black dots show an accumulated equivalent inelastic strain at the maximum point in Cu plating in PTH from the start of 0 cycle to the end of 2nd cycle.

The 2nd cycle was sufficient to represent the continuous strain range in a cycle. The half value of the strain range of this cycle could therefore be adopted to have caused damage or cracks in the Cu plating of PTH. This is ⊿ε_{in}. ⊿ε_{in} of temperature condition 1 is about 17 times greater than that of temperature condition 2.

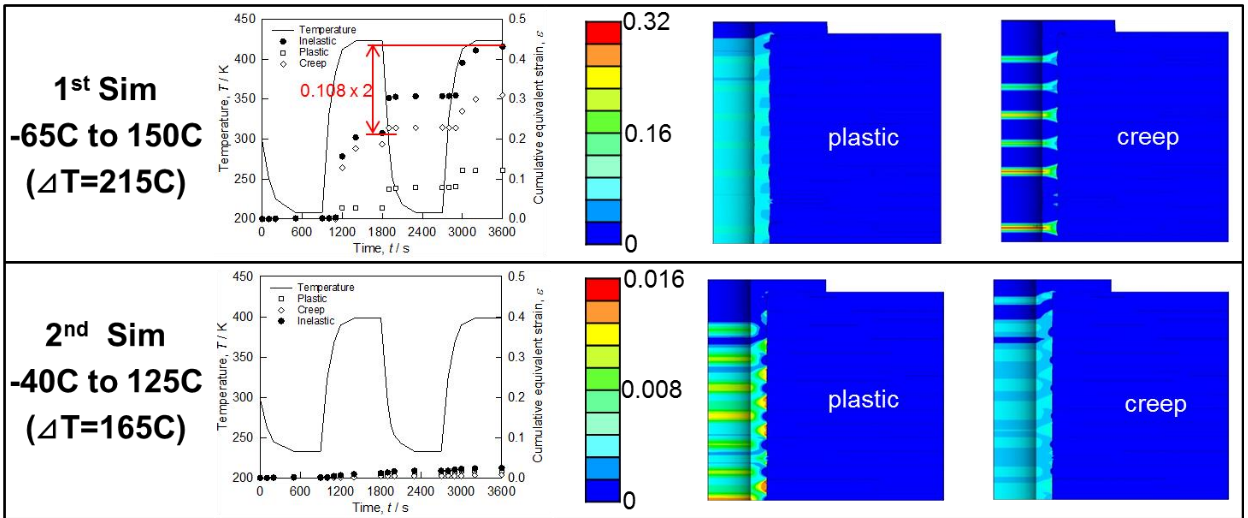


Figure 7 – 1st investigation center-point model simulation results

Table 2 – 1st investigation center-point model strain range in 2nd cycle

	Factor							⊿ε_{in} in 2nd cycle	
	PTH length	Cu plating thickness	Drill dia.	Pitch	CTE	Young's Modulus	Tg	Temp. condition -65degC to 150degC	Temp. condition2 -40degC to 125degC
Level	0	0	0	0	0	0	0	0.108	0.00626

4.3 Single factor effect – 1st investigation

The diagrams below show the single factor effect from the temperature condition 1. The top factor was material CTE, the second Tg, and the third Cu plating thickness which was slightly more effective than Young's Modulus. PTH length, drill diameter and PTH pitch did not exhibit many effects.

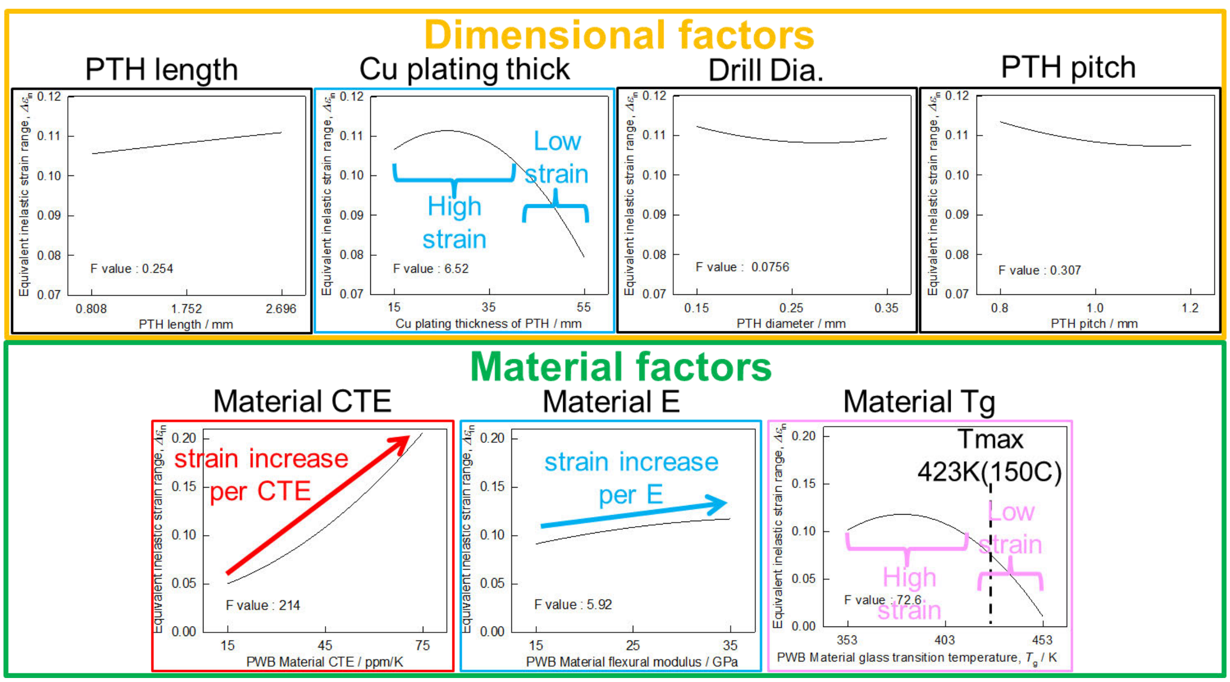


Figure 8 – 1st investigation single factor effect results (Temp. condition 1)

The diagrams below show the single factor effect from temperature condition 2. The top factor was Tg, the second was CTE and the third was Young's Modulus. In dimensional factors, contributing factors include Cu plating thickness, PTH length and drill diameter.

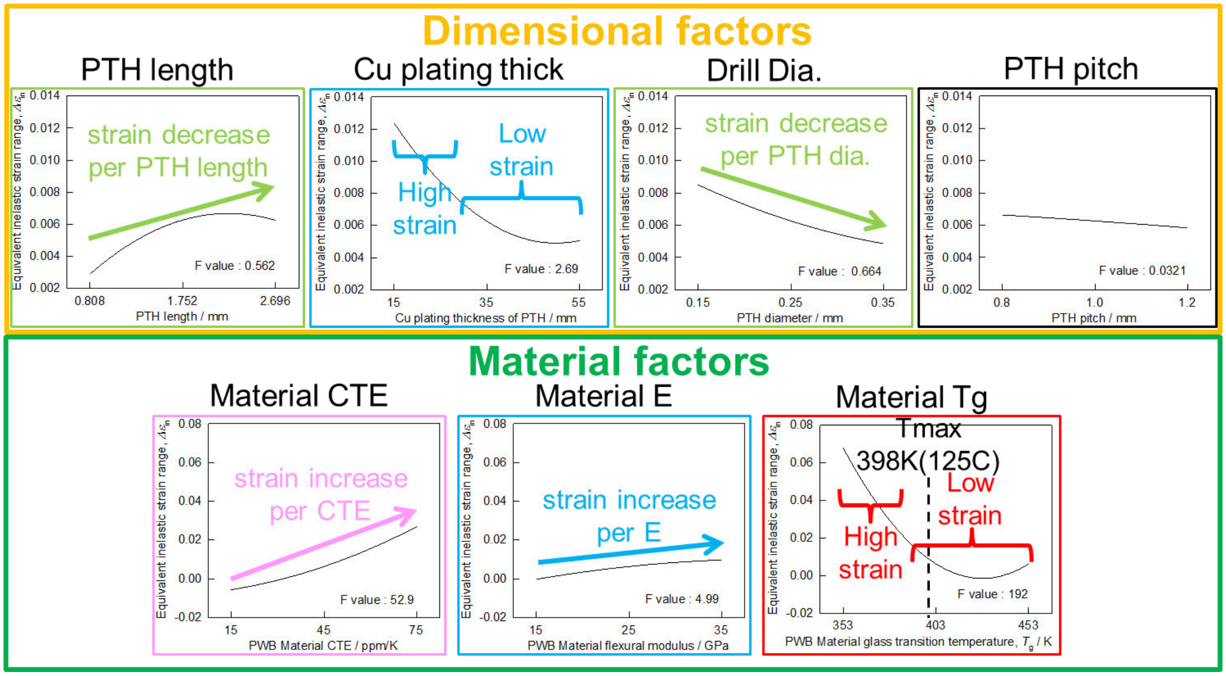


Figure 9 – 1st investigation single factor effect results (Temp. condition 2)

4.4 Mutual factor effect – 1st investigation

The mutual factor effect charts below show interactions of two factors. For example, the left contour figures with combined effects of Tg and CTE, as CTE increases, a larger Tg yielded proportionately smaller increase of ⊿ε. In general, interaction effects of temperature condition 2 was greater than that of temperature condition 1.

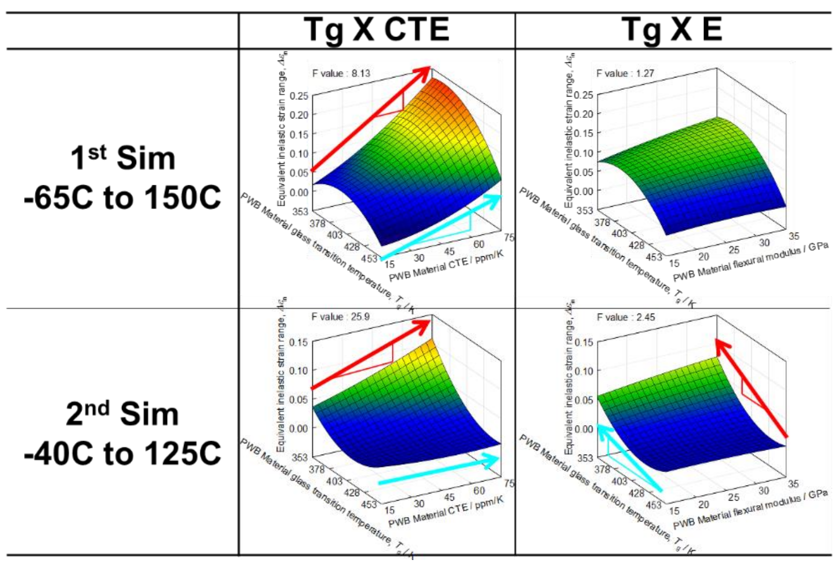


Figure 10 – 1st investigation mutual factor effect results

In many simulation runs of temperature condition 1, -65 deg C to 150 deg C, with Tmax (150 deg C) exceeded Tg [Level(-1) = 80 deg C, Level(0) = 130 deg C], the effects of Tg and CTE($\alpha 2$) were so overwhelming that the effects of other factors could not be seen clearly. To better see the effects, simulation results of temperature condition 2, -40 deg C to 125 deg C were therefore used for analysis.

4.5 Consideration – 1st investigation

The strength of effect of each factor was determined by the F value from an analysis of variance and the interactions between 2 factors from the 7 factors. The higher F value, the greater impact the factor had on the occurrence of PTH Cu plating cracking. Based on this value, ranking of the single and mutual factors from temperature condition 2 was tabulated below.

Effect	Rank	Single factor	F value
Large effect	1	Material Tg	192.0
	2	Material CTE	52.9
Middle effect	3	Material E	5.0
	4	Cu plating thick	2.7
Small effect	5	Drill Dia.	0.7
	6	PTH length	0.6
Little effect	7	PTH pitch	0.0

Material Tg and CTE occupy most part of total effect.

PTH pitch's effect is negligible.

Red ･･･ PWB material properties
Blue ･･･ PTH dimensions

Effect	Rank	Mutual factor(Interaction)	F value
Large effect	1	Material Tg X Material CTE	25.90
Middle effect	2	Material Tg X Material E	2.45
	3	Material Tg X Cu plating thick	1.49
	4	Material CTE X Cu plating thick	1.15
Small effect	5	Material CTE X Material E	0.51
	6	Material E X PTH length	0.26
	7	Material Tg X PTH pitch	0.20
Little effect		・・・	
	28	PTH length X PTH pitch	0.00

Top five interactions are related with Material Tg or CTE.

Figure 11 – 1st investigation Factors effect ranking

The top 3 single factors were material factors, Tg, CTE, and Young's Modulus. In fact, Tg and CTE occupied significant parts of all the single factor effects. PTH pitch can be ignored because its effect is negligible.

The top mutual factor was the interaction between Tg and CTE. The top 5 interactions were related to either Tg or CTE. From the results of Box-Behnken design by using FEM simulations, Tg's effect was very large. The acceleration characteristics differed greatly between when Tmax was below Tg and when Tmax was over Tg. When Tmax exceeds Tg, the PTH life was shortened tremendously because dynamics changed with overwhelming influence of Tg (CTE and Young's modulus change at Tg). To match the acceleration characteristic of TCT to that of operation, TCT's Tmax should be below Tg. Therefore, temperature conditions of 2nd investigation were set below 125 deg C. Thus, material Tg, CTE(α2) and PTH pitch were omitted in the 2nd investigation to better understand the equation structure for AF.

5. 2nd Investigation

5. 1 2nd investigation parameters and conditions

FEM simulations were conducted in 2nd investigation based on Box-Behnken design with 5 factors (Table 3). To get a more accurate equation, all levels of the factors were changed into realistic values used in the current PWB. The values of CTE and Young's Modulus were therefore slightly changed to bring them closer to the current laminate specifications.

Table 3 – 2nd investigation simulation parameters

Factors	level(-1)	level(0)	level(+1)
1. PTH length	0.81mm	1.75mm	2.70mm
2. Cu plating thickness of PTH	15um	35um	55um
3. Drill diameter	ϕ0.15mm	ϕ0.25mm	ϕ0.35mm
4. PWB Material CTE(a1)	33ppm/C	49ppm/C	65ppm/C
5. PWB Material Young's modulus	15GPa	22GPa	29GPa

To better study the effects of and dependency on temperature, the changes in strain with changes in temperature, or ΔT, were analysed by conducting FEM simulations under 3 temperature conditions which were set centrally symmetrical for clearer comparison.

- Harsh temperature condition: ⊿T=165 deg C (-40 deg C to 125 deg C)
- Middle temperature condition: ⊿T=100 deg C (0 deg C to 100 deg C)
- Mild temperature condition: ⊿T=60 deg C (20 deg C to 80 deg C)

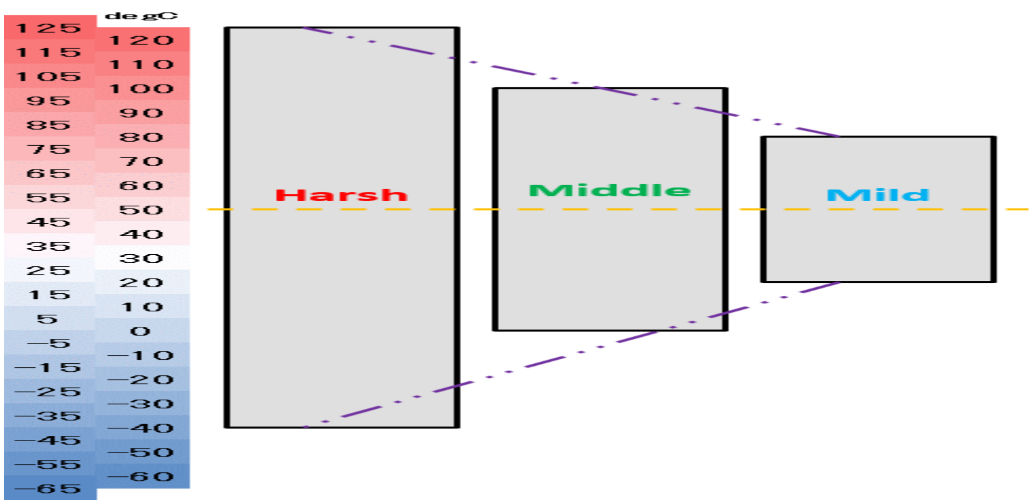


Figure 12 – 2nd Investigation simulation conditions

5.2 Single factor effect – 2nd investigation

The 2nd investigation single factor effect for all 3 simulation conditions were shown below, separating the dimensional factors from the material factors. The results showed that CTE, Young's modulus and Cu plating thickness had strong effects on strain in a PTH. PTH length and drill diameter had weak effects. These lines are almost the same for the 3 temperature conditions in each factor, indicating that the temperature dependency is very small.

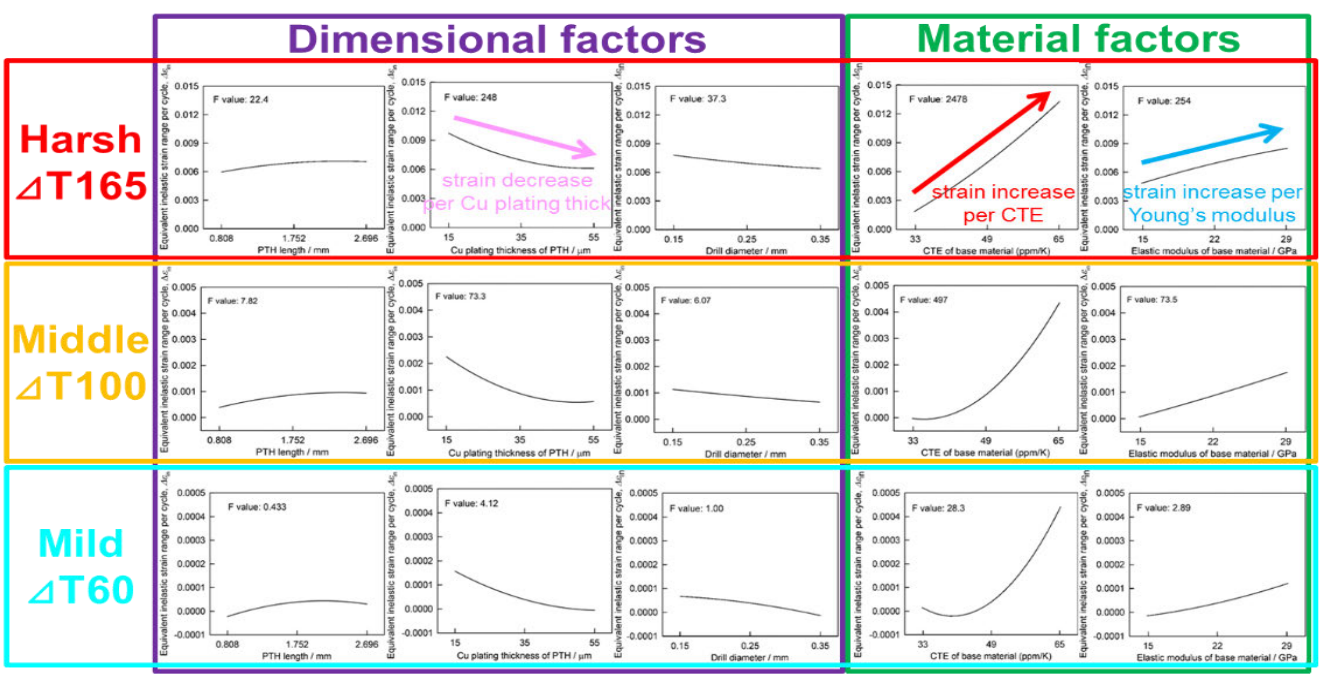


Figure 13 – 2nd Investigation single factor effect results

5.3 Mutual Factor Effect – 2nd investigation

Three mutual factor effects, each from the 3 temperature conditions, pairing one with dimensional and material factors and another with both material factors, are shown in Figure 14. They were the top 2 interactions of the 3 conditions. The first interaction was CTE and Cu plating thickness, the other was CTE and Young's Modulus. The effects were almost identical in all 3 temperature conditions. This demonstrated that the effects of the interactions were not dependent on temperatures.

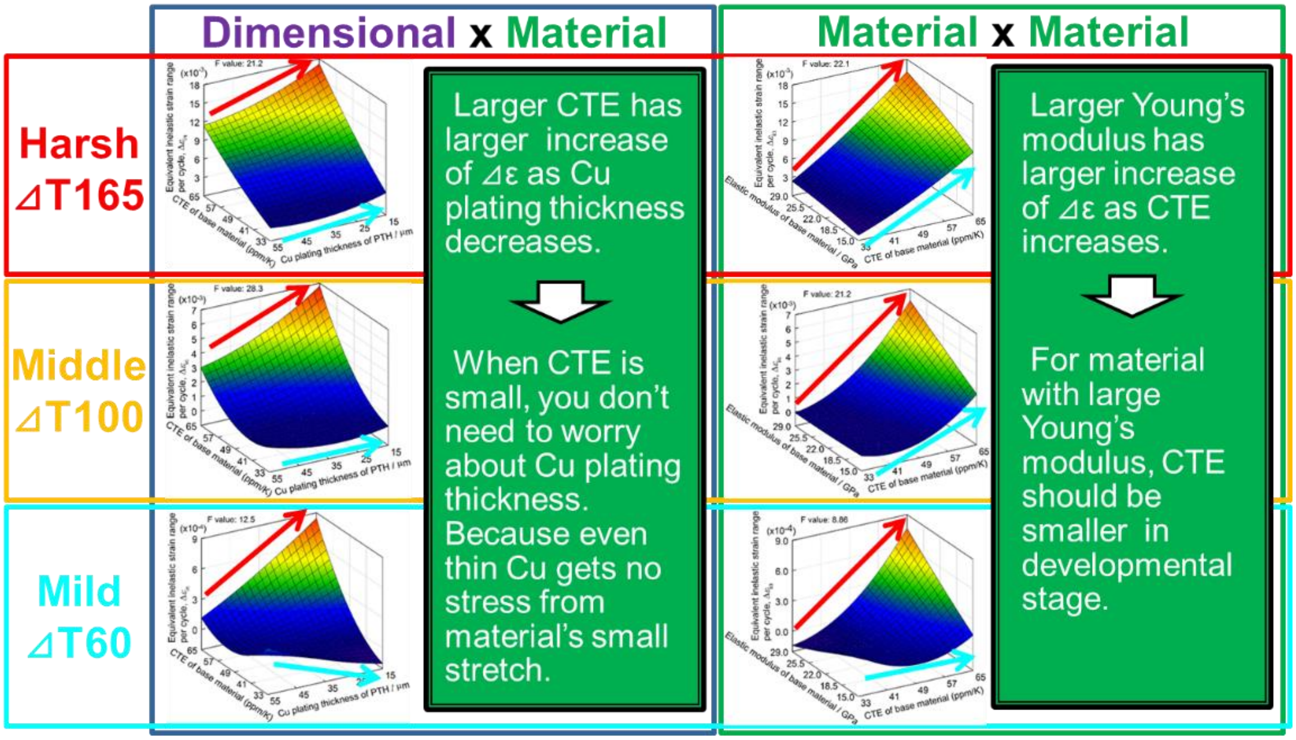


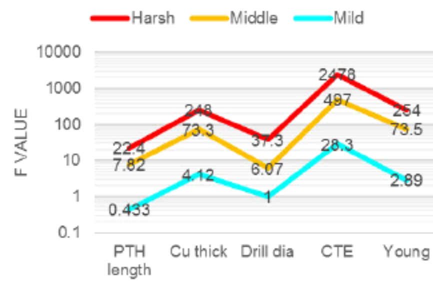
Figure 14 – 2nd investigation mutual factor effect results

5.4 Consideration – 2nd investigation

The ranking of the factors in the 3 temperature conditions is shown below. CTE, Young's Modulus and Cu plating thickness had a strong effect on strain in a PTH. PTH length and drill diameter had weak effect. The top 2 interactions were found that could be re-created to be used in deriving the equation.

	Rank	Single factor	F value Harsh	F value Middle	F value Mild
Large effect	1	Material CTE	2478	497	28
Middle effect	2	Material E	254	74	3
	3	Cu plating thick	248	73	4
Small effect	4	PTH length	22	8	0.4
	5	Drill Dia.	37	6	1

Green ・・・ PWB material properties
Purple ・・・ PTH dimensions



	Rank	Mutual factor(Interaction)	F value Harsh	F value Middle	F value Mild
Large effect	1	Material CTE X Cu plating thick	21.2	28.3	12.5
	2	Material CTE X Material E	22.1	21.2	8.9
Small effect	3	Material CTE X PTH length	0.8	4.2	1.3
	4	Material CTE X Drill Dia.	0.01	2.8	3.0
	5	Material E X PTH length	2.5	0.3	0.00
	6	Material E X Drill Dia.	9.7	0.01	0.00
		・・・			
Little effect	10	PTH length X Drill Dia.	0.4	0.09	0.00

These interactions should be re-created in equation.

Figure 15 – 2nd Investigation factor effect ranking

6. Roughness influence investigation

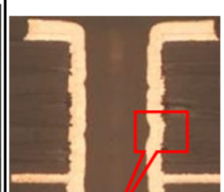
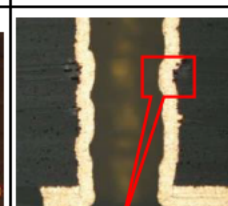
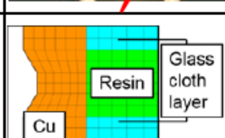
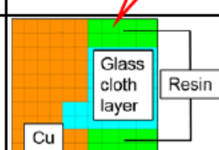
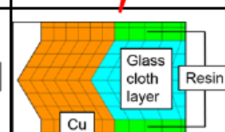
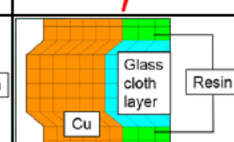
6.1 Roughness in plated through hole

In PWB manufacturing process, through holes are formed by drilling, then plated with copper. Thus many PTH are formed in the PWB at the same time. In accordance with drilling condition, a wall of the through hole has various convex and concave features as roughness. It is said that a crack would tend to occur in a PTH with large roughness. An investigation of roughness influence to PTH life is needed.

6.2 Roughness classification

Two shapes of convex features in the resin layer and 3 shapes of concave features in the glass cloth layer were observed in cross-sections. The convex and the concave features were formed in a circle in 55um Cu plating of PTH in their models.

Table 4 – 5 shapes of roughness

	Convex in resin part		Concave in glass cloth part		
	Model R1	Model R2	Model G1	Model G2	Model G3
Cross-section					
Model	 Depth:12um Width:20/58um	 Depth:12um Width:10/58um	 Depth:18um Width:20/60um	 Depth:18um Width:60um	 Depth:12um Width:40/60um

Simulation result – roughness influence investigation

Simulations were conducted with 2.70mm PTH length, 0.25mm drill diameter, CTE and Young's Modulus of FR4 at -40 deg C to 125 deg C. In the model of the convex feature in the resin layer, strain concentration was confirmed due to the roughness by comparing to the model without roughness. At the convex feature of Model R1, strain concentrated on the inner side of PTH comparing to PTH without roughness having strain concentration on the outer side of PTH. This means that PTH life is supposed to be shortened. On the other hand, in the model of the concave feature in glass cloth layer, strain concentration was not confirmed because the Young's Modulus of both Cu plating and glass cloth are similar.

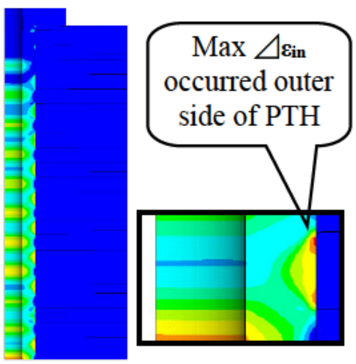
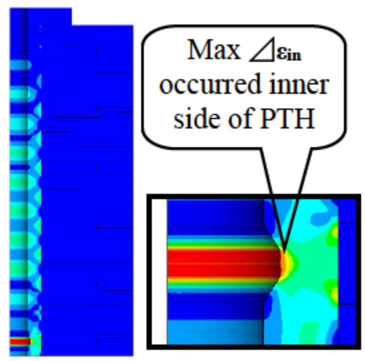
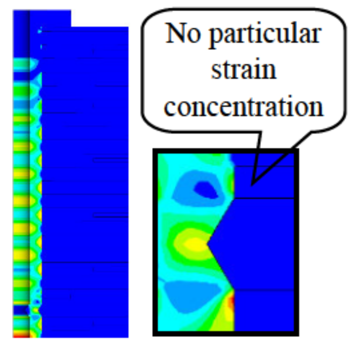
	Without roughness	With roughness	
		Model R1	**Model G2**
Contour figure			
$\Delta\varepsilon_{in}$	6.57×10^{-3}	9.33×10^{-3}	6.60×10^{-3}

Figure 16 – Contour figures according to roughness shape

The PTH of these models has a land near the center of the stack-up, shown in Figure 3, so maximum $\Delta\varepsilon_{in}$ position changed from the center (1289um depth from surface) to a little above center (935um depth from surface) between the surface layer and the land connection.

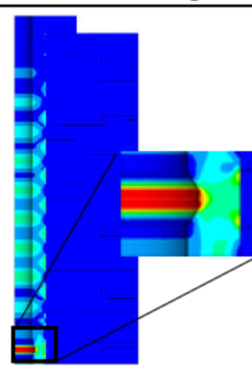
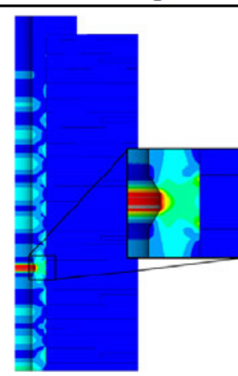
	Model R1	
	1289um depth	**935um depth**
Contour figure		
$\Delta\varepsilon_{in}$	9.33×10^{-3}	1.17×10^{-2}

Figure 17 – Contour figures according to roughness position

In the land connection model, Model R1, $\Delta\varepsilon_{in}$ became largest at 935um depth, however if the PTH does not have the land connection, $\Delta\varepsilon_{in}$ became largest at the center (1289um depth).

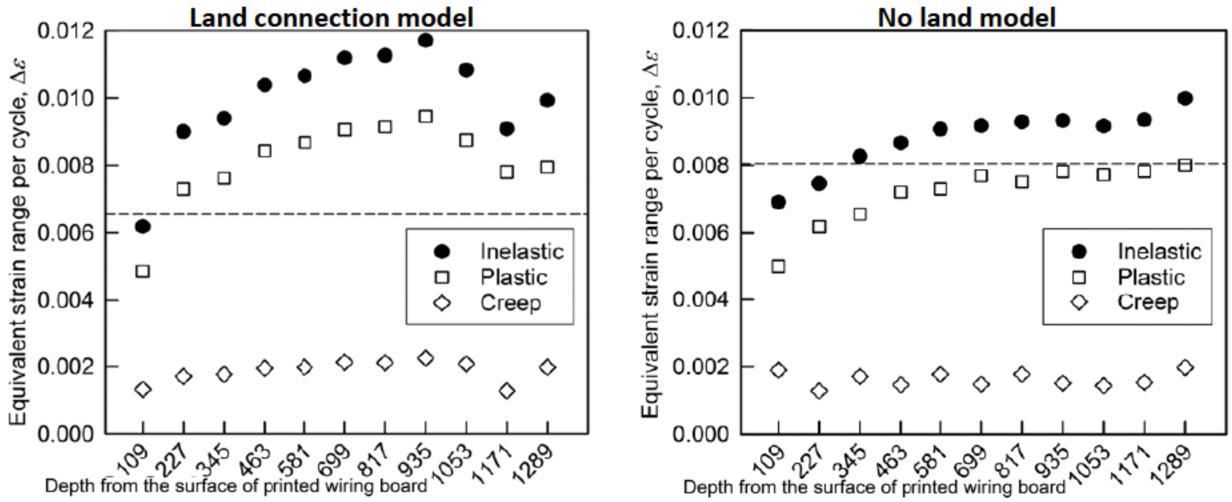


Figure 18 – $\Delta\varepsilon_{in}$ according to position with/without land connection

7. Equation

7.1 Strain Equation

The strain equation shown in Figure 19 was derived from the 5 single factor effects and 2 mutual factor effects in section 5.4. This equation works only if the $\Delta\varepsilon$in is greater than 0.0003. If $\Delta\varepsilon$in is lower than 0.0003, the strain is mainly creep strain which does not obey Manson-Coffin's rule. A creep strain, or creep fatigue equation, would be required.

$$\Delta\varepsilon_{in}=f(\Delta T)\times[9.44\times10^{-4}\ln L_{Cu}+1.62\times10^{-4}T_{Cu}+2.85\times10^{-3}T_{Cu}^{-0.388}+5.00\times10^{-3}D_{Cu}^{-0.234}+2.51\times10^{-6}\alpha^{2}-5.23\times10^{-6}E^{2}+1.90\times10^{-5}E+(9.65\times10^{-6}E-3.31\times10^{-6}T_{Cu}+1.60\times10^{-5})\alpha-2.29\times10^{-3}]$$

L_{Cu} …PTH Length
T_{Cu} …Cu plating thickness of PTH
D_{Cu} …PTH Diameter
α …Material CTE
E …Material Young's modulus
f(⊿T) … a scaling term of temperature range

Figure 19 – Strain Equation

7.2 N and AF Equations

The scaling factor (S) of $\Delta\varepsilon_{in}$, N and AF equations were shown in Figure 20. $\Delta\varepsilon_{in}$ should be corrected by S, a ratio of temperature effect compared to the harsh condition which was used in simulations on Box-Behnken design. This N equation is from the previous study. N means number of cycles. AF, Acceleration Factor, equals to, for example, N of field divided by N of test.

- $\Delta\varepsilon_{in}$ corrected by scaling factor

$$\Delta\varepsilon_{in}' = \Delta\varepsilon_{in} \times S$$

$$S = 1 - \frac{\left(0.007\Delta\varepsilon_{in}^{H} + 3.94\times10^{-5}\right)\times\left(165-\Delta T\right)}{\Delta\varepsilon_{in}^{H}}$$

$\Delta\varepsilon_{in}^{H}$ … $\Delta\varepsilon_{in}$ of Harsh condition
ΔT … Temperature range

- N equation   * not be validated for accuracy

$$N = \left(\frac{0.41}{\Delta\varepsilon_{in}'}\right)^{1.16}$$

- AF equation

$$AF = \frac{Nf}{Nt}$$

Nf … Number of cycles to failure in the field
Nt … Number of cycles to failure in the test

Figure 20 – N and AF Equations

7.3 Lifetime Prediction

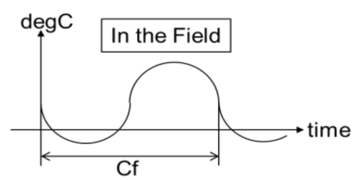
The predicted lifetime can be derived from the formula shown in Figure 21. Life (L) equals to N of field multiplied by Cf. Cf is cycle of temperature change in the field. This temperature should be PTH's temperature. The predicted lifetime, L, equals to Cf multiplied by AF and N of test.

- predicted Life : L

$$Nf = AF \times Nt$$

$$L = Nf \times Cf$$

L … Life
Cf … Cycle of temperature change in the field(from on/off, etc)
*should be PTH's temperature



$$\frac{L}{Cf} = AF \times Nt$$

$$L = Cf \times AF \times Nt$$

Figure 21 – Lifetime

8. Validation

The AF from the equation was verified by TCT results using real PWB without roughness only.

8.1 TCT samples

The board specifications and the number of sample (N) of PWBs having 660 PTHs connected in daisy chain loop are tabulated as shown in Table 5. Type 2 is used as the base model, with which

- Compare against Type 1 for effects on PTH length
- Compare against Type 3 for effects on Cu plating thickness
- Compare against Type 5 for effects on PTH diameter

Table 5 – Specification of PWB

	Layer count	Cu plating thick	PTH dia.		N
PTH type 1	**16 (1.75 mmt)**	15 um	0.35 mm dia.		6 boards
PTH type 2	**24 (2.70 mmt)**	**15 um**	**0.35 mm dia.**		**6 boards**
PTH type 3	24 (2.70 mmt)	**55 um**	0.35 mm dia.		6 boards
PTH type 5	24 (2.70 mmt)	15 um	**0.15 mm dia.**		6 boards

8.2 TCT conditions

PWBs fabricated as TCT samples were tested in the following harsh condition, from -40 deg C to 125 deg C on a 30-minute cycle. The loop resistance of the PWBs were monitored during the TCT.

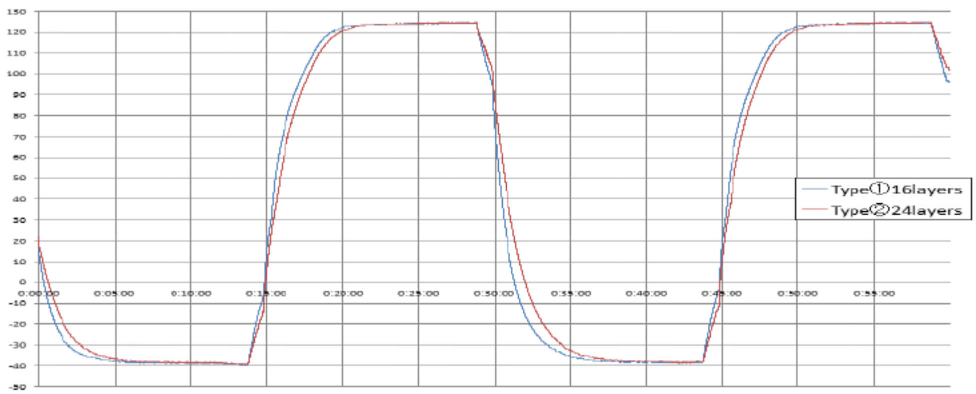


Figure 22 – Monitored temperature profile of harsh condition

8.3 Monitored resistance change in TCT

The resistance changes of type 2, 3 and 5 in harsh condition were monitored, as shown in Figure 23.
Type 2, with 0.35 mm dia. and 15 um Cu plating, showed a steep slope.
Type 3, with 0.35 mm dia. and 55 um Cu plating, did not produce a slope.
Type 5, with 0.15 mm dia. and 15 um Cu plating, showed a gentle slope.

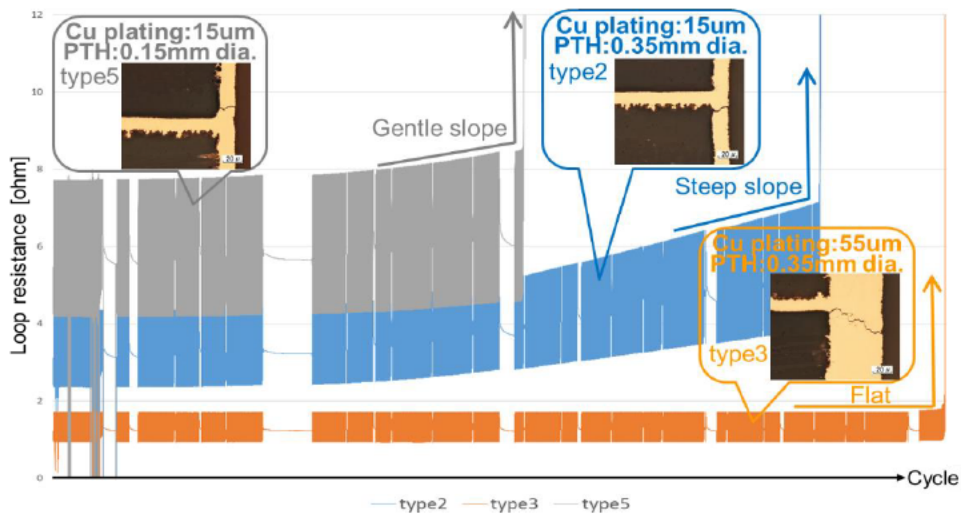


Figure 23 – Monitored resistance profiles

8.4 Weibull plot in different judgements

The number of cycles to failure of the above PWBs was read from the profiles of monitored resistance change, then analysed by Weibull plot separated by 3 judgements of resistance increase of 10%, 20% and 50% as shown in Figure 24. Type 2's result changed with increasing percent of resistance rise. With thicker Cu plating in Type 3, the plot showed no change in result.

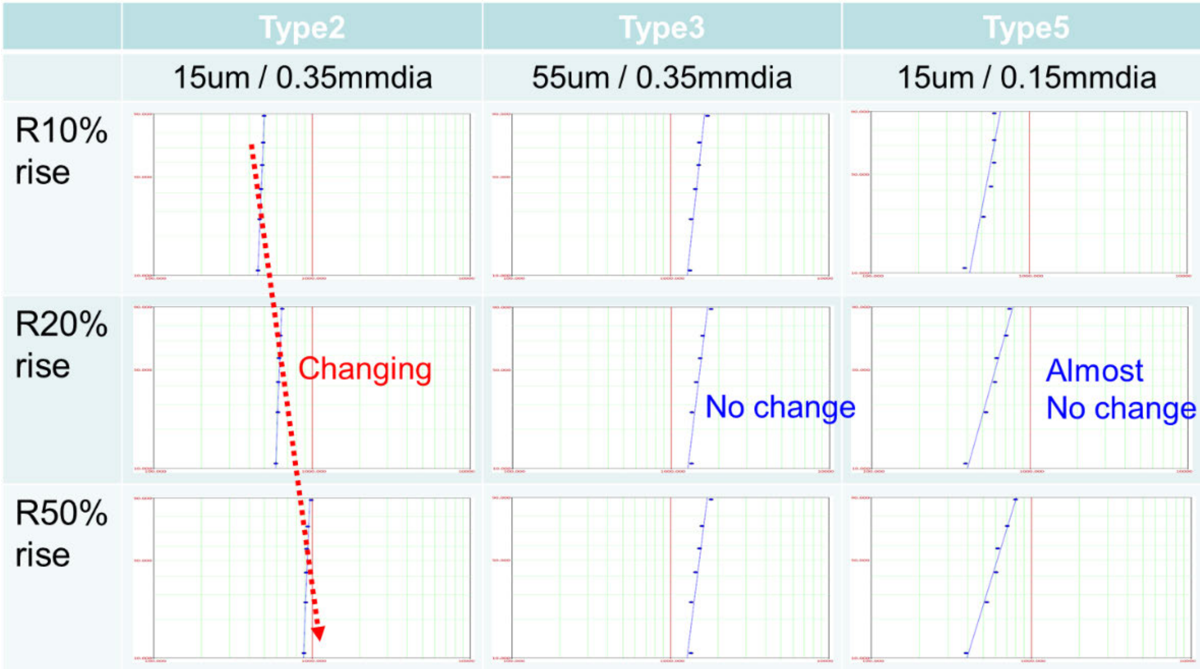


Figure 24 – Weibull Plot for Harsh Condition TCT

8.5 AF equation validation

To validate the AF equation, the AF from the acquired equation by FEM simulation based on Box-Behnken design was compared to the AF from the normal average and Weibull average by TCT results using the PWBs in Table 6. The Weibull average of test seems to fit the equation best when resistance increased by 20%. The best correlation would be at resistance 30% (the table only shows 10%, 20%, 50% and 100%) increase, which is from 81% to 134%, range is 52%. Some other aspects of this validation were listed below. In general, Weibull average of test seems to fit equation better than normal.

Table 6 – Validation results

difference: 71% | 83% | 120% | 140%

		equation	test							
			normal average				weibull average			
			R10%UP	R20%UP	R50%UP	R100%UP	R10%UP	R20%UP	R50%UP	R100%UP
AF eqation / AF test	type③/type⑤		150.4%	140.6%	138.7%	138.2%	146.8%	134.4%	132.1%	131.5%
	type③/type②		183.9%	145.3%	96.9%	83.5%	188.1%	149.4%	99.8%	83.1%
	type③/type①		147.7%	116.5%	95.5%	95.4%	148.2%	116.8%	92.7%	92.6%
	type①/type②		124.5%	124.7%	101.5%	87.5%	127.0%	127.9%	107.7%	89.8%
	type⑤/type②		122.2%	103.3%	69.9%	60.5%	128.2%	111.2%	75.5%	63.2%
	type⑤/type①		98.2%	82.9%	68.9%	69.1%	100.9%	86.9%	70.1%	70.4%
			R10%rise	R20%rise	R50%rise	R100%rise	R10%rise	R20%rise	R50%rise	R100%rise
AF	type③/type⑤	1.79	2.70	2.52	2.49	2.48	2.63	2.41	2.37	2.36
	type③/type②	1.68	3.08	2.44	1.63	1.40	3.16	2.51	1.67	1.39
	type③/type①	1.56	2.30	1.82	1.49	1.49	2.31	1.82	1.45	1.44
	type①/type②	1.08	1.34	1.34	1.09	0.94	1.37	1.38	1.16	0.97
	type⑤/type②	0.94	1.14	0.97	0.65	0.57	1.20	1.04	0.71	0.59
	type⑤/type①	0.87	0.85	0.72	0.60	0.60	0.88	0.76	0.61	0.61

9. Conclusions

1) FEM simulation based on Box-Behnken design is useful for understanding both single and multiple factor effects, knowing interactions of PWB key parameters, and reducing the number of simulations to calculate strain on PWB's PTH causing an occurrence and propagation of cracks.

2) By eliminating the overwhelming factors such as Tg, and negligible factors such as PTH pitch, and setting Tmax below Tg to better focus on the remaining factors and make their effects clear, the relationship of these factors can be established.

3) Between the dimensional and material factors, the latter (CTE and Young Modulus) has greater impact. Cu plating thickness also has a great impact.

4) The $\Delta\varepsilon_{in}$ equation can be derived from the relationship based on Box-Behnken design and an influence of ⊿T, then by using Manson-coffin rule, $\Delta\varepsilon_{in}$ can be converted into the number of cycle to failure. Finally, the AF equation can be derived.

5) The $\Delta\varepsilon_{in}$ equation can only be applied for cyclic strain. If the $\Delta\varepsilon_{in}$ is small, damage would be from mainly creep strain which does not obey Manson-Coffin rule, and the acquired equation is not applicable.

6) Regarding roughness on Cu plating of PTH, the $\Delta\varepsilon_{in}$ becomes large with convex features in the resin layer, potentially leading to a short-lived PTH.

7) With land connection, maximum $\Delta\varepsilon_{in}$ position changes from the center of the stack-up.

8) The validation for the AF equation was conducted by comparing the AF equation from various TCT results with AF from equation from simulation equation. Most differences (AF of equation / AF from TCT) fell in the 67% (=1/1.5) to 150% (=1.5), confirming that the equation is preferable.

9) The larger differences would be suspected to be caused by the roughness and/or the creep strain of the Cu plating of PTH of PWBs.

10. Acknowledgement

This work was conducted as a research project within the HDP User Group International, Inc. The authors would like to thank the organization and its members for their support.

11. References

1) Yoshiyuki HIROSHIMA et al., "FATIGUE LIFE ESTIMATION OF ELECTROPLATED THROUGH HOLE IN PWB BY FEM WITH THIN CU MATERIAL PROPERTIES," FUJITSU ADVANCED TECHNOLOGIES LIMITED, 2015 SMTA International, 2015.

2) Yoshiharu KARIYA et al., "Low-cycle Fatigue Testing and Thermal Fatigue Life Prediction of Electroplated Copper Thin Film for Through Hole Via," Department of Materials Science and Engineering, Shibaura Institute of Technology, submitted to Microelectronics Reliability.

Derivation of Equation on Thermal Life Prediction of Plated Through Hole for Printed Wiring Board
- A project from HDP User Group -

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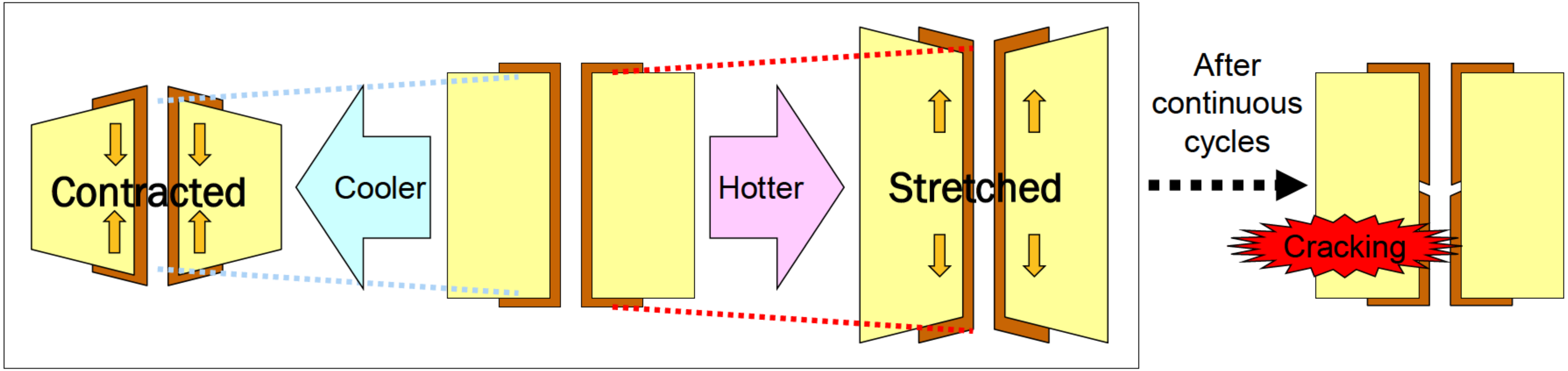
Agenda

- Introduction
- Benefits of Equation
- Experimental plan
- 1st Simulation
- 2nd Simulation
- Roughness influence
- TCT
- Validation
- Conclusion

Introduction

- Plated through hole (PTH) are formed by copper (Cu) plating after drilling.
- The PTH contracts and stretches due to resin as the temperature changes during operation.
- The repeated stress can cause PTH cracking.

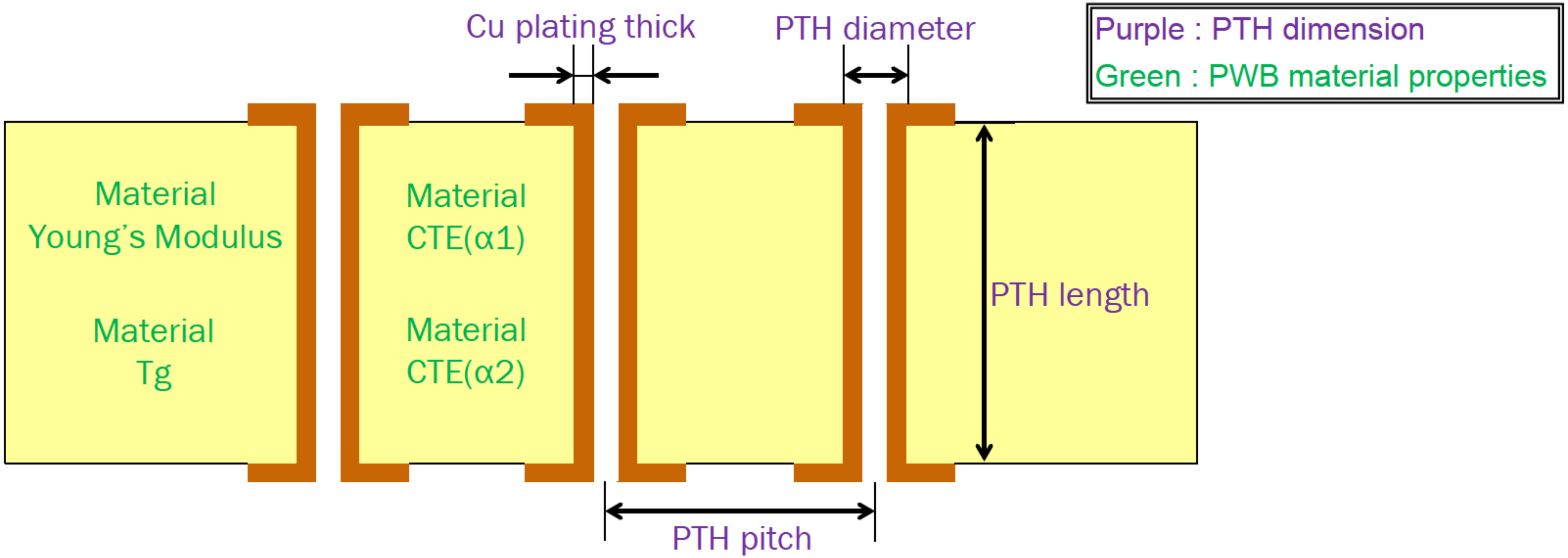


Benefits of Equation

- You can not determine the following by conducting TCT.

1) At an early stage, which is a critical design factor of PTH life?

2) In case of crack in plating of PTH, which and how much should factor be changed?



Objective : calculate the number of cycles to failure from these factors

Experimental plan

- Design of experiments is needed to find key factors and effects.
- Box-Behnken design can both save the number of runs and make an equation with the factors.
- FEM simulation was applied in the Box-Behnken design.

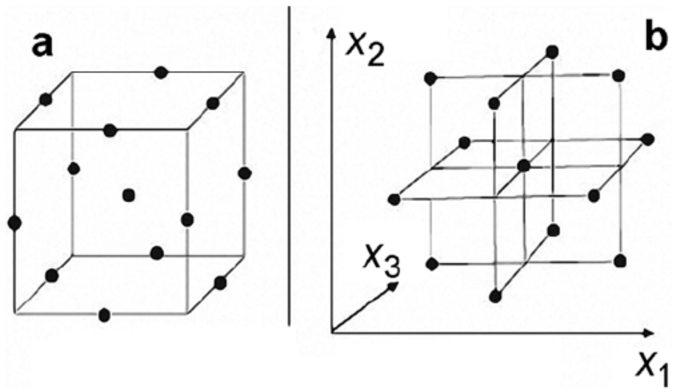


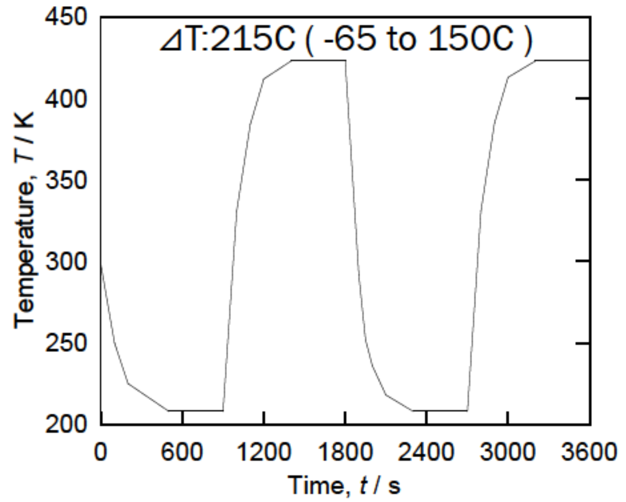
Table of 7 factors and 3 levels of Box-Behnken design

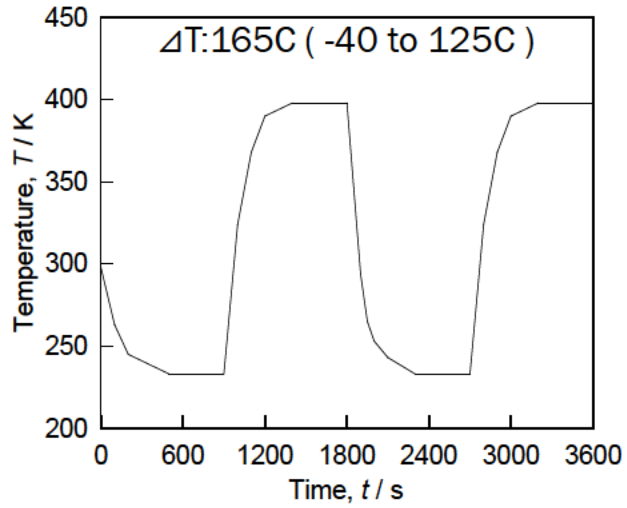
No	PTH length	Cu plating thick	PTH diameter	PTH pitch	PWB material CTE	PWB Material Young's modulus	PWB material T_g
1	0	0	1	-1	0	0	-1
2	0	0	1	-1	0	0	1
3	-1	0	1	0	1	0	0
4	-1	0	1	0	-1	0	0
5	0	0	0	1	1	-1	0
6	0	0	0	1	-1	-1	0
7	0	1	1	0	0	1	0
8	0	-1	1	0	0	1	0
9	-1	-1	0	1	0	0	0
□	□	□	□	□	□	□	□
□	□	□	□	□	□	□	□
□	□	□	□	□	□	□	□
60	1	0	0	0	0	1	-1
61	0	1	0	0	-1	0	1
62	1	0	-1	0	1	0	0

Factors and levels, 2 temperature conditions

- 3 levels of 7 factors were set widely.
- 2 temperature conditions, ⊿T:215C and ⊿T:165C.

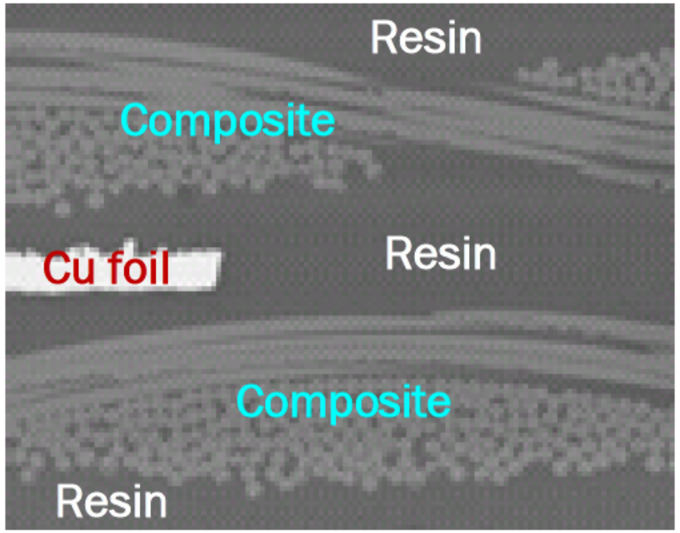
Factors		Level (-1)	Level (0)	Level (+1)
1. PTH length		0.81mm	1.75mm	2.70mm
2. Cu plating thick of PTH		15um	35um	55um
3. Drill diameter		ϕ0.15mm	ϕ0.25mm	ϕ0.35mm
4. PTH pitch		0.8mm	1.0mm	1.2mm
5. PWB Material CTE	α1	14.8ppm/C	44.8ppm/C	75.4ppm/C
	α2	100ppm/C	200ppm/C	300ppm/C
6. PWB Material Young's modulus		14.6GPa	23.0GPa	33.2GPa
7. PWB Material Tg		80C	130C	180C

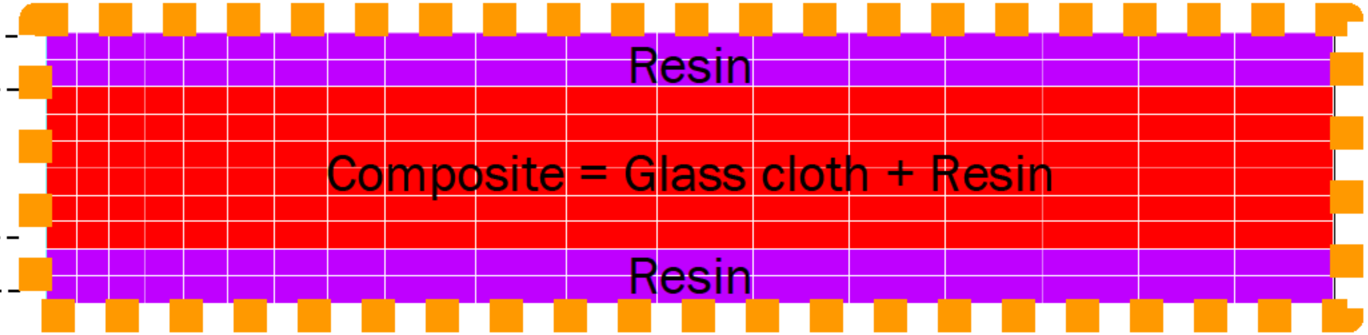




Modeling for FEM simulation

- Separate laminate and prepreg into resin part and composite part.
- Set value of both resin and composite for the 3 levels of PWB material factor.





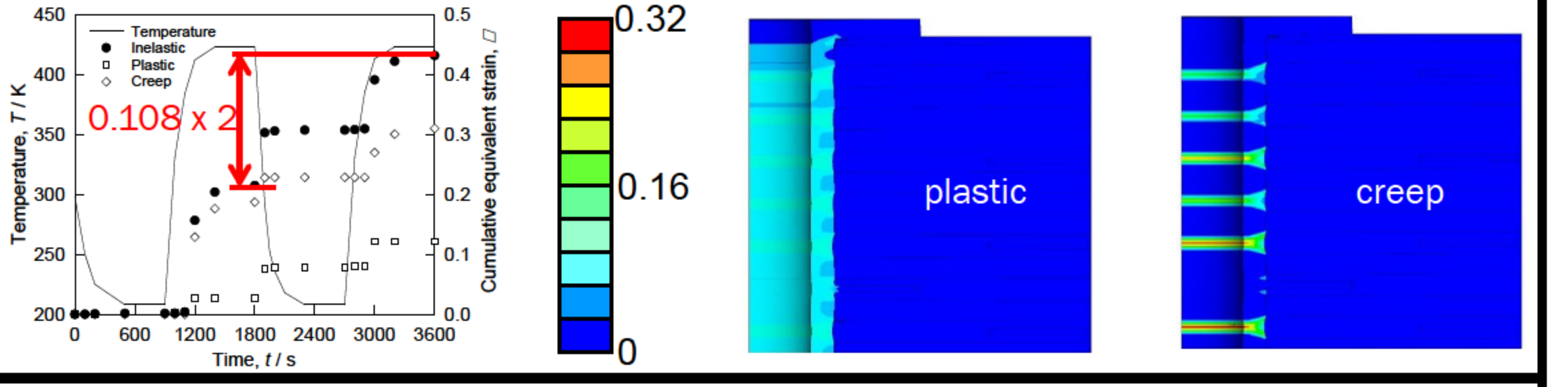
Factor	Elastic modulus of Composite	Instantaneous elastic modulus of Resin	Bending elastic modulus of PWB material
Level (-1)	36	0.9	14.6
Level (0)	48	2.7	23.0
Level (+1)	60	8.1	33.2

FEM simulation results

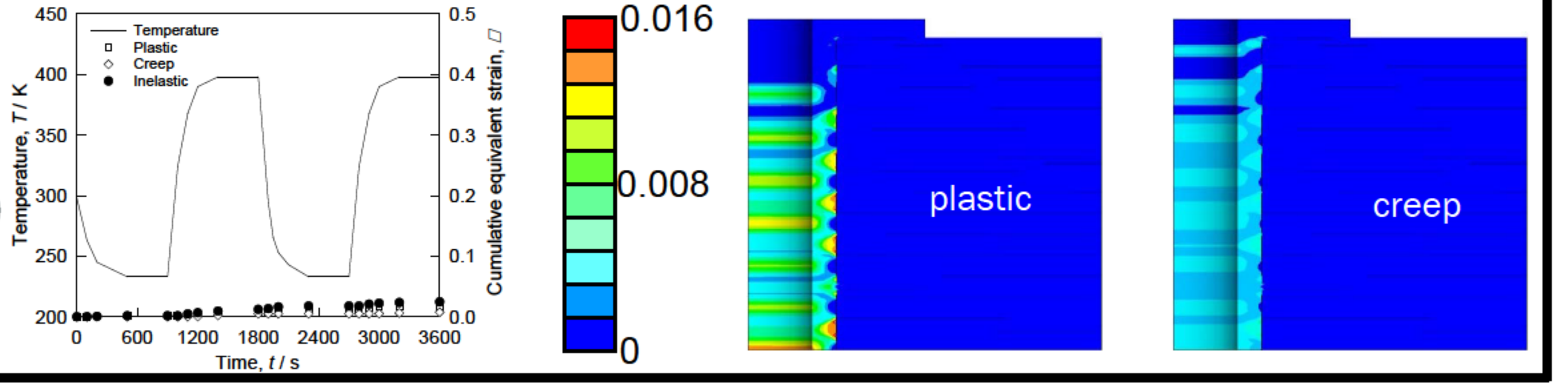
- Equivalent inelastic strain range($\Delta\varepsilon_{in}$) in 2nd cycle was adopted.

	Factor							$\Delta\varepsilon_{in}$ in 2nd cycle	
	PTH length	Cu plating thick	Drill dia.	Pitch	CTE	Young's modulus	T_g	ΔT:215C	ΔT:165C
Level	0	0	0	0	0	0	0	0.108	0.00626

ΔT:215C
(-65 to 150C)



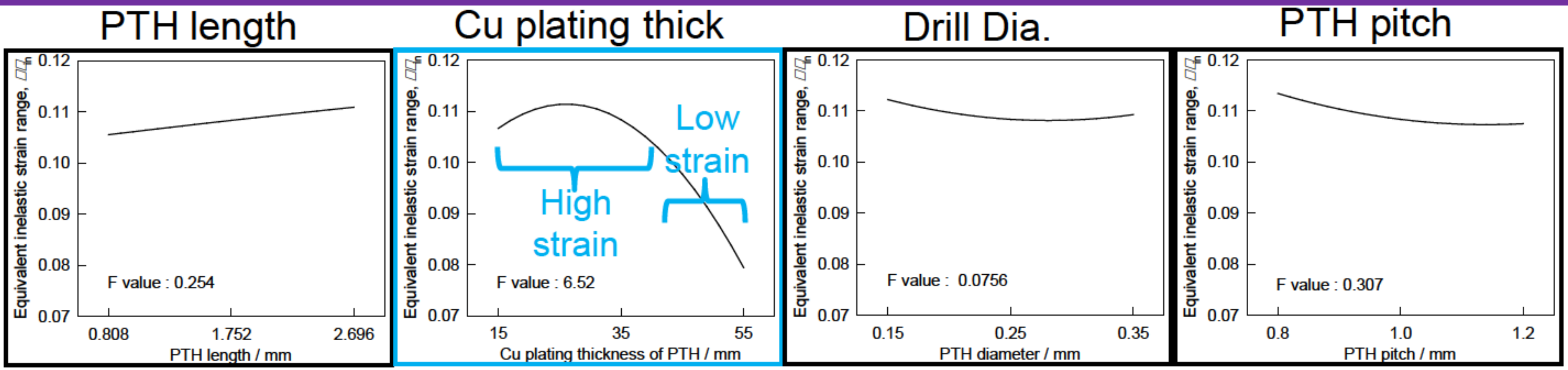
ΔT:165C
(-40 to 125C)



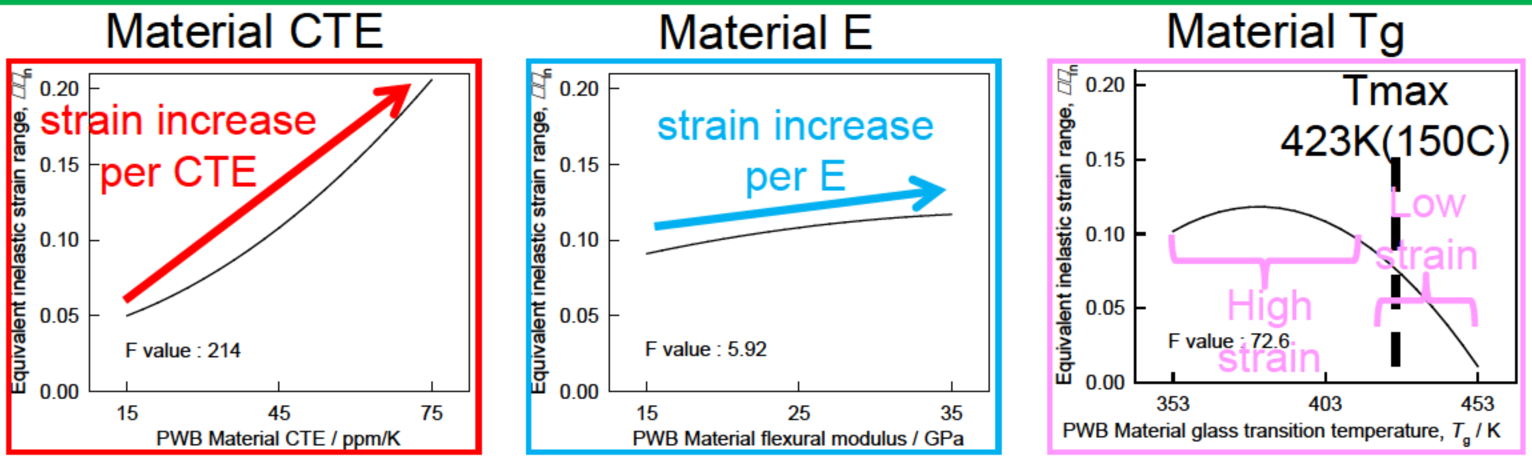
Single factor effect (⊿T:215C)

- Top factor is Material CTE, followed by Tg, and Cu plating thickness.
- Only Cu plating thickness in dimensional factors has effect.

Dimensional factors



Material factors

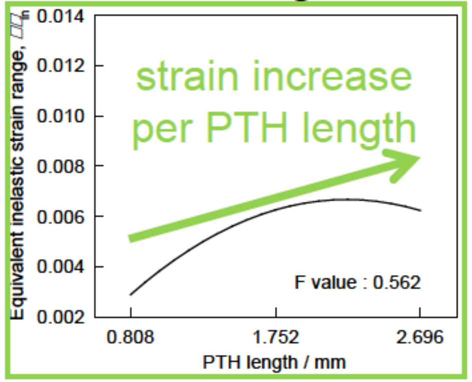


Single factor effect (⊿T:165C)

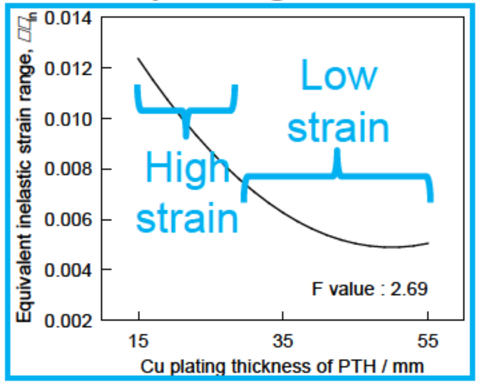
- Top factor is Material Tg, followed by CTE, and Young's modulus.
- Dimensional factors without PTH pitch have effect.

Dimensional factors

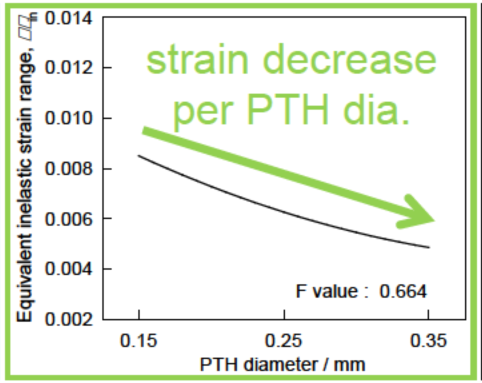
PTH length



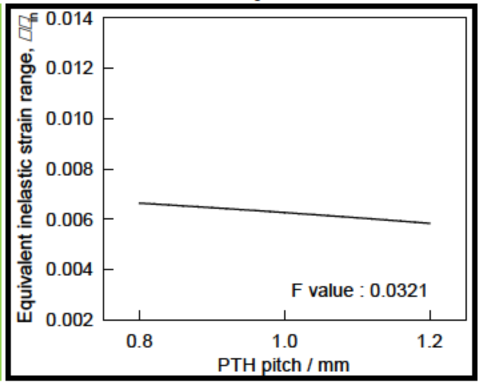
Cu plating thick



Drill Dia.

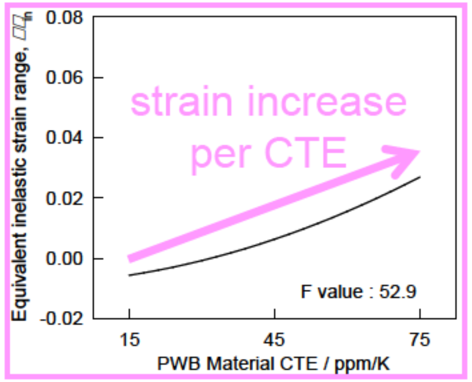


PTH pitch

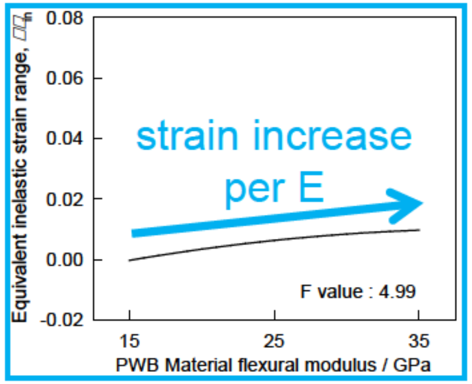


Material factors

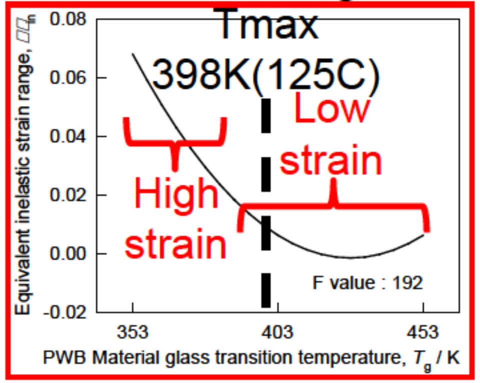
Material CTE



Material E

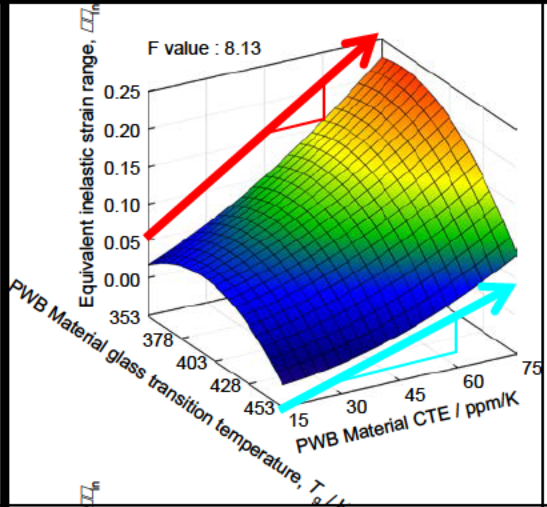
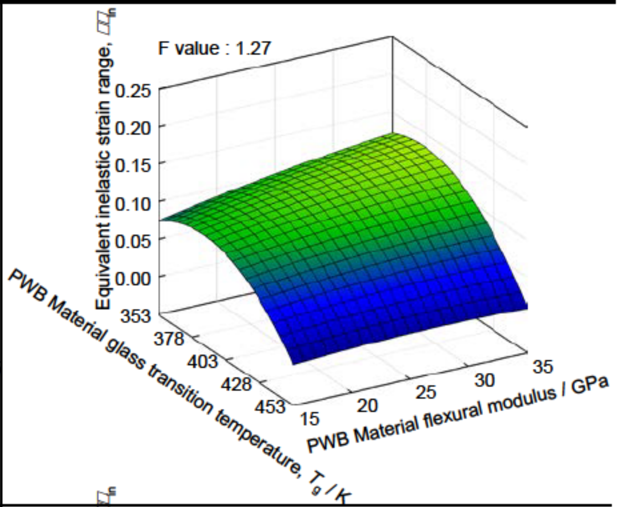
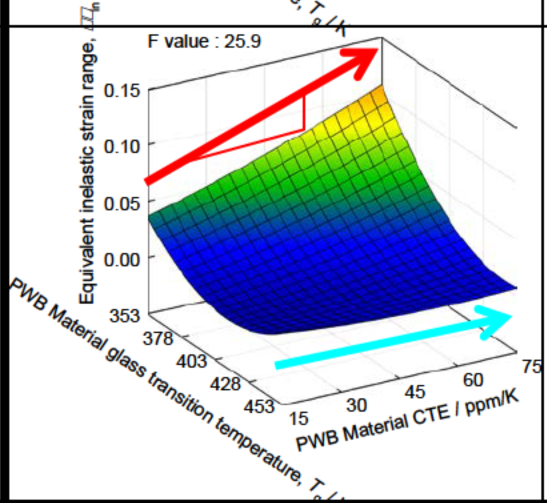
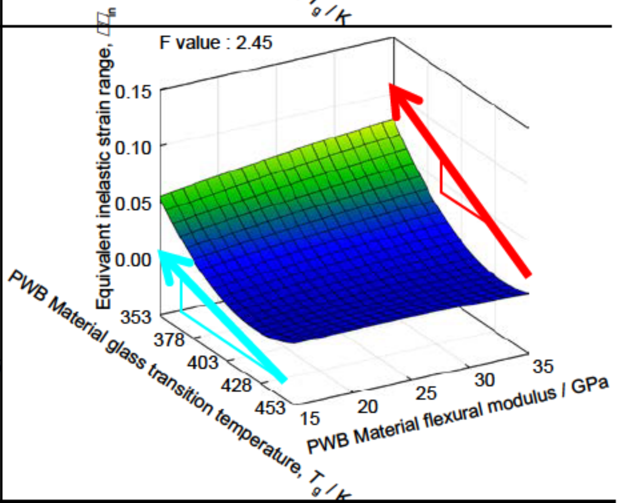


Material Tg



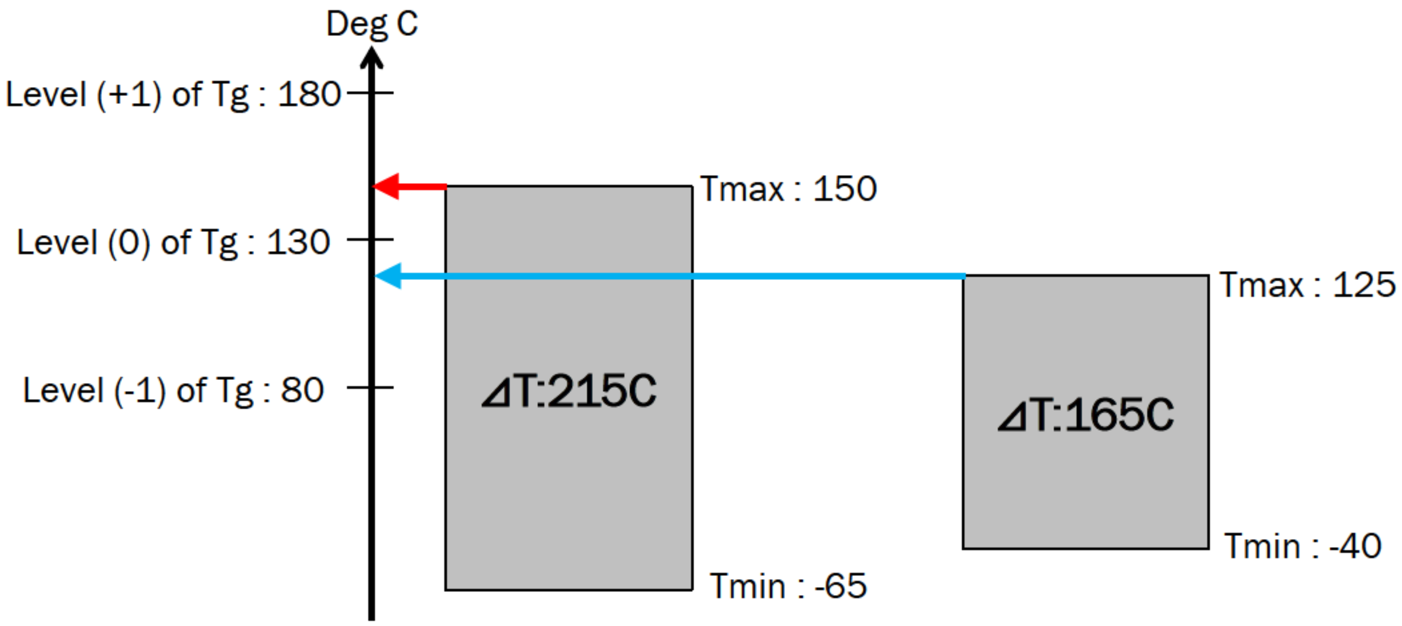
Mutual factor effect (⊿T:215C, ⊿T:165C)

- Interactions of ⊿T:165C are stronger than ⊿T:215C.

	Tg X CTE	Tg X E
⊿T:215C (-65 to 150C)		
⊿T:165C (-40 to 125C)		

Consideration

- In ⊿T:215C, Tmax 150C exceeding level (0) and (-1) of Tg led an overwhelming effect of CTE(α2), so the effect of other factors became unclear.



Decision 1 : adopt results of ⊿T:165C suitable for analysis

Factor effect ranking (⊿T:165C)

- Material Tg and CTE are the most dominant factors.
- PTH pitch's effect is negligible.
- Top five interactions are related to Material Tg or CTE.

Purple : PTH dimension
Green : PWB material properties

Rank	Single factor	F value
1	Material Tg	192.0
2	Material CTE	52.9
3	Material E	5.0
4	Cu plating thick	2.7
5	Drill Dia.	0.7
6	PTH length	0.6
7	PTH pitch	0.0

Rank	Mutual factor (Interaction)	F value
1	Material Tg X Material CTE	25.90
2	Material Tg X Material E	2.45
3	Material Tg X Cu plating thick	1.49
4	Material CTE X Cu plating thick	1.15
5	Material CTE X Material E	0.51
6	Material E X PTH length	0.26
7	Material Tg X PTH pitch	0.20
	□ □ □	
28	PTH length X PTH pitch	0.00

Narrow down factors

- Tg's effect was found to be too large. When Tmax exceeds Tg, the PTH life is shortened tremendously due to a mismatch of acceleration characteristics.
- PTH pitch was found to have negligible impact.

Decision 2 :

1) Tmax should be set below Tg. -> Material Tg and CTE(α2) are not needed to be used anymore.

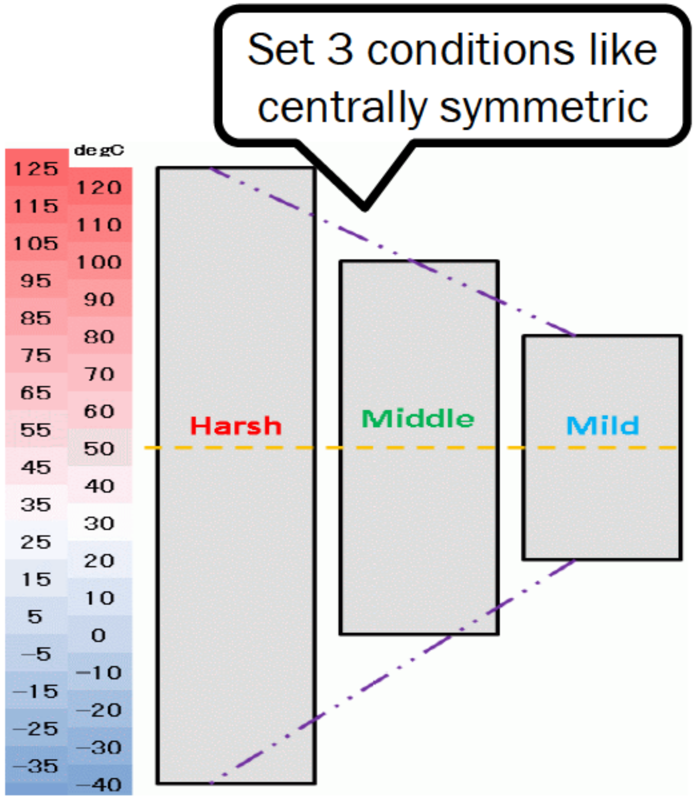
2) PTH pitch could be omitted for faster and simpler analysis.

Focused factors and levels, 3 temperature conditions

- 3 levels of 5 factors were set narrowly.
- To be close to reality, all levels were changed into realistic values used in current PWB.
- 3 temperature conditions, ⊿T:165C, ⊿T:100C, and ⊿T:60C.

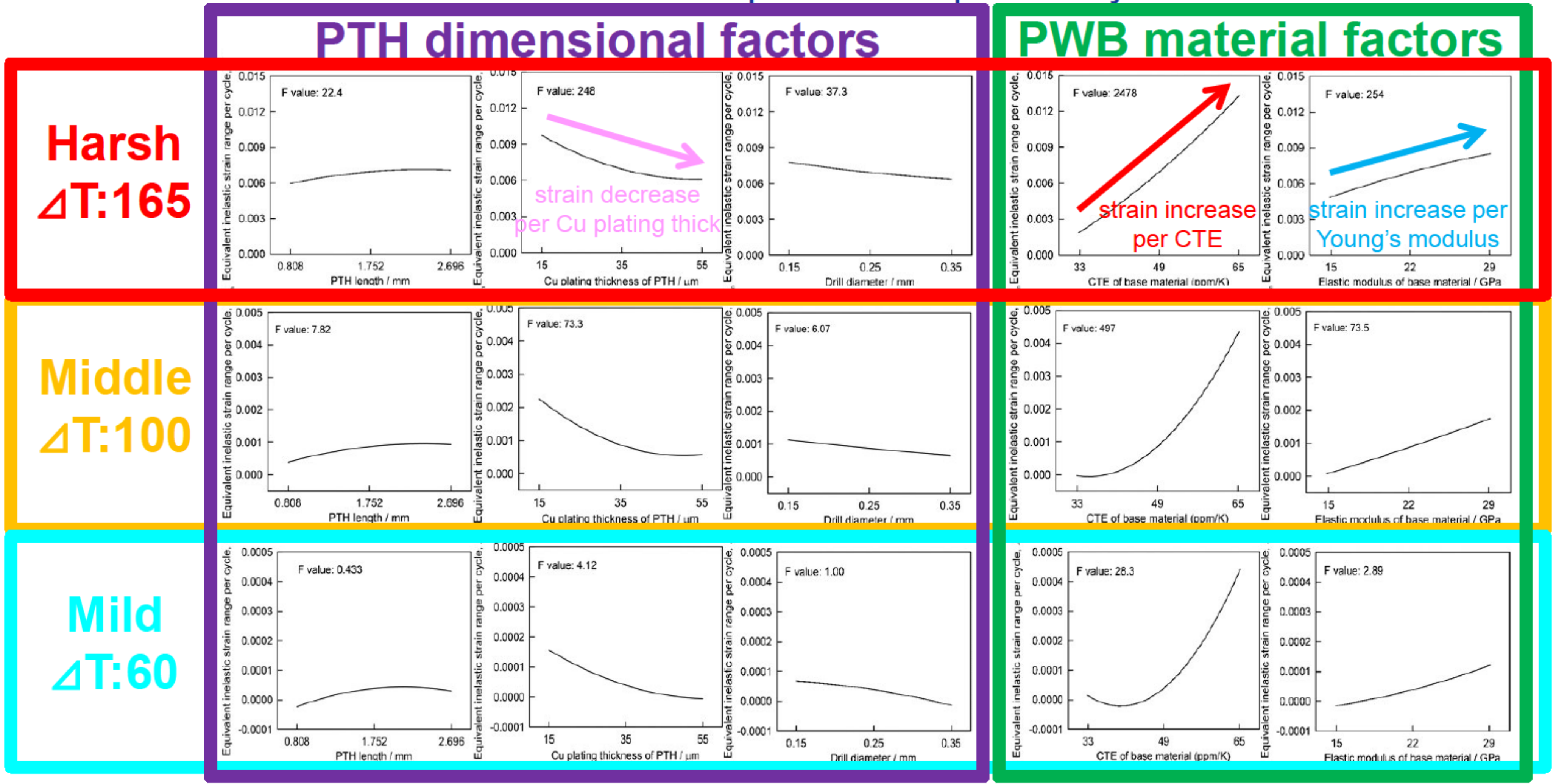
Factors	level(-1)	level(0)	level(+1)
1. PTH length	0.81mm	1.75mm	2.70mm
2. Cu plating thick of PTH	15um	35um	55um
3. Drill diameter	φ0.15mm	φ0.25mm	φ0.35mm
4. PWB Material CTE(a1)	33ppm/C	49ppm/C	65ppm/C
5. PWB Material Young's modulus	15GPa	22GPa	29GPa

*PTH pitch : 1 mm (fixed value)



Single factor effect (Harsh, Middle, Mild)

- Top factor is Material CTE, followed by Cu plating thickness and Young’s modulus.
- Same lines between conditions. = Small temperature dependency.

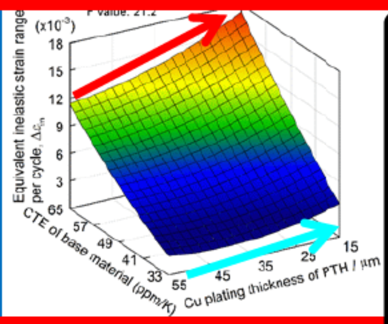


Mutual factor effect (Harsh, Middle, Mild)

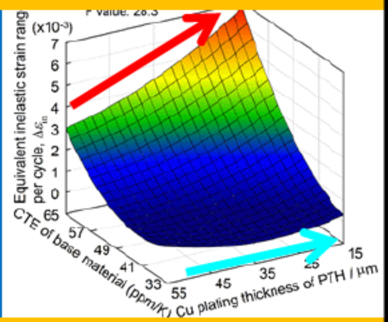
- Same surfaces between conditions. = Small temperature dependency.

CTE x Cu plating thick

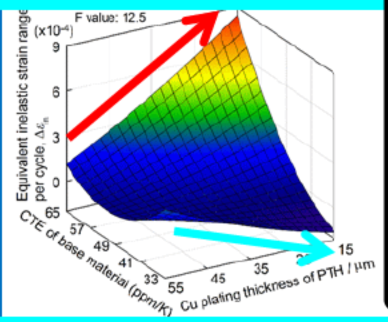
Harsh ΔT:165



Middle ΔT:100



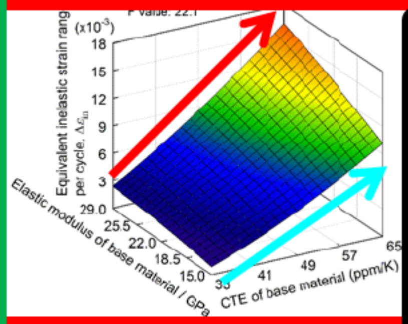
Mild ΔT:60

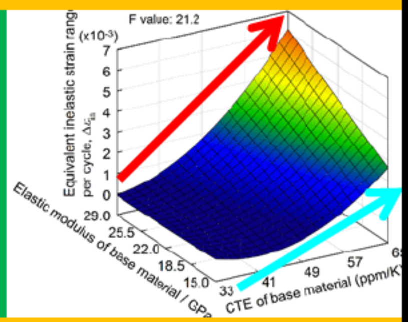


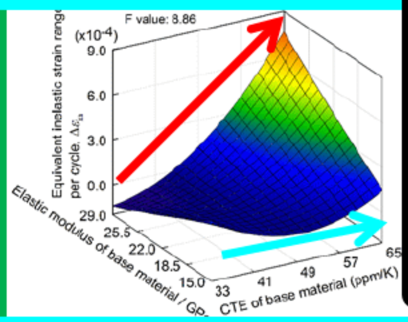
Larger CTE has larger increase of $\Delta\varepsilon$ as Cu plating thickness decreases.

When CTE is small, you don't need to worry about Cu plating thickness. Because even thin Cu gets no stress from material's small stretch.

Young's modulus x CTE







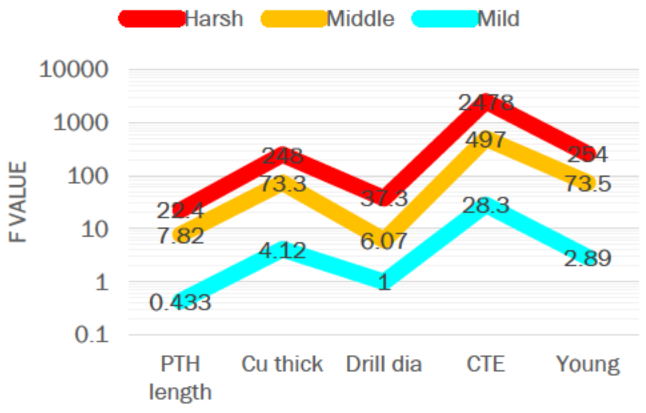
Larger Young's modulus has larger increase of $\Delta\varepsilon$ as CTE increases.

For material with large Young's modulus, CTE should be smaller in developmental stage.

Factor effect ranking (Harsh, Middle, Mild)

- In single factor, Material CTE, Young's modulus and Dimensional Cu plating thickness have larger effect.
- In mutual factor, two interactions between Material CTE and Cu plating thickness / Material Young's modulus have large effect.

Rank	Single factor	F value		
		Harsh	Middle	Mild
1	Material CTE	2478	497	28
2	Material E	254	74	3
3	Cu plating thick	248	73	4
4	PTH length	22	8	0.4
5	Drill Dia.	37	6	1



Rank	Mutual factor (Interaction)	F value		
		Harsh	Middle	Mild
1	Material CTE X Cu plating thick	21.2	28.3	12.5
2	Material CTE X Material E	22.1	21.2	8.9
3	Material CTE X PTH length	0.8	4.2	1.3
4	Material CTE X Drill Dia.	0.01	2.8	3.0
5	Material E X PTH length	2.5	0.3	0.00
6	Material E X Drill Dia.	9.7	0.01	0.00
	□ □ □			
10	PTH length X Drill Dia.	0.4	0.09	0.00

Factors in yellow cells should be adopted in equation

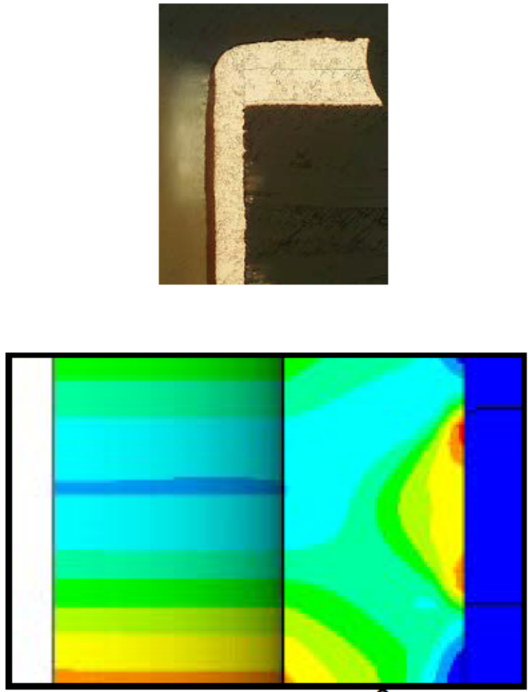
Purple : PTH dimension
Green : PWB material properties

Roughness influence (Resin)

- Convex feature on resin poses strain concentration, leading to increase of $\Delta\varepsilon_{in}$.

< Reference >

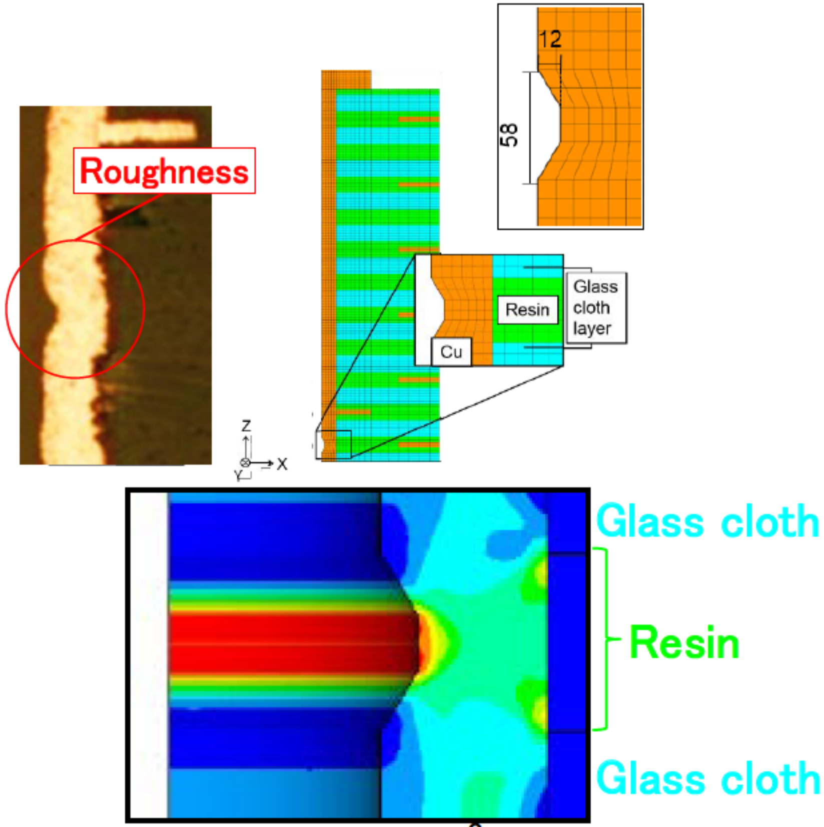
No roughness model



6.57×10^{-3}

100%

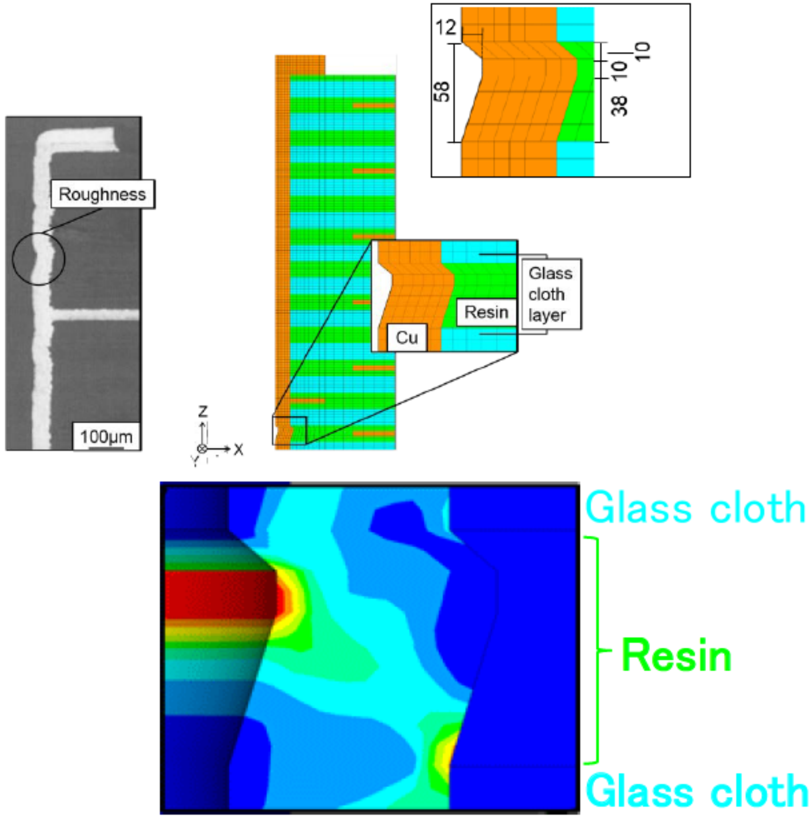
< Model R1 >



1.17×10^{-2}

178%

< Model R2 >



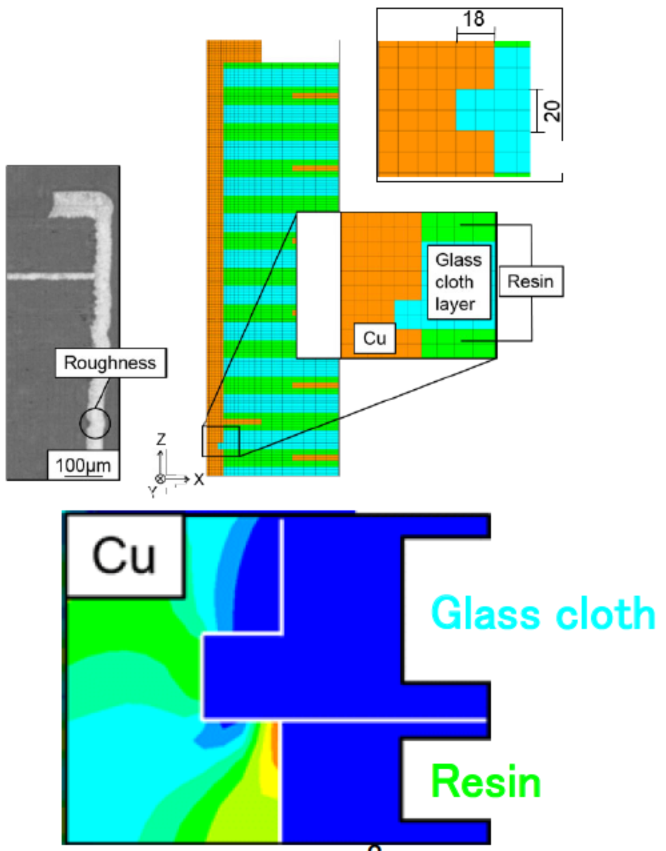
1.10×10^{-2}

167%

Roughness influence (Glass cloth)

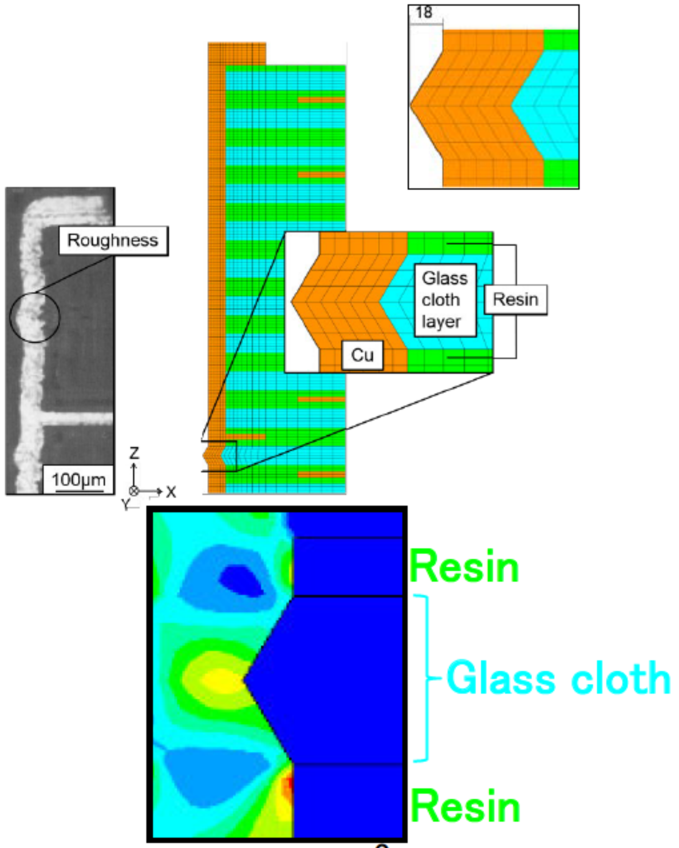
- Concave feature on glass cloth part does not pose strain concentration.

< Model G1 >



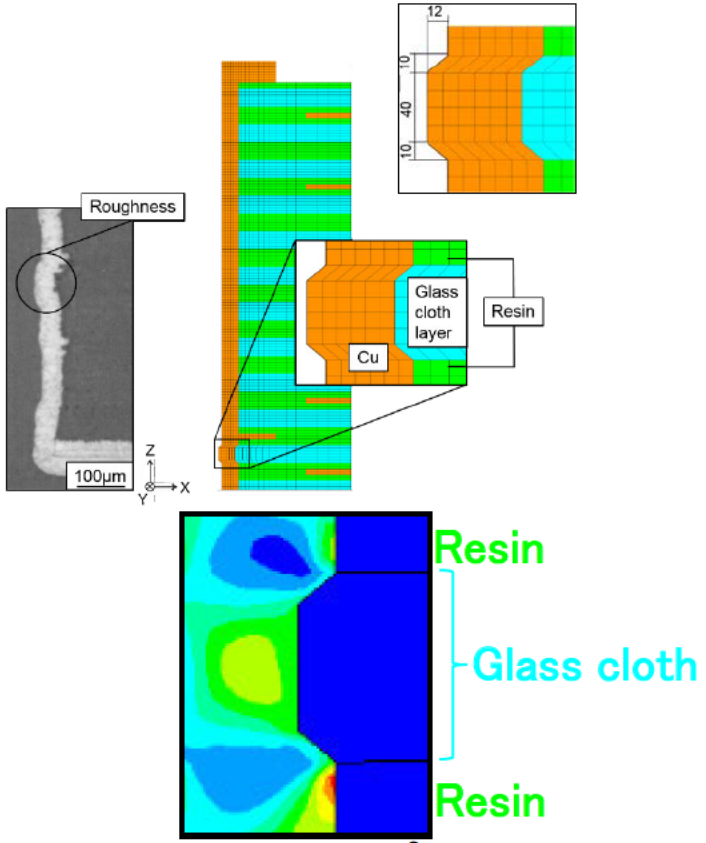
6.35×10^{-3}
97%

< Model G2 >



6.60×10^{-3}
100%

< Model G3 >



6.62×10^{-3}
101%

Equation

- $\Delta\varepsilon$ equation ($\Delta\varepsilon_{in} > 3.0 \times 10^{-4}$)

$$\Delta\varepsilon_{in} = 9.44\times10^{-4}\ln L_{Cu} + 1.62\times10^{-4}T_{Cu} + 2.85\times10^{-2}T_{Cu}^{-0.393} + 5.00\times10^{-3}D_{Cu}^{-0.234} + 2.51\times10^{-6}\alpha^{2} - 5.23\times10^{-6}E^{2} + 1.90\times10^{-5}E + (9.65\times10^{-6}E - 3.31\times10^{-6}T_{Cu} + 1.60\times10^{-5})\alpha - 2.29\times10^{-2}$$

- Corrected $\Delta\varepsilon_{in}$ by roughness influence

$\Delta\varepsilon_{in} = \Delta\varepsilon_{in} \times R$ R : rate of $\Delta\varepsilon_{in}$ increase by roughness

- Corrected $\Delta\varepsilon$ by scaling factor

$\Delta\varepsilon_{in} = \Delta\varepsilon_{in} \times S$

$$S = 1 - \frac{\left(0.007\Delta\varepsilon_{in}^{H} + 3.94\times10^{-5}\right)\times\left(165 - \Delta T\right)}{\Delta\varepsilon_{in}^{H}}$$

$\Delta\varepsilon_{in}^{H}$: $\Delta\varepsilon_{in}$ of Harsh condition

- N equation

$$N = \left(\frac{0.41}{\Delta\varepsilon_{in}}\right)^{1.16}$$

N : Number of cycles to failure

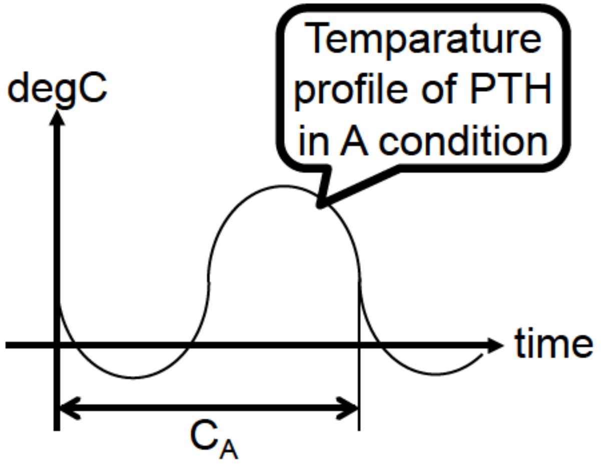
- AF equation

$$AF = \frac{N_A}{N_B}$$

AF : Acceleration Factor
N_A : Number of cycles to failure of A PWB spec. and condition
N_B : Number of cycles to failure of B PWB spec. and condition

- Life calculation

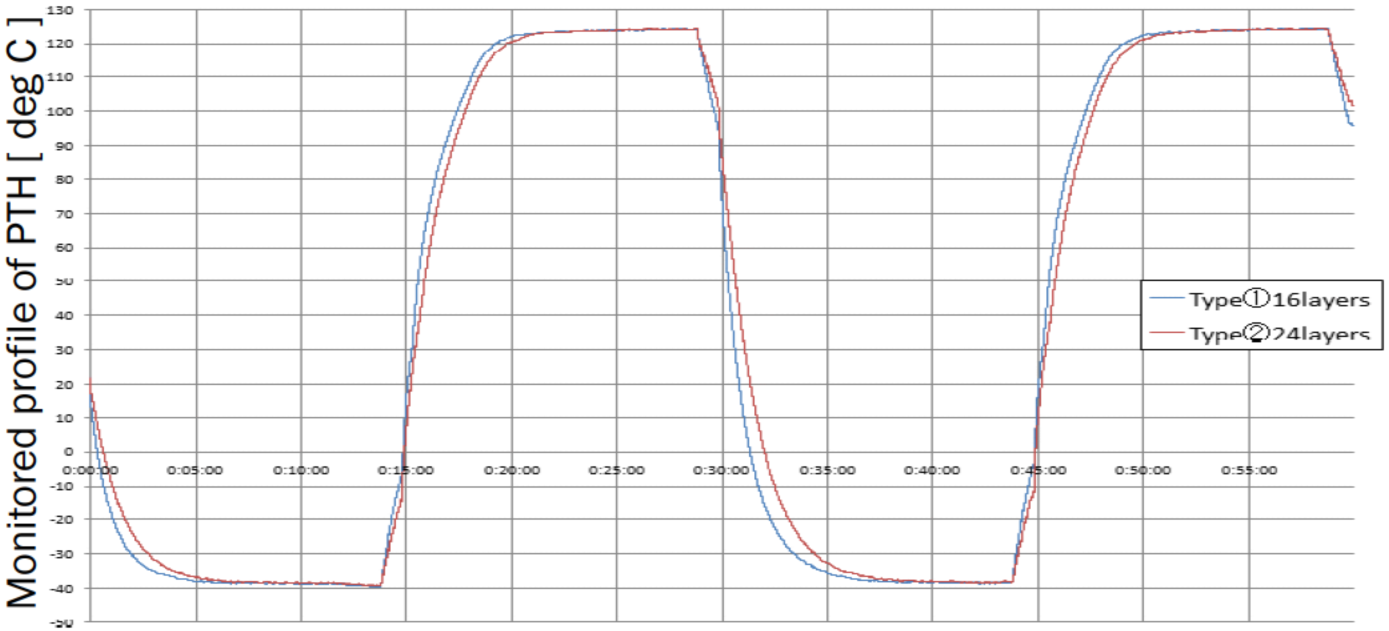
$L_A = C_A \times AF \times N_B$ C_A : cycle of temperature profile of A PWB condition

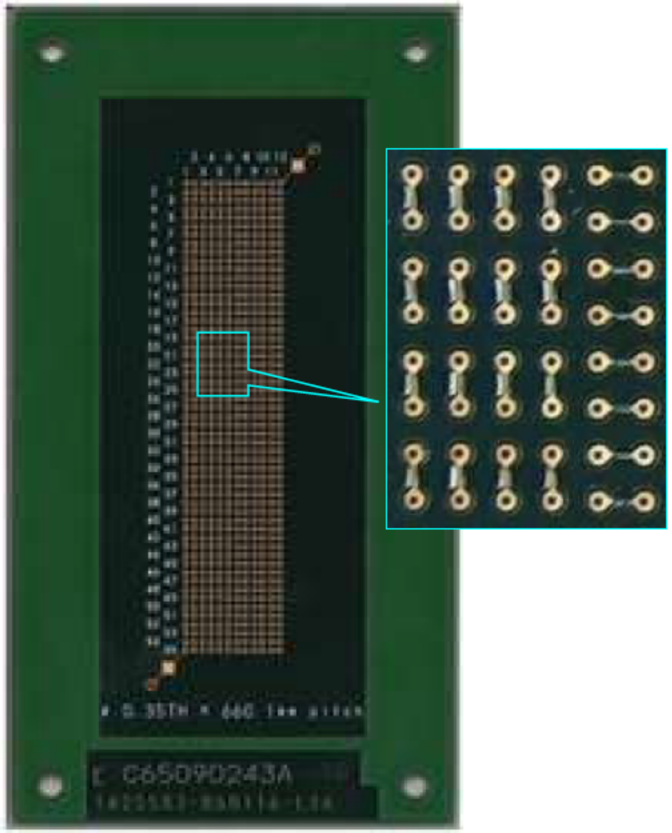


TCT board and condition

- 4 kinds of board having 4 type of PTH each.
- Temperature condition is ⊿T:165C same as FEM simulation.

PTH	Layer count	Cu plating thick	PTH dia.	N
type 1	16 (1.75 mmt)	15 um	0.35 mm dia.	6 boards
type 2	24 (2.70 mmt)	15 um	0.35 mm dia.	6 boards
type 3	24 (2.70 mmt)	55 um	0.35 mm dia.	6 boards
type 5	24 (2.70 mmt)	15 um	0.15 mm dia.	6 boards



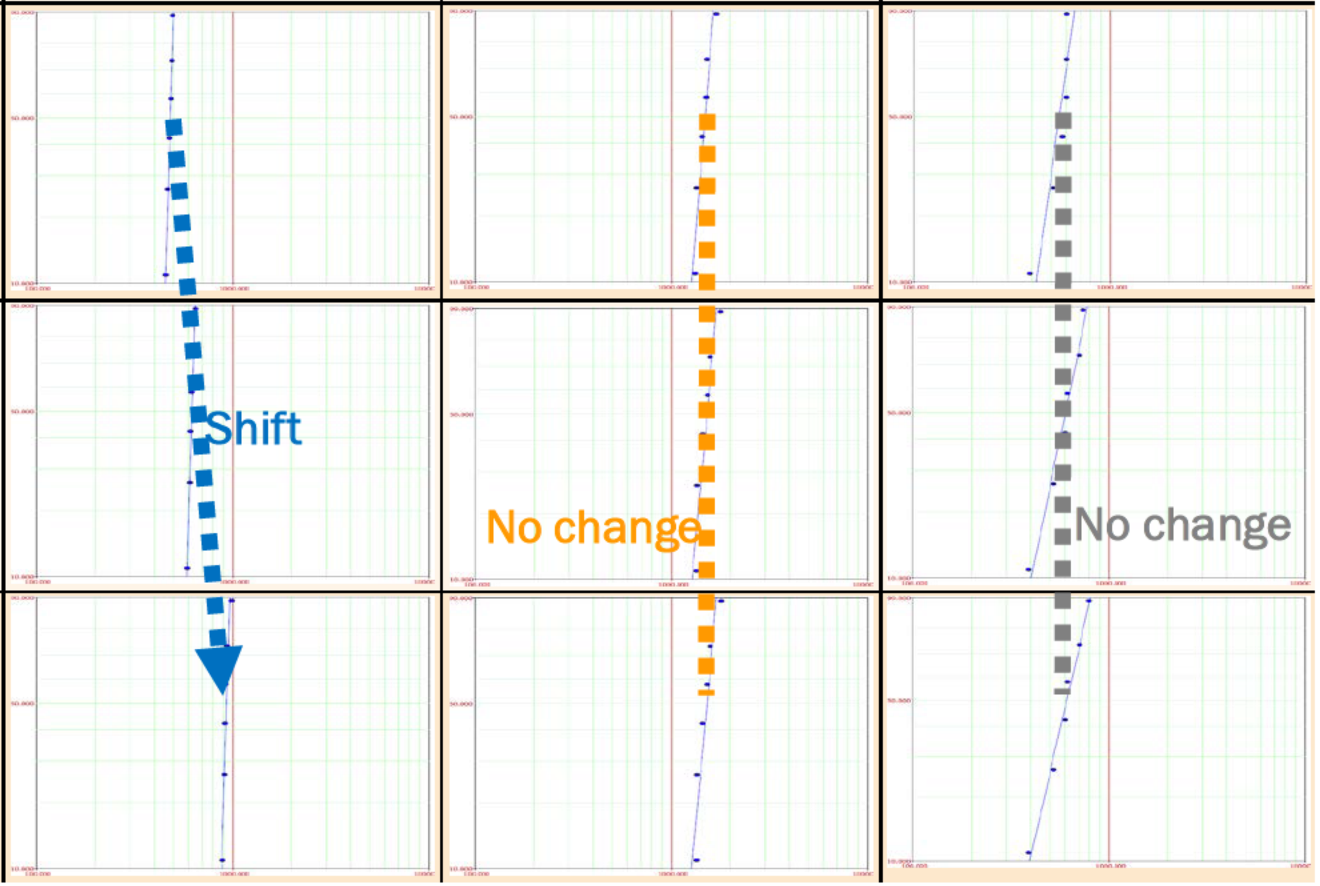


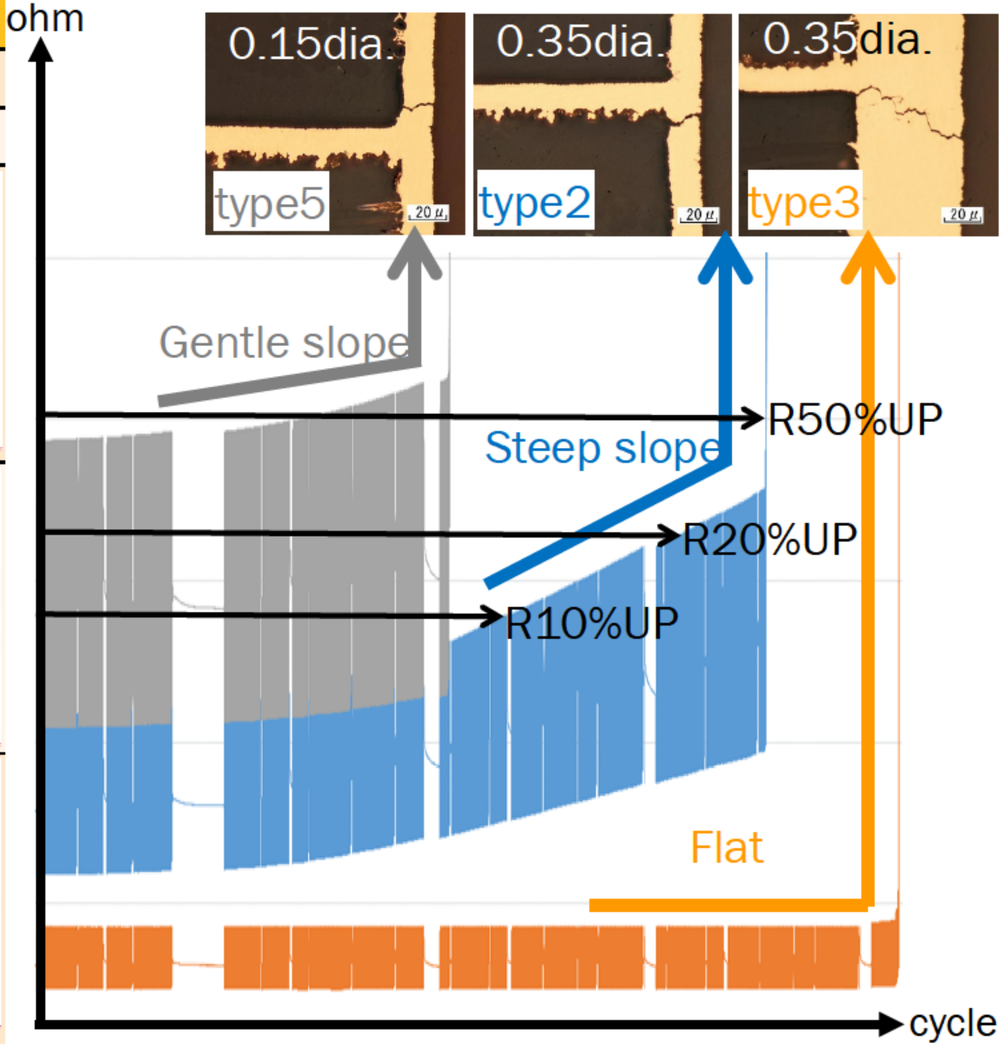
660 PTHs connected in daisy chain
for monitoring loop resistance during test

Weibull analysis of TCT results

- Number of cycles to failure of Type 2 is different with criteria.

PTH	Type 2	Type 3	Type 5
Cu plating	15um thick	55um thick	15um thick
PTH dia.	0.35mm	0.35mm	0.15mm
R10% UP			
R20% UP			
R50% UP			





Validation

- Check differences by comparing acceleration factor (AF) from equation to AF from TCT results for validating equation.
- There is the best coincidence between R20%UP and R50%UP of Weibull average.

71% 83% 120% 140%

AF	AF from equation / AF from TCT result							
	Normal average				Weibull average			
	R10%UP	R20%UP	R50%UP	R100%UP	R10%UP	R20%UP	R50%UP	R100%UP
N_type 3 ÷ N_type 5	150.4%	140.6%	138.7%	138.2%	146.8%	134.4%	132.1%	131.5%
N_type 3 ÷ N_type 2	183.9%	145.3%	96.9%	83.5%	188.1%	149.4%	99.8%	83.1%
N_type 3 ÷ N_type 1	147.7%	116.5%	95.5%	95.4%	148.2%	116.8%	92.7%	92.6%
N_type 1 ÷ N_type 2	124.5%	124.7%	101.5%	87.5%	127.0%	127.9%	107.7%	89.8%
N_type 5 ÷ N_type 2	122.2%	103.3%	69.9%	60.5%	128.2%	111.2%	75.5%	63.2%
N_type 5 ÷ N_type 1	98.2%	82.9%	68.9%	69.1%	100.9%	86.9%	70.1%	70.4%

Conclusions

- FEM simulation based on Box-Behnken design is useful for understanding both single and multiple factor effect and reducing simulation runs to calculate strain.
- Material CTE, Young's modulus and Cu plating thickness have strong impact for an occurrence of crack in Cu plating of PTH.
- Regarding roughness on Cu plating of PTH, ⊿ε becomes larger at convex on resin.
- ⊿ε equation can be formed of effective factors then corrected by roughness influence and scaling factor. After that, PTH life can be calculated.
- As the validation of comparing to TCT results, most differences of AF fell in between 67% (=1/1.5) to 150% (=1.5), confirming that the equation seems to be preferable.

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Active period : 2014 – 2017

Members : Fujitsu Advanced Technologies

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Thank you !

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