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FR4 – CERAMIC "Z" AXIS SOLDER INTERCONNECTION

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Special FR4-ceramic Z-axis connection was designed and realised which allows to decrease thermomechanical stress. Fatigue life measurement was performed on a special specimen. Temperature cycles with a period of 9 minutes and temperature amplitude from 20 to 95 °C were applied. The solder joint fatigue was measured for eutectic Sn/Pb and LF solders. Practical results were compared with the results from FEA. Viscoplastic, plastic strain, and dissipated strain energy density per cycle ΔW were computed and used as failure indicators for fatigue analysis. Darveaux's energy density model was used for solder joint fatigue calculation.

K e y w o r d s: 3D system, SMVPH (Special Modified Via Plated Hole), FR4 frame, fatigue life, Sn/Pb, LF solder, FEM simulation, thermo-mechanical stress, plastic work, Darveaux's theory

1 INTRODUCTION

This study explores a cheap 3D construction, which could be applicable for micro-system connection. A special construction SMVPH (Special Modified Via Plated Hole) using an adaptation of the classical Via Plated Hole technique was designed. The application of SMVPH with a FR4 frame and a ceramic layer can be an acceptably cheap solution in which the ceramic layer in connection with an organic FR4 substrate is used. The FR4 frame gets a lower thermo-mechanical stress and increased reliability of the solder connection.

2 THEORETICAL PART

Connecting different types of materials with different CTE (Coefficient of Thermal Expansion) in 3D constructions with leadless connection (Fig. 1) is a very frequent problem.

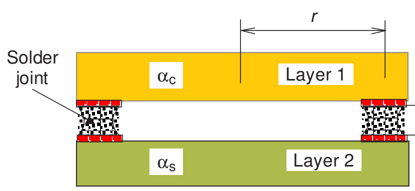

Fig. 1. Geometry of leadless connection.

The change of the shear strain $\Delta\varepsilon$ developed when materials with different CTE are soldered is subjected to temperature cycling [1]. The general equation that describes such deformation can be expressed as (1).

$$\Delta\varepsilon = F\frac{r\Delta(\alpha\Delta T)}{h}\,. \tag{1}$$

Here h is the height of the joint and r is its distance from the centre of the system. ΔT is the temperature cycle amplitude and α is the CTE of layers, F is a dimensionless parameter (1 to 1.5). The value of the shear strain $\Delta\varepsilon$ has an influence on solder joint fatigue prediction. A big number of theoretical models how to predict the solder joint fatigue life were presented in [2].

Darveaux's modelling methodology utilizing the finite element analysis to calculate the viscoplastic strain energy density accumulated per cycle during thermal or power cycling is presented in the next part.

This method was utilized in [3] to predict ball and bump solder joint reliability of the silicon based MCM package under accelerated temperature cycling conditions. By measuring the crack growth correlation constants (K1 through K4) and using two equations, the finite element simulation can be utilized to calculate the thermal cycles to crack initiation and the crack propagation rate per thermal cycle. However, the methodology is sensitive to the finite element modelling procedure.

The equations for the calculation [3] of thermal cycles to crack initiation N_0 and crack propagation rate per thermal cycle $\mathrm{d}a/\mathrm{d}N$ are shown below as (2) and (3), respectively, where ΔW_{ae} is the element volumetric average of the stabilized change in plastic work. The characteristic solder joint fatigue life N_f (number of cycles to 63.2 % population failure) can then be calculated by summing the number of cycles to crack initiation N_0 with the number of cycles it takes for the crack to propagate N_{CP} across the entire solder joint diameter. This is explained in equation (4).

$$N_0 = K_1(\Delta W_{ae})^{K_2}\,, \tag{2}$$

$$\frac{\mathrm{d}a}{\mathrm{d}N} = N_{CP} = K_3(\Delta W_{ae})^{K_4} \tag{3}$$

$$N_f = N_0 + N_{CP}\,. \tag{4}$$

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Table 1. Results of the measurements of the fatigue life of the stacked system FR4-FR4 frame-ceramic layer.

Measuring FR4-FR4 frame-ceramic layer							
	Cycles	Sn/Pb solder		LF solder		Reference Eutectic Sn/Pb solder	
		Total number of failures	%	Total number of failures	%	Total number of failures	%
Temperature cycles 20/95 °C/9 min.)	0–1000	1	2.1	0	0	7	29.2
	1000–3000	20	41.7	1	2.1	7	29.2
	3000–5000	25	52.1	14	29.2	7	29.2
	5000–7000	37	77.1	28	58.3	7	29.2
	7000–9000	47	97.9	33	68.8	7	29.2
	9000–11000	48	100	38	79.2	9	37.5

Darveaux's methodology requires that the solder mask not be considered in the finite element model. The mechanical effects of the intermetallic phenomena are not considered either.

2 EXPERIMENTAL PART

A special vertical terminal structure SMVPH was realized directly by a printed board producer (Fig. 2).

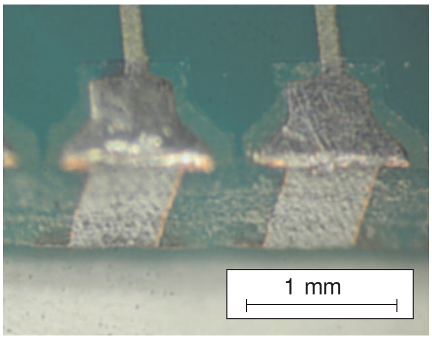

Fig. 2. Design of SMVPH structure

A special specimen for measuring the reliability of the connection was designed (Fig. 3). The solution with FR4 frame and ceramic layer with this vertical connection was realized. The FR4 frame with a thickness of 1.5 mm acts as an interlayer. It allows to stack ceramic boards with SMD components in Z-axis direction. This solution allows to create a bigger height of solder connection and to decrease the thermomechanical stress. On the top side of the frame there is a ceramic layer with thickness 0.35 mm with a thick AgPd layer with daisy chain electrical connection.

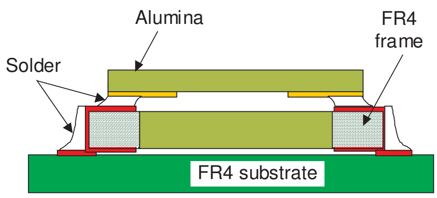

Fig. 3. A cross section of the specimen with FR4-FR4 frame and ceramic layer

Electric disconnection of soldered junction was indicated by a powered LED diode.

As a comparative specimen, a direct FR4-ceramic solders connection with eutectic Sn/Pb solder was made. The solder connection was made directly on the edge of the ceramic layer.

Specimens with KESTER eutectic Sn/Pb solder (type R 256 NC, Sn62/Pb/Ag2/90-3) and LF KESTER solder (Lead-free solder paste type R910, Sn95.5/3.8/Cu0.7/89-3) were created.

The measurement of the reliability of the solder connections of the specimens was performed on specially developed equipment [4]. Testing of the solder joint took place in thousands of thermal cycles, and that is why the period of thermal cycles had to be as short as possible. Therefore, a special low-capacity measuring system was designed.

The temperature limits for reliability tests were determined as 20 and 95 °C with a period of 9 minutes. The results of the practical measurement of the fatigue life of the designed system are presented in Tab. 1 and Fig. 4.

Compared to the eutectic Sn/Pb system, the practical reliability of the LF system is by about 30 % higher. The measurements on the edge of the soldered ceramic layer with the FR4 mainboard without F4 frame show that it is impossible to use a large ceramic material directly soldered on FR4 material. The results of measurement of the same ceramic layer connected without the frame are in Tab. 1, column reference.

The equivalent stress, total equivalent strain and plastic work were calculated by simulating the thermomechanical stress. The software ANSYS was used for this simulation. The created geometrical model is similar to a real specimen. It should be noted that the simulation was conducted with simplifications of the shape and of the intermetallic phenomenon.

The material properties used for the simulation are presented in Tab. 2. Table 3 shows the geometry of the specimen. The surface equivalent stress for slit and nonslit FR4 frame were compared. The slit frame had no influence on the stress and therefore it was not considered. The distributions of Von-Misses stress SEQV for Lead Free (LF) Sn/Ag/Cu and eutectic Sn/Pb solder are presented in Fig. 5a,b.

Table 2. Properties of the materials for the simulation.

	Global model			Local model			
Material	**E** Modulus of Elasticity (MPa)	μ (–)	α = **CTE** Coef. of Thermal Expansion (ppm/K)	t (°C)	**E** Modulus of Elasticity (MPa)	μ (–)	α = **CTE** Coef. of Thermal Expansion (ppm/K)
LF Solder Sn/Ag/Cu	52 600	0.35	24.5	20	52 600	0.35	24.5
				140	44 000		
Eutectic Solder 63Sn37Pb	30 642	0.35	24.5	t	$\mathbf{E} = 34\,434 - 151.7t$	0.35	24.5
				20	31 400		
				100	19 264		
FR 4 Laminate	Directions **X,Y**						
	$\mathbf{E}_x = \mathbf{E}_y$	$\mu_{xz} = \mu_{yz}$	$\alpha_x = \alpha_y$	t	$\mathbf{E}_x = \mathbf{E}_y$ $\mathbf{E} = 17\,779 - 37.16t$	$\mu_{xz} = \mu_{yz}$	$\alpha_x = \alpha_y$
	16 850	0.29	14.5	20	17 036	0.29	14.5
	Direction **Z**						
	$\mathbf{E}_z$	μ_{xy}	α_z	t	$\mathbf{E}_z$ $\mathbf{E}_z = 7\,781 - 16.2t$	μ_{xy}	α_z
	7 376	0.11	67.2	20	7 457	0.11	67.2
Alumina (Al_2O_3)	303 000	0.21	23.4	−55	303 000	0.21	3.9
				22			4.5
				100			6.7
Copper (Cu)	129 000	0.344	16.61	t	129 000	0.34	$\alpha = 13.8 - 0.0094t$
				20			16.55
				100			17.31

Table 3. Geometry of the model for simulation.

Material	**Dimensions**		
	Width (mm)	Rectangular (mm)	Thickness (mm)
Mainboard (FR4)	–	40 × 40	1.5
Frame (FR4)	4.5	22.5 × 22.5	1.5
Ceramic (Alumina)		20 × 20	0.35
Solder joint Connection Mainboard-FR4	–	–	0
Solder joint Connection Frame-ceramic	0.635	1.90	0.2
Copper layer	Horizontal thickness		77 μm
	Vertical thickness		50 μm

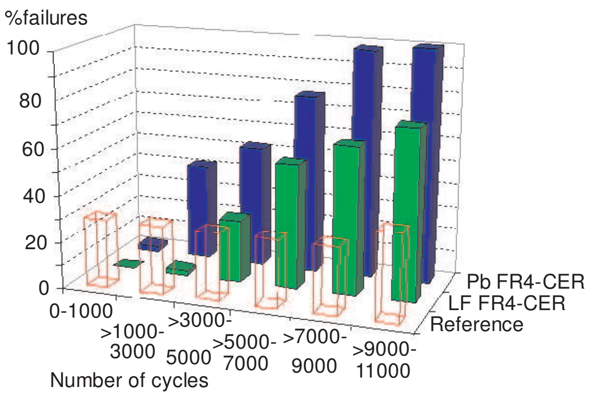

Fig. 4. Diagram of the measurements of the fatigue life of the stacked system FR4-FR4 frame-ceramic layer.

When the results for both types of solder are compared it can be concluded that the place with a maximum value is situated on the top of system in the connection between the frame and the ceramic layer. This should be the place with biggest probability of failure. The non-linear FEM analysis was created in the next step. The material properties of the solder were defined by Anand's viscoplastic model [5]. The calculation of plastic work by Anand's material model was realized only for eutectic 63Sn37Pb solder (Fig. 6). The material constants for LF solder were not available. The Anand's viscoplastic material constants modified by Darveaux are presented in [6].

3 DISCUSSION

Calculation of the characteristic fatigue life by Darveaux by means of the viscoplastic model for eutectic Sn/Pb solder was used. Darveaux's constants and results of computing the fatigue life are in Tab. 4.

When the results of real measurement and FEM simulations are compared, it can be concluded that the place of real crack corresponded to the place with the biggest thermomechanical stress. This place is situated on top of the system in the connection between the frame and the ceramic layer.

The calculated results of the fatigue life are lower than real measurements. This may be caused by the differences between the real specimen and the simulated geometrical model.

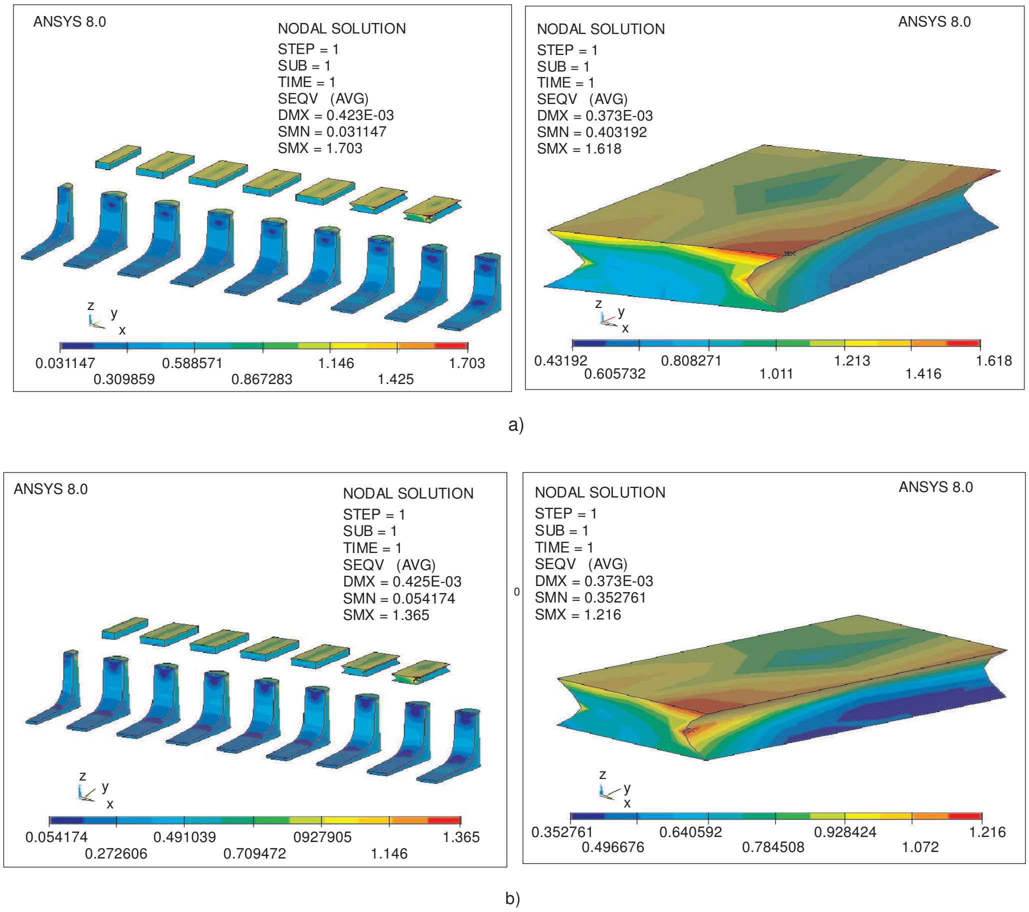

Fig. 5. Equivalent stress (SEQV)distribution [MPa]: a) for Sn/Ag/Cu (LF), b)for eutectic Sn/Pb solder, non-slit frame solder.

Since the solder joint of the FR4-FR4 frame-ceramic layer structure has not a classic shape, the equations for calculating the shear strain from the dimensions as explained in equation (1) could not be used. The FEM simulations with ANSYS, which uses Anand's model, allow to calculate also the total equivalent strain (EPTOEQV) $\Delta\varepsilon_T$. This value was used for fatigue life calculation.

Table 4. Material constants and computing fatigue life of solder joint structure FR4–FR4 frame-ceramic by Darveaux.

"a" width of solder joint	(mm)	0.635
ΔW_{ae} (Sn/Pb)	(MPa/cycle)	0.33
Constants by Darveaux [6]		
K1	(Cycle/MPa)	11.614
K2	(–)	−1.52
K3	(mm/cycle/MPa)	1.954×10^{-3}
K4	(–)	0.98
Calculation N_f by Darveaux		
N_0	(Cycles)	63
N_{CP}	(Cycles)	963
$N_f = N_0 + N_{CP}$	(Cycles)	**1026**

The calculated value of the total equivalent strain for eutectic solder is $\Delta\varepsilon_T = 0.00814$ and when the classic Engelmaier's equation [7] for

$$N_f = \frac{1}{2}\Big(\frac{\Delta\varepsilon}{0.65}\Big)^{1/c} \tag{5}$$

eutectic solder (equation 5) is used, the calculated value $N_f = 1630$ is similar to the result calculated by Darveaux in Tab. 4.

The characteristic fatigue life was calculated only for the eutectic Sn/Pb solder. A visco-plastic analysis model was used because the material constants of this model are known. Another way for LF solder would be calculating the fatigue life with a creep material model. The ANSYS software allows using the generalized Garofallo model [5]. The material constants are presented in [8].

4 CONCLUSION

The paper presents the solution of a real electric connection of FR4 material with a ceramic layer. This solution allows decreasing the thermo-mechanical stress. The same specimens with lead free (LF) and eutectic Sn/Pb solder connection were investigated.

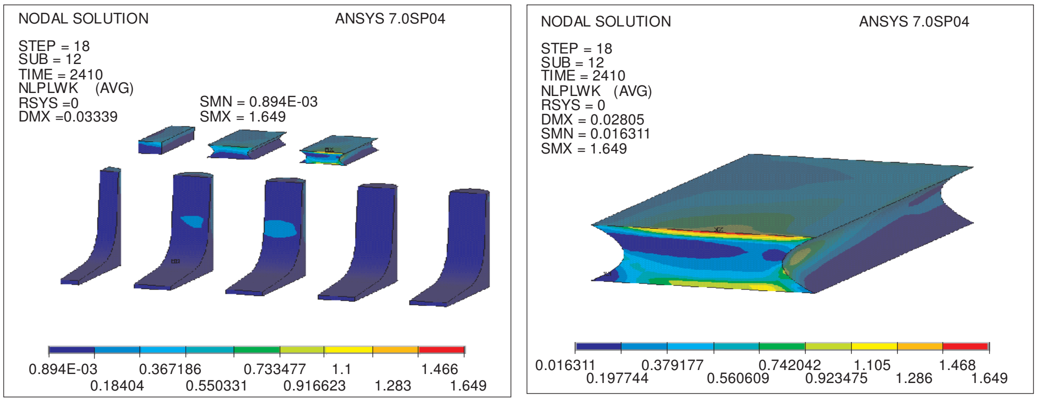

Fig. 6. The value of plastic work NLPLWK [MPa] after the 4th temperature cycle for eutectic Sn/Pb solder.

The leadless connection of FR4 material and ceramic material with FR4 inter-layer decreases the thermo-mechanical stress and mechanically allow to stack those materials in a 3D structure.

The method of thermal cycling that uses convection heating seems to be convenient for thermal cycling. A similar method with a heating element inside is used in [9].

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