

Thermo-Mechanical Assessment of Epoxy-filled Vias in High-Density Interconnected PCBs for Advanced Telecommunication Applications

Chaoran Yang*
Quality Engineering
Amazon
Shenzhen, China
cryang@amazon.com

Leo Huang
Quality Engineering
Amazon
Shanghai, China
hchunlei@amazon.com

David Ren
Quality Engineering
Amazon
Shanghai, China
xiaoboam@amazon.com

Eric Cao
Quality Engineering
Amazon
Shenzhen, China
ericcao@amazon.com

Fubin Song
Quality Engineering
Amazon
Hong Kong SAR, China
songf@amazon.com

Abstract—This paper presents a thermo-mechanical reliability investigation of two epoxy-filled via structures, Via-in-Pad Plated over (VIPPO) vias and the stacked microvias, combining finite element analysis (FEA) with experimental failure analysis. For VIPPO structures, pad crater susceptibility after reflow exposure was assessed using the first principal stress within the prepreg laminate, while for stacked microvias, crack initiation near the microvia base after thermal shock loading was evaluated using accumulated equivalent plastic strain. The effects of prepreg laminate system, resin fill material, and via structural configurations on localized thermo-mechanical behavior were comparatively investigated. Copper sidewall thickness was identified as the dominant factor influencing VIPPO pad crater susceptibility, with the first principal stress increasing by 205% as the thickness increased from 12 μm to 60 μm . In contrast, stacked microvia reliability was more strongly influenced by prepreg laminate material selection than by via structural geometry. Resin filler material exhibited comparatively limited influence on both structures. Simulation results showed strong agreement with experimentally observed failure locations. The study demonstrates that different epoxy-filled via structures exhibit distinct thermo-mechanical sensitivities and dominant failure mechanisms, indicating that reliability optimization should be performed based on the local failure mode rather than a unified design criterion.

Keywords—epoxy-filled via, VIPPO, microvia, thermo-mechanical, FEM

1. INTRODUCTION

Modern communication systems, such as 5G/6G networks and Internet-of-Things (IoT) applications, demand increasingly sophisticated High-Density Interconnect (HDI) PCB architectures capable of delivering superior signal integrity, low insertion loss, and cost-effectiveness [1-4]. To meet the escalating requirements for miniaturization and routing density, epoxy-filled via structures have emerged as an alternative to conventional air-filled or copper-plated via designs. Unlike traditional via structures, epoxy-filled vias offer greater design flexibility and can be implemented across a range of configurations, including through-hole vias, blind vias, and buried microvias, making them a versatile solution adaptable to diverse PCB stack-up requirements. In epoxy-filled via structures, polymer resins are introduced into PCB vias to provide structural support, planar surface

finishing, and improved thermal performance. A schematic illustration of representative epoxy-filled via structures is demonstrated in Figure 1.

However, the inherent mismatch in coefficient of thermal expansion between the epoxy filler and the surrounding laminate materials (including both copper foil and prepreg) creates complex internal stress during thermal excursions [5,6]. Therefore, rigorous evaluation of epoxy-filled via structures, including the selection of appropriate filler materials and PCB stack-up configurations, as well as the identification of potential failure modes, must be conducted during the early design stage to guarantee long-term mechanical and thermal reliability.

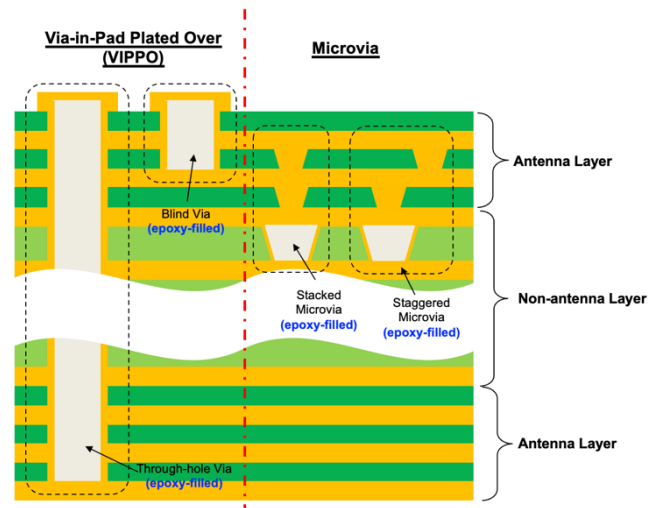


Figure 1. Schematic illustration of the resin-filled via structures

This paper presents a combined finite element analysis (FEA) and experimental failure investigation of Via-in-Pad Plated Over (VIPPO) and stacked microvia structures in HDI PCBs. For VIPPO structures, the study focuses on pad crater susceptibility using the first principal stress within the prepreg laminate as the primary assessment metric. For stacked microvia structures, accumulated equivalent plastic strain was employed to evaluate the localized thermo-mechanical damage behavior near the microvia base. The

effects of copper sidewall thickness, prepreg material systems, and resin fill materials were comparatively studied. The simulation result was further correlated with experimentally observed failure locations.

2. FINITE ELEMENT MODELING

Two independent three-dimensional finite element models were developed using commercial FEM tool to simulate the thermo-mechanical behavior of epoxy-filled via structures in HDI PCBs. The first model represents a through-hole VIPPO structure for pad crater risk assessment, while the second model consists of a stacked microvia PCB for evaluating the thermo-mechanical behavior around the resin-filled via.

In the VIPPO configuration, the through-hole barrel was filled with epoxy resin and subsequently over-plated with a copper cap layer, forming a planar pad surface suitable for surface mount assembly. The microvia structure consisted of three vertically stacked blind vias, where the upper two microvias were fully copper-filled and the bottommost microvia comprised a resin-filled barrel with a surrounding copper wall.

To improve computational efficiency, quarter-symmetry models were employed for both structures. Structured hexahedral meshes were used throughout both models, with refinement applied at the pad edge and microvia base interface to accurately capture the localized stress and strain gradients during thermal loading. These two models are shown in Figures 2 and 3, respectively.

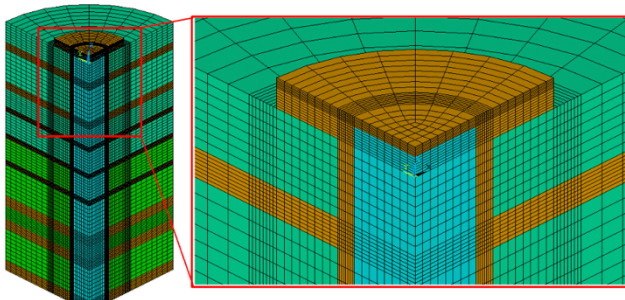


Figure 2. Quarter-symmetry finite element model of the VIPPO through-hole structure

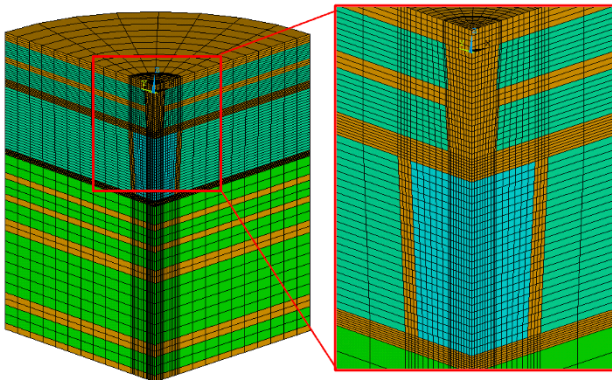


Figure 3. Quarter-symmetry finite element model of the stacked microvia structure

All prepreg laminates and resin fill materials were modeled as temperature dependent orthotropic elastic materials. All the key material properties are listed in Table 1. For the VIPPO model, copper was treated as a linear elastic material, as the dominant failure mechanism was associated with laminate cracking rather than copper yielding. In contrast, copper in the stacked microvia model was modeled as a temperature-dependent elastoplastic material using a bilinear kinematic hardening formulation to capture the cyclic plastic strain accumulation around the stacked vias.

Material		Young's Modulus (GPa)	Tg (°C)	CTE in z-direction (ppm/°C)	Poisson Ratio
Cu		117	-	16.7	0.34
Antenna layer laminate	A1	27.8	215	55(a1)/290(a2)	0.222
	A2	20.0	200	45(a1)/230(a2)	0.18
Non-antenna layer laminate	N1	33.4	180	40(a1)/220(a2)	0.155
	N2	26	190	35(a1)/180(a2)	0.14
Resin	R1	7.3	170	24(a1)/61(a2)	0.19
	R2	8.1	158	38(a1)/89(a2)	0.32
	R3	5.2	168	39(a1)/105(a2)	0.325

Table 1. Key material properties used in VIPPO and microvia finite element models

3. RESULTS AND DISCUSSION

3.1. VIPPO Thermo-Mechanical Assessment

3.1.1. Failure Mode Correlation between Experimental Observation and Finite Element Modeling

Pad crater failure was experimentally observed in the VIPPO structure after reflow assembly processes. Cross-section failure analysis revealed localized crack within the prepreg laminate underneath the copper pad, indicating a tensile opening dominated failure mechanism. Figure 4 shows a representative cross-section image of the pad crater failure observed after reflow exposure.



Figure 4. Optical image of VIPPO pad crater cross-section

To investigate the underlying thermo-mechanical driving mechanism as well as the contributing factor of the VIPPO design, finite element analysis was performed using thermal cool-down loading from peak reflow temperature (240 °C) to room temperature (25 °C). The first principal stress distribution within the prepreg laminates is presented in Figure 5. A localized stress concentration was identified near the pad edge region, where the first principal stress was highest. The orientation of the principal stress vectors indicated an opening tendency at the pad-prepreg interface,

which was consistent with the experimentally observed crack initiation and propagation path.

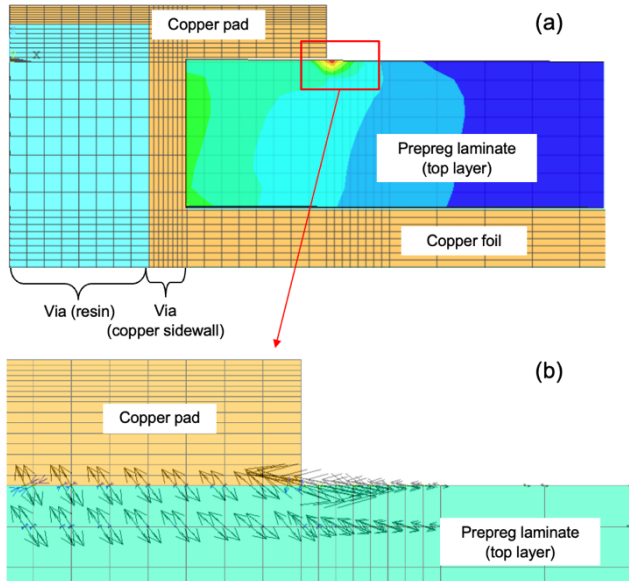


Figure 5. Distribution of the first principal stress inside prepreg laminate at the VIPPO pad edge (a) contour plot (b) vector plot at the marked area

3.1.2. Influence of Structural and Material Parameters

The influence of structural configuration and material selection on pad crater susceptibility was further investigated through comparative thermo-mechanical simulations. Parameters including copper sidewall thickness, prepreg material system, and resin filler material were evaluated based on the localized first principal stress near the pad edge region. The resulting stress values are summarized in Figures 6-8.

Among all investigated parameters, copper sidewall thickness exhibited the most significant influence on localized tensile stress behavior. As the copper sidewall thickness increased from 12 μm to 60 μm , the maximum first principal stress increased from 81.0 MPa to 247.6 MPa. The increased stress concentration was mainly attributed to the higher structural stiffness introduced by the thicker copper barrel, which enhanced the local thermo-mechanical constraint imposed on the surrounding prepreg laminate during thermal loading. For comparison, the pad-only configuration without via-in-pad structure exhibited a substantially lower first principal stress of only 18.4 MPa. This result further suggests that the resin-filled VIPPO structure significantly amplifies localized opening behavior near the pad edge region.

Compared with structural parameters, laminate material selection showed a moderate influence on pad crater susceptibility. Replacing the baseline laminate system (A1/N1) with the alternative system (A2/N2) at a fixed copper sidewall thickness of 30 μm reduced the maximum first principal stress by 29.4%. The improvement was mainly associated with the lower out-of-plane thermo-mechanical mismatch of the A2/N2 laminate system at elevated temperature conditions. In contrast, the influence of resin fill material was comparatively less significant, with the maximum first principal stress varying within approximately

10% across the three evaluated materials. Among the investigated resin materials, R2 exhibited the lowest stress level, indicating relatively improved thermo-mechanical performance for VIPPO reliability.

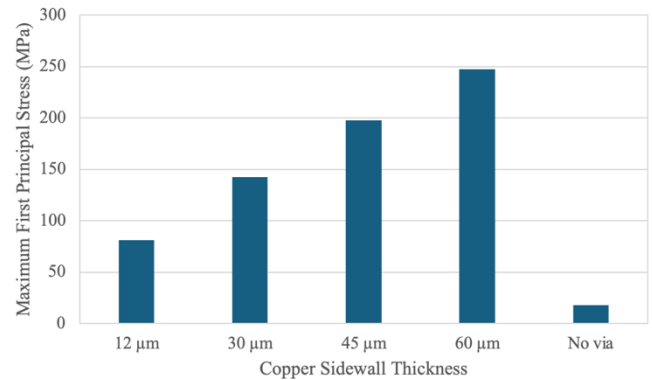


Figure 6. Effect of copper sidewall thickness (N1/A1 prepreg laminate system)

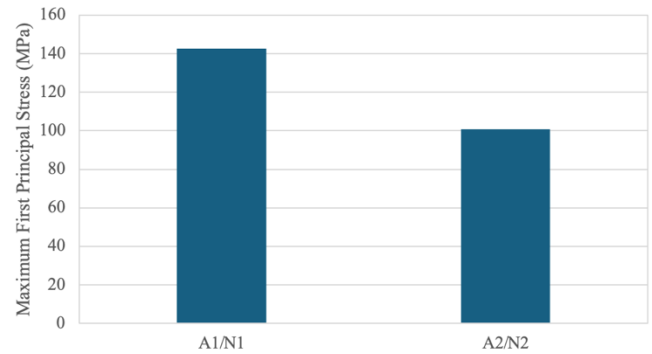


Figure 7. Effect of prepreg laminate (30 μm copper sidewall)

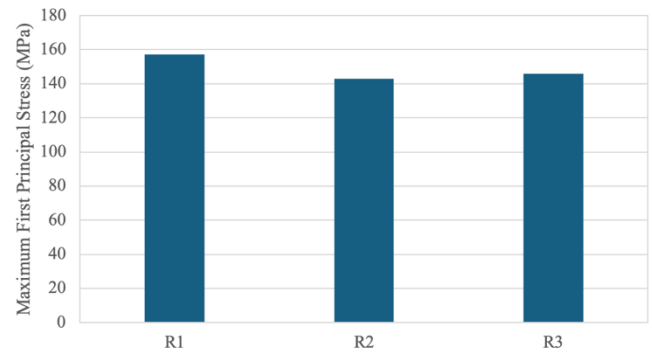


Figure 8. Effect of resin filler material (30 μm copper sidewall)

3.2. Microvia Thermo-Mechanical Assessment

3.2.1. Failure Mode Correlation between Experimental Observation and Finite Element Modeling

Crack at the microvia base was observed during board-level qualification testing, as shown in Figure 9. The investigated structure consisted of two stacked copper-filled microvias positioned above a resin-filled via structure. Optical microscopic and scanning electron microscopic images show that the delamination occurs at the bottom corner of the lower copper-filled microvia directly above the resin-filled via region. The failure was identified after hot oil

thermal shock testing which consisted of repeated thermal cycling between 260 °C and 20 °C for 50 cycles following a pre-bake process at 135 °C. The failure rate was 35%, and the failure mode was consistent across all failed boards.

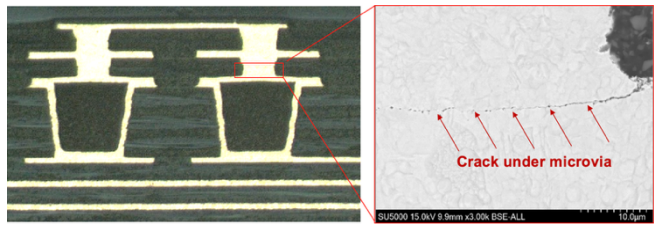


Figure 9. Cross-section image of the microvia base crack

Unlike the VIPPO structure, where the failure was dominated by tensile opening behavior within the prepreg laminate and therefore evaluated using first principal stress, the stacked microvia failure mechanism was associated with the copper crack after cyclic thermal loading. Since the failure was driven by the accumulation of localized cyclic plastic deformation within the copper, accumulated equivalent plastic strain was employed as the primary assessment metric. Figure 10 shows the contour plot of the accumulated equivalent plastic strain after one cycle of hot oil thermal shock loading. The location of the peak accumulated equivalent plastic strain predicted by the simulation corresponds directly to the crack initiation site identified in the cross-section image of failed samples.

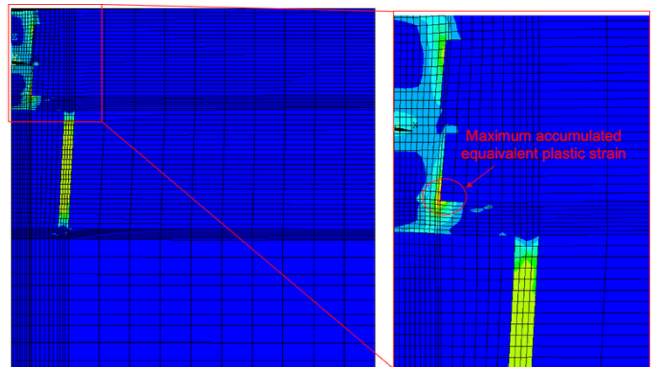


Figure 10. Contour plot of accumulated equivalent plastic strain

3.2.2. Influence of Structural and Material Parameters

A parametric study was conducted for the stacked microvia structure using the same three parameter categories investigated for the VIPPO structure: copper sidewall thickness, prepreg laminate material system, and resin filler material. The peak accumulated equivalent plastic strain was used as the assessment metric instead of the maximum principal stress.

Among the investigated parameters, copper sidewall thickness exhibited a comparatively limited influence on localized plastic strain accumulation at the microvia base. As shown in Figure 11, increasing the copper sidewall thickness from 12 µm to 60 µm increased the peak strain value from 0.1006 to 0.1125, corresponding to a variation of approximately 11.8% across the investigated range. This trend differs significantly from the VIPPO structure. As a baseline, the configuration without a resin-filled via structure

exhibited a lower peak plastic strain accumulation value of 0.0833. This result indicates that the presence of the resin-filled via underneath the stacked microvia change the local stiffness distribution and increased the thermo-mechanical constraint near the microvia base region, thus increasing localized plastic deformation during thermal loading.

Figure 12 shows that replacing the baseline laminate system (A1/N1) with the alternative system (A2/N2) reduced the accumulated plastic strain by approximately 25.4%. The variation across the three investigated resin materials is approximately 4.1%, as shown in Figure 13. These two results show similar trend to the observation from the VIPPO assessment, that the thermo-mechanical behavior around the resin-filled via is more sensitive to the prepreg laminate system than to the resin filler material.

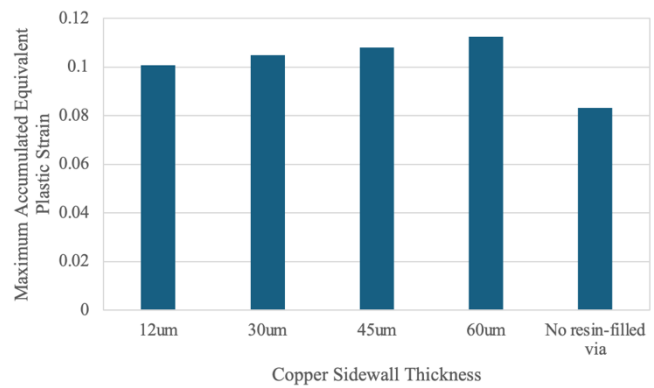


Figure 11. Effect of copper sidewall thickness (N1/A1 prepreg laminate system)

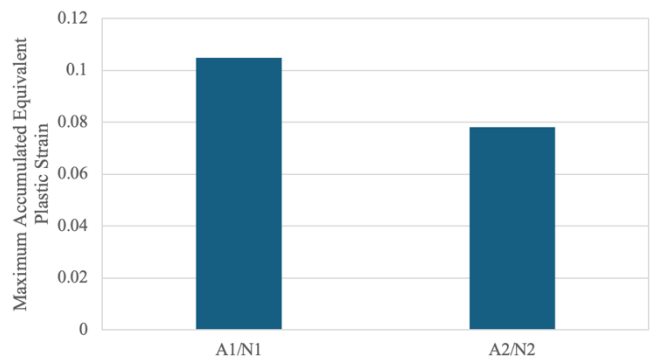


Figure 12. Effect of prepreg laminate (30 µm copper sidewall)

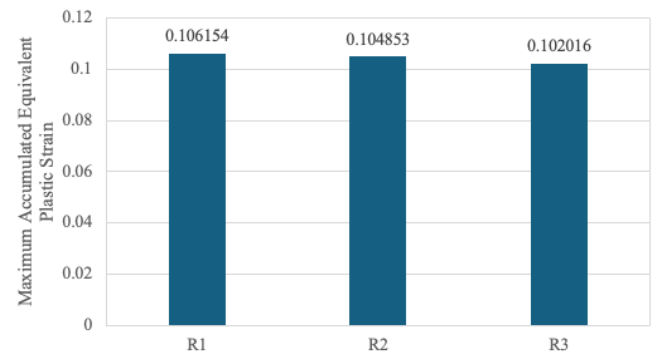


Figure 13. Effect of resin filler material (30 µm copper sidewall)

4. CONCLUSIONS

The paper presented a combined finite element analysis and experimental failure investigation of two epoxy-filled via structures under thermo-mechanical loading conditions representative of PCB assembly and qualification processes: VIPPO vias and stacked microvias. The key conclusions are drawn as follows:

1. The two via structures exhibited different dominant failure mechanisms. VIPPO pad crater behavior was governed by localized opening stress within the prepreg laminate near the pad edge region and can be characterized using first principal stress. In contrast, stacked microvia failure was associated with localized cyclic plastic deformation near the microvia base and was evaluated using accumulated equivalent plastic strain. The results indicate that different reliability assessment metrics are required for different epoxy-filled via structures depending on the local failure mechanism.
2. In both structures, the FEA-predicted stress/strain concentration locations showed strong agreement with experimentally observed failure initiation sites identified through cross-sectional analysis. The correlation between simulation and experimental observations supports the validity of the proposed thermo-mechanical assessment methodology.
3. Copper sidewall thickness exhibited significantly different sensitivity between the two via structures. Increasing sidewall thickness from 12 μm to 60 μm increased the local first principal stress in VIPPO

structures by approximately 205%, while only 11.8% variation in peak plastic strain was observed for stacked microvias. In contrast, prepreg laminate material selection consistently improved both structures, reducing localized stress in VIPPO structures by 29.4% and peak plastic strain in stacked microvias by 25.4%. Resin filler material exhibited comparatively limited influence, with less than 10% variation observed across the investigated material systems.

REFERENCES

- [1] D. M. Bozzi, "Substrate integrated waveguide (SIW): an emerging technology for wireless systems," 2012 Asia Pacific Microwave Conference Proceedings, Kaohsiung, 2012, pp. 788-790.
- [2] SM Kang, et al., "Low Dk/Df thermosetting siloxane hybrid material for microwave communication printed circuit board," 73rd IEEE ECTC, FL, USA, May 2023, pp. 2144-2149.
- [3] V. Kumar, S. Bhadri, "Life assessment of micro-via used in thin printed circuit board under thermal cycling loadings and influence of selected design parameters", IEEE 25th EPTC, Singapore, December 2023, pp. 710-715.
- [4] SY Teng, et al., "Via-in-pad plated over (VIPPO) design considerations for the mitigation of a unique soldering separation failure mode," Proceedings of SMTA international, 2016, pp. 161-167.
- [5] S. K. Kang, et al., "Development of conductive adhesive material for via fill applications," IEEE Transactions on Components and Packaging Technologies, Vol. 24, Issue 3, September 2001.
- [6] R. Kisiel, et al., "Problems of PCB microvias filling by conductive paste," Microelectronics Reliability, Vol. 47, Issue 2, February 2007.