

Thermal Cycling and the Adhesion of Glob Tops

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SUMMARY

In this study we investigate different methods of assessing the influence that thermal cycling has on the adhesion of curable plastic encapsulants to substrates using a range of both destructive and non-destructive test techniques. The results show that non-destructive measurements such as surface insulation resistance (SIR) or capacitance are unable to differentiate between bound and delaminated encapsulants. The results of the destructive (mechanical) test methods appear to be independent of the geometry of the encapsulant and the area that it covers. The results show that there is an excellent adhesive bond between most of the encapsulants studied and both FR-4 and ceramic substrates that is not adversely affected by a prolonged period of thermal cycling in a dry environment.

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1 INTRODUCTION

Plastics used to encapsulate IC's and COB's (chip on board) are designed to protect the underlying components from exposure to harsh environmental conditions and from mechanical damage. Encapsulant materials can be classified into two types – 'glob tops' and 'dam and fill'. Glob top materials are relatively high viscosity formulations that are applied directly to the components and a limited area of the underlying circuit board. Dam and fill encapsulation is a similar process except that a high viscosity material is used to create a wall or dam around the component. This dam is then filled with a low viscosity polymeric solution. Glob top materials due to their relatively high viscosity are relatively slow to dispense and can cause problems in underfilling components. To some extent these limitations can be overcome by using the dam and fill encapsulants although they require a more complex and consequently expensive twin head assembly for dispensing.

Boards containing encapsulated components are often used in environments that are subject to vibration and variations in temperature such as engine compartments in land based vehicles or aircraft. In their service life these boards will be subjected to considerable amounts of vibration and a large number of thermal cycles. To maintain functionality the adhesive bond between both the encapsulant and the component and the substrate has to withstand exposure to these conditions. Currently there are no robust methods for measuring the quality of this adhesive bond. In this report we present a comparison of both destructive and non-destructive test methods to assess their potential for measuring this quantity. The techniques are applied to a range of different encapsulants dispensed on to different substrates.

2 EXPERIMENTAL

The initial strength of the adhesive bond formed between the encapsulant and the substrate depends on the surface finish of the board, its surface chemistry and how clean it is. The in-service performance of the encapsulant mounted on the board depends on the similarity between the thermal expansion coefficients of the substrate and the encapsulant and the temperature range experienced by the assembly during thermal cycling. Where electronic circuitry is exposed to vibration the ability of the adhesive bond formed between the encapsulant and the substrate to resist fatigue is an important property. Understanding the behavior of an encapsulated component on a circuit board is further complicated due to the components geometry and differences between the properties of the component surface finish and that of the substrate. Other factors such as the thickness of the encapsulant and the presence of fillets around the base of components also contribute to the complexity of the system. Therefore for this investigation we have chosen a 'simple' system that consists of encapsulated double comb patterns deposited on to a substrate.

2.1 MATERIALS

2.1.1 Test board design and materials

The simple board design shown in Figure 1 consists of four double comb patterns i.e. two differently sized squares of length 25 mm and 13 mm respectively and two circles of diameter 7.2 mm. The circular double combs although the same size have different connection rails. The guardrails shield the double comb patterns from noise. Each double

comb pattern comprises of a 0.7mm pitch, gold over nickel track (350 μm track and 350 μm spacing).

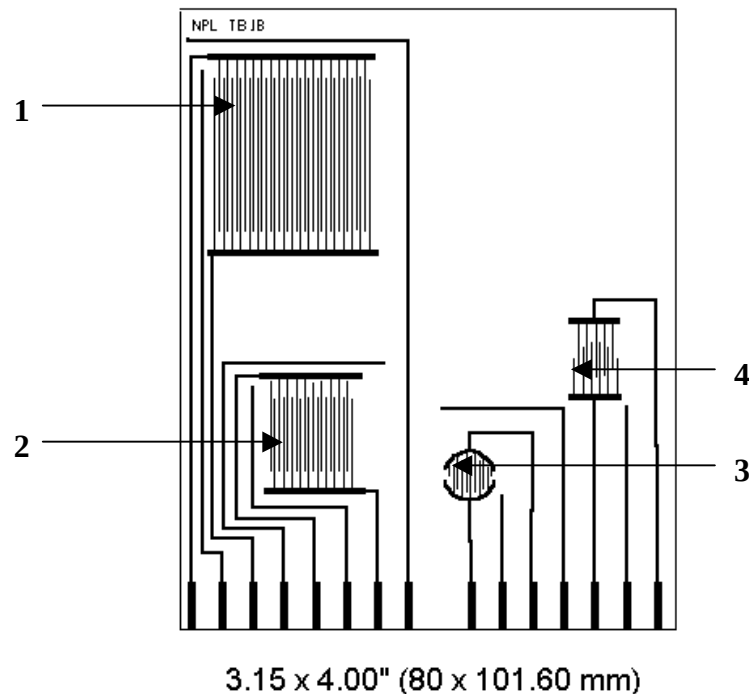


Figure 1: The test board comprises of four double comb patterns.

FR-4, flex (polyimide) and ceramic boards were used as substrates. These boards were cleaned using an IPA/deionised water mixture (75:25). An ionograph was used to monitor the level of ionic contamination which fell to zero after a period of approximately 10 minutes at 45°C. After cleaning, the boards were only handled by personnel wearing gloves to minimize the risk of contamination.

Half of the FR-4 and ceramic boards were coated with solder resist to determine whether or not this finish affects the quality of the adhesive bond formed between the encapsulant and the substrate. However it should be noted that the encapsulants are only in contact with a small amount of resist located around the periphery of the SIR patterns. The bulk of the encapsulant adheres to the bare board and track of the double combs.

2.1.2 Glob top materials and cure schedules

Table 1 lists the materials used in this study together with the cure schedules used. All the materials with the exception of UR1 and ER1 were stored at -40°C prior to use.

A Camalot 1818 machine was used to dispense the materials on to the boards. This machine can be programmed to dispense a constant volume of material at a specific rate over a particular area. Care was taken to ensure that the double comb patterns were

Material code	Type of material	Curing conditions
ER1	Epoxy	23°C, 24 Hours
ER2	Epoxy	150°C, 1 Hour
ER3	Epoxy	150°C, 1 Hour
ER4	Epoxy	150°C, 1 Hour
UR1	Urethane	23°C, 24 Hours
DF1	Epoxy	150°C, 1 Hour
DF2	Epoxy	150°C, 1 Hour
SR1	Silicone	150°C, 1 Hour

Table 1: Details of the encapsulant materials and their curing cycles.

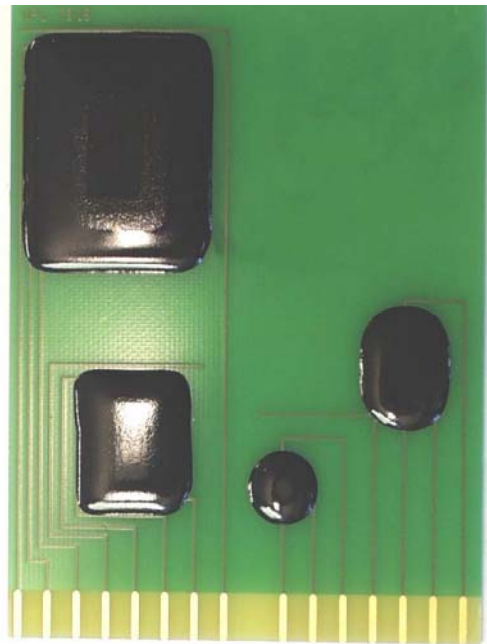


Figure 2 : UR1 dispensed on to a ceramic board covers not only the double comb areas but also regions of the board coated with solder resist.

completely covered by the encapsulating material as shown in Figure 2. A single head was used to dispense all the materials including the ‘dam and fill’ encapsulants – the ‘dams’ were dispensed and cured prior to adding the ‘fills’. All the materials were cured at 150°C for a period of at least 1 hour with the exception of UR1 and ER1.

Problems were experienced in using some materials dispensed on to ceramic test boards. Coating DF2 tended to detach itself from the ceramic boards as they were cooled after curing at high temperature. The large double comb 1 was particularly susceptible to delamination which is presumably due to a mismatch in thermal expansion coefficient between it and the ceramic substrate. These observations are discussed in more detail in section 3.1.

2.2 THERMAL CYCLING

Two test boards i.e. 8 double combs for each encapsulant/substrate combination were subjected to 100 cycles of thermal cycling where the temperature ranged from -40°C to 80°C as shown in Figure 3. Ramp rates of $10^{\circ}\text{C min}^{-1}$ were used to raise or lower the temperature to the limiting values where the samples were allowed to equilibrate for a period of 5 minutes.

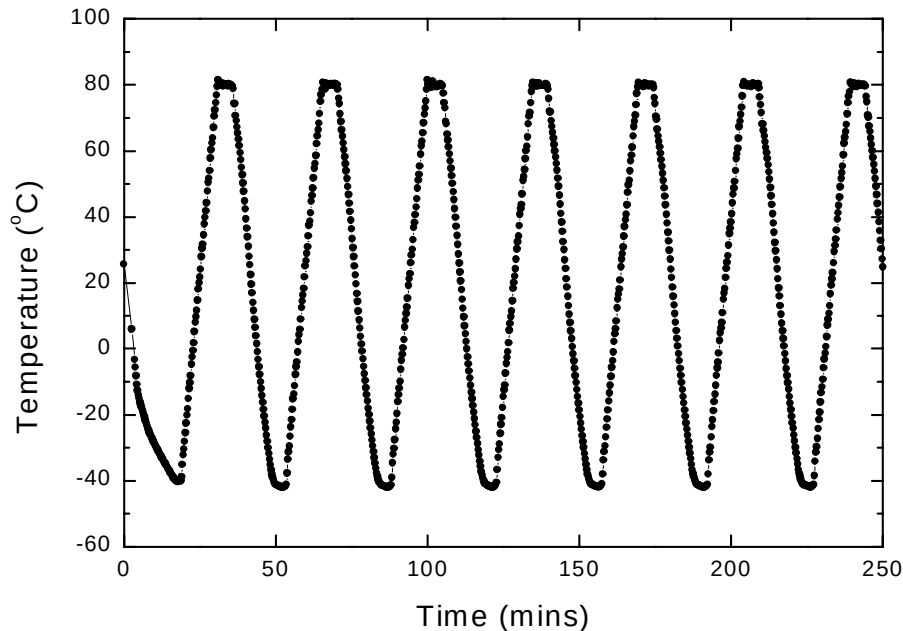


Figure 3: Part of the measured temperature profile used for thermal cycling.

The samples were placed horizontally on to shelves within the thermal cycling chamber (Climatic Test Systems, model FT210LLSP). Dry nitrogen was continuously passed through the chamber throughout the test period to prevent condensation from occurring on the surface of the board which could complicate the interpretation of the results.

2.3 NON-DESTRUCTIVE TEST METHODS

2.3.1 Resistance Measurements

A potential difference of 10V applied to each double comb pattern resulted in a small picoamp current flow. This current was measured using a calibrated high voltage source measurement unit (Keithley model 237) and subsequently used to calculate the resistance of the double comb via Ohm's law. The current flow between adjacent arms of the double comb pattern changed significantly with time after applying the voltage making accurate measurements difficult. This instability was accommodated by ensuring that current measurements were taken at approximately the same time after applying the voltage (2s). The continually changing current appears to be linked with charging of the encapsulant and substrate material.

A purpose built shielded housing was used to house the test boards during the measurement period.

2.3.2 Capacitance Measurements

A Hewlett Packard LCR4284A was used to measure the capacitance of each of the double comb patterns on the test boards that were mounted in a purpose built shielded connector. The model used to generate the capacitance as shown in Figure 4 comprises of a resistance (R) in parallel with a capacitance (C_p).

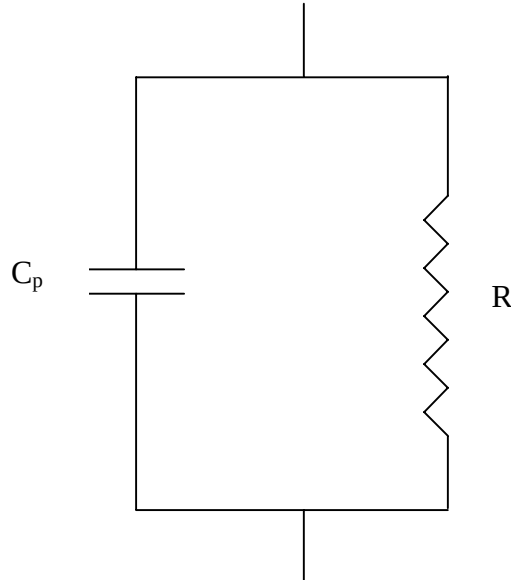


Figure 4: The model for capacitance measurement used by the LCR measurement unit.

The equipment generates values of C_p and D where D is a dissipation factor. The small values of D that were measured ($<10^{-3}$) are consistent with the high resistances of the double combs ($>10^{12}$ Ohms).

The capacitance of each double comb pattern was determined using an applied voltage of 1V at a frequency of 10 kHz. The capacitance of the double combs varied from approximately 2 to 40 pF depending on the type of encapsulant, the encapsulated area and the type of substrate. The measurements were found to be very stable and reproducible to at least within 0.1 pF.

2.4 DESTRUCTIVE TEST METHODS

Whilst mechanical test methods can be used to test the adhesion of encapsulants these tests are destructive and therefore of limited use in routine screening of encapsulated components. Most test methods designed to measure the strength of the adhesive bond formed between encapsulants and substrates are tailored for specific systems i.e. flexure tests are suitable for flexible substrates but not ceramics. The need to use different test methods to assess different encapsulant/board combinations increases the difficulty in comparing the results. We have therefore chosen to use the butt tension test (section 2.4.1) to determine the force required to fail the bond between the encapsulant and substrate in tension as it can be used for all substrates except flexible materials.

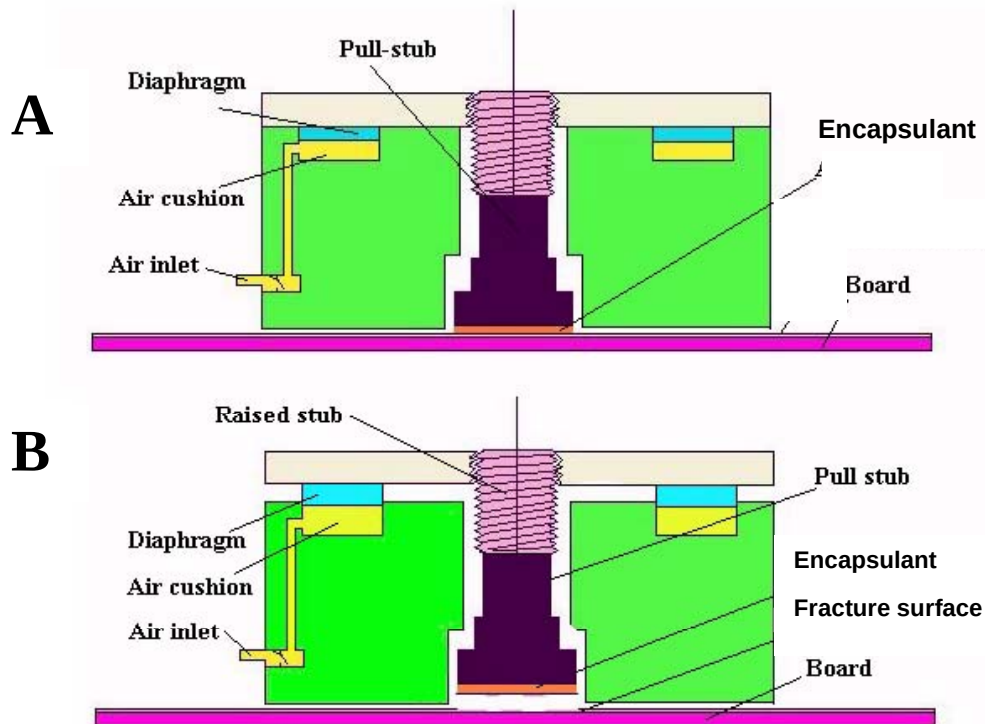


Figure 5: A schematic representation of the butt tension test, A) before and B) after detachment of the pull stub (and encapsulant) from the substrate.

2.4.1 Butt tension test

In the butt tension test a pull stub is attached to the encapsulant using a suitable adhesive, after curing the assembly is mounted into the test apparatus as shown schematically in Figure 5. Compressed air is used to inflate the collar so that the pull stub and hence the encapsulant is subjected to a tensile force. The point at which the assembly fails is recorded as a burst pressure. The burst pressure is converted into a tensile force by dividing it by the area of the pull stub.

The encapsulants were cleaned using isopropyl alcohol (IPA) and lightly abraded (400 grit) prior to bonding a pull stub of diameter 12.5 mm to them. The surface of the pull stub also has a keyed surface to improve bond strength. The pull stub was attached to the surface of the coatings using an adhesive (Redux 312) which is applied as a film. The pull stub and encapsulant assembly are then cured at 125°C for 30 minutes. Care was taken to remove the fillet of adhesive that can form around the base of the pull stub during the bonding process as this can have a significant effect on the mechanical properties of the joints. Good adhesive bonds are formed between the adhesive and epoxy or acrylic based encapsulants. However adhesion to polyurethane based encapsulants is poor. Attempts to find suitable adhesives for this material were not successful.

3 RESULTS

3.1 VISUAL INSPECTION

Visual examination of the boards after both curing the encapsulant and after thermal cycling revealed no obvious change in the appearance of the glob tops bound to FR-4 and flex boards.

Some encapsulants deposited on to ceramic boards became detached as the assemblies were cooled from the curing temperature of 150°C. Further adhesive bond failures occurred between some of the encapsulants and the ceramic boards after thermal cycling. From Table 2 it is apparent that most of these failures occurred in rectangular combs 1 and 2. The limited amount of data available suggests that some of the encapsulating materials are more prone to failure than others. There is also a suggestion that bond strengths may be weakened in the presence of a resist. These results suggests that further work is required in this area to establish the cause of failure and to confirm that the resist coating does actually play a role in determining the durability of encapsulant bond strengths.

Time of failure	Encapsulant type	Identity of detached combs
After cure	DF2	1
	SR1 + resist	1,2,3,4
After thermal cycling	DF2	1,2,4
	DF2 + resist	1,2,3
	ER4	1,2*
	ER4	1,2
	DF1 + resist	1,2,3
	SR1 + resist	1,2,3,4

Table 2: Details of adhesive bond failures for encapsulated double comb patterns deposited on to ceramic substrate. (* Encapsulant cracked during thermal cycling)

3.2 RESISTANCE MEASUREMENTS

Measurements of the resistance of the double comb SIR patterns proved to be difficult due to the small current flow (pA) between adjacent arms coupled with excessive noise. Measurements of the current flow in the small double combs (3 and 4 of Figure 1) were abandoned due to these difficulties as were measurements of the SIR patterns deposited on ceramic substrates. The resistance data for the large square combs (1 and 2 of Figure 1) do not reflect their different sizes that again suggests that the measurements are of limited accuracy. Resistance values were measured before and after thermal cycling for both FR-4 and flexible substrates. These data are shown in Figure 7. From figure 7 it is apparent that thermal cycling of encapsulants deposited on SIR patterned FR-4 has no measurable influence on resistance. Data for the flexible substrate showed the same insensitivity to thermal cycling.

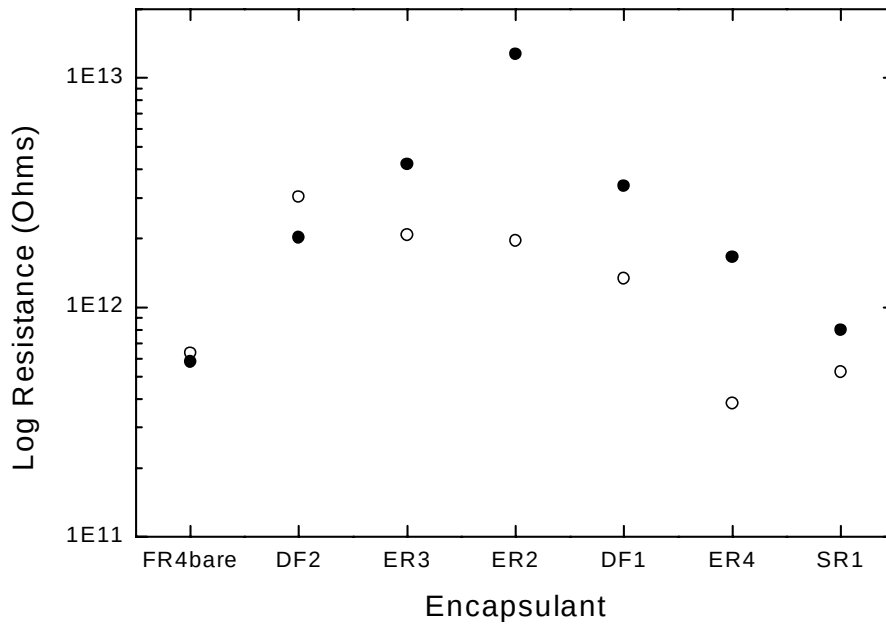


Figure 6. The resistance of double combs 1 (●) and 2 (○) deposited on FR-4 appears to show some dependence on the type of encapsulant material but not on pattern area.

3.3 CAPACITANCE MEASUREMENTS

3.3.1 The influence of double comb size

Capacitance, C is defined as

$$C = \epsilon_0 \cdot a / d \quad (1)$$

where a and d are the area and separation of the two parallel plates respectively and ϵ_0 is the permittivity of the medium separating them. Since a common medium i.e. air separates the ‘plates’ of the double comb patterns of an uncoated board we expect the capacitance of each double comb to be proportional to its area. Figure 8 shows the measured capacitances as a function of different double comb patterns.

The ratio of these capacitances is 1: 0.267: 0.061: 0.077. These values are in reasonable agreement with those predicted from equation (1) i.e. 1: 0.253: 0.052: 0.052 assuming ϵ_0 to be constant. The difference in capacitance between double combs 3 and 4 is probably attributable to differences in the arrangement of the external connections. The measured ratio of 1: 0.267 : 0.061: 0.077 is preserved to within tight limits irrespective of whether or not the double comb patterns have been encapsulated or thermally cycled as shown in Table A1 (Appendix 1). This finding suggests that the measured capacitance is independent of the physical size and shape of the encapsulant.

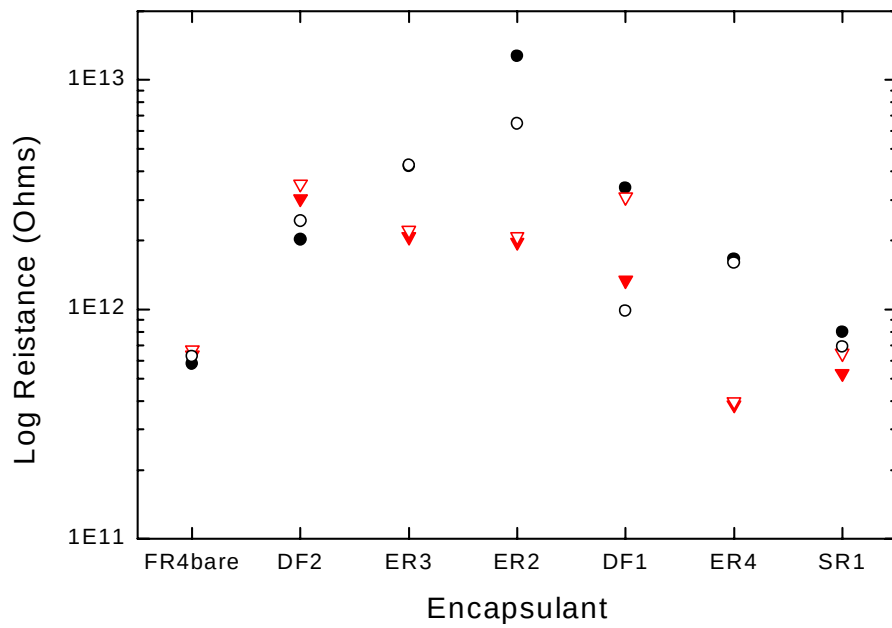


Figure 7: The resistance of double combs 1 (●) and 2 (▼) deposited on FR-4 before (closed symbols) and after thermal cycling (open symbols).

3.3.2 The influence of different substrates

Figure 9 shows how the measured capacitance of each of the double comb patterns varies with different substrates. Such differences presumably reflect variations in the dielectric properties of the substrates in the vicinity of the double combs that are not affected by coating the boards with solder resist.

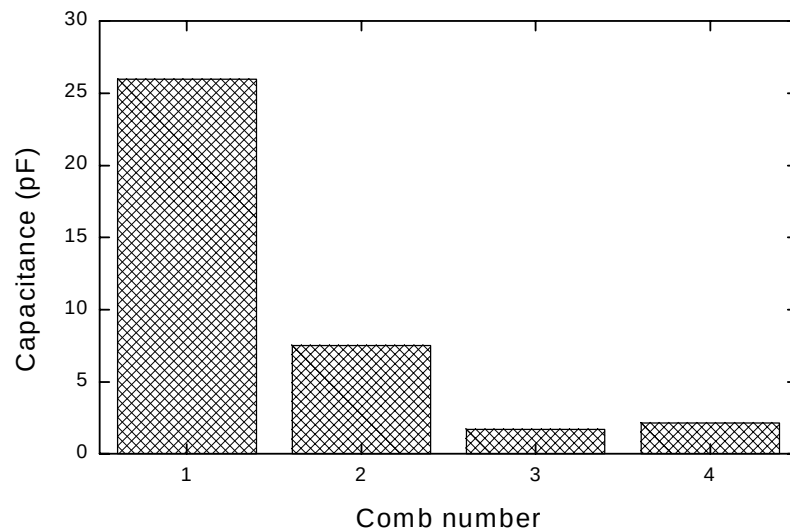


Figure 8: The capacitance varies with the size of the double comb pattern as shown here for a bare FR-4 test board.

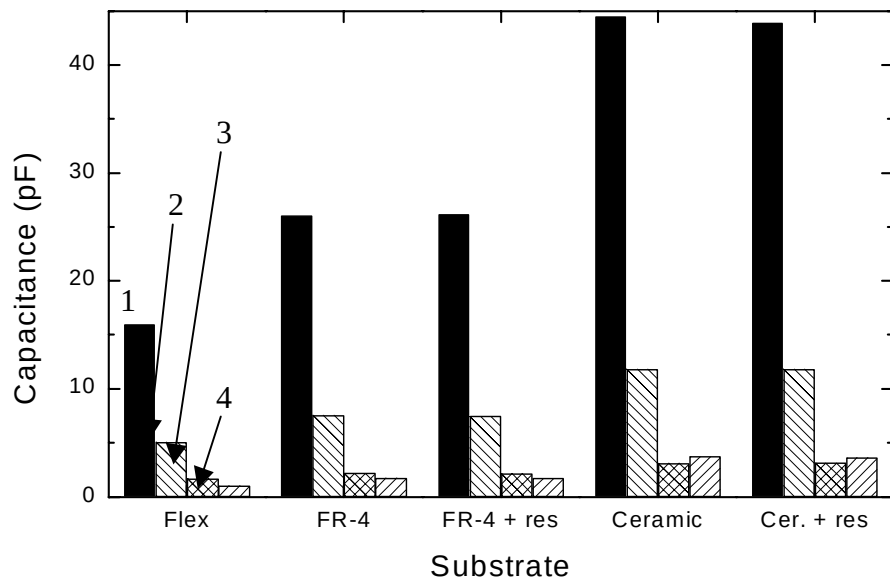


Figure 9: The influence that different substrates have on the capacitance of the double comb patterns. Numbers 1 to 4 refer to the different comb patterns shown in Figure 1.

Encapsulating the double combs increases the capacitance of the boards as shown in Figure 10. The capacitances of the differently coated boards are essentially the same with the exception of coating SR1 which has a lower capacitance value than the other coatings both on ceramic and flex boards. Note that the difference in the size of the double comb patterns are easily measurable for all the substrates using capacitance in comparison with measurements of resistance.

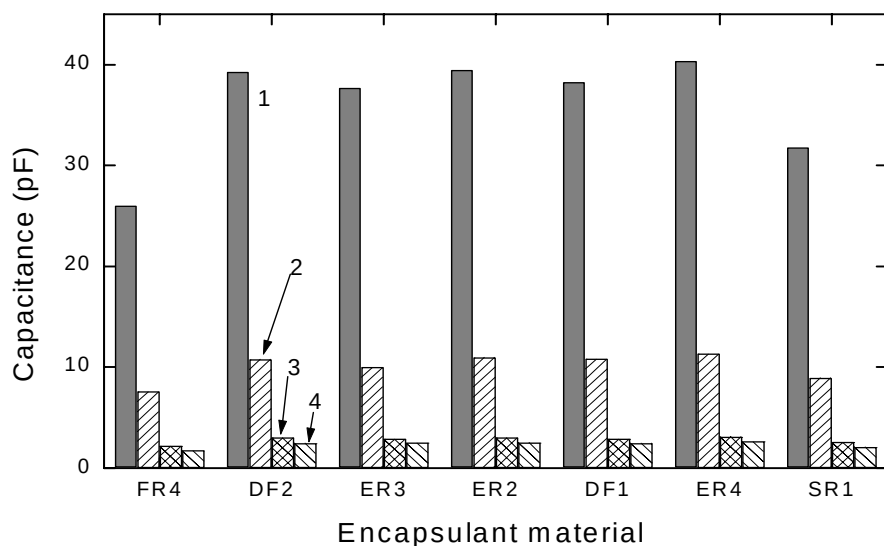


Figure 10: The dependence of capacitance on different types of encapsulant materials covering double combs on FR-4 board. Numbers 1 to 4 refer to the different comb patterns shown in Figure 1.

3.3.3 The influence of thermal cycling

Capacitance data obtained before and after thermal cycling can be compared following equation (2).

$$C_{\text{comp.}} = \frac{\text{Capacitance before thermal cycling}}{\text{Capacitance after thermal cycling}} \quad (2)$$

Figures 11 and 12 show that within experimental error thermal cycling does not affect the capacitance of double comb patterns on FR-4 substrate either with or without a resist layer with the possible exception of encapsulants SR1 and DF2. These two materials show respectively a ~10% increase and ~10% decrease in capacitance after thermal cycling. The same insensitivity to thermal cycling is also observed in data obtained from ceramic substrates (shown in Figures 13 and 14) with the possible exceptions of coatings DF2 and ER4.

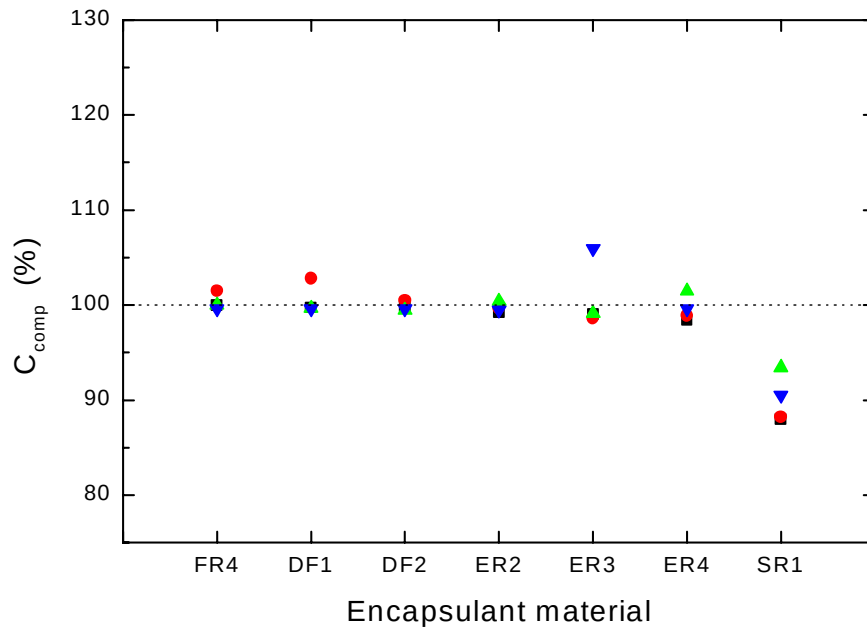


Figure 11: A comparison of capacitances measured before and after thermal cycling following equation 2 for un-coated and coated double combs deposited on FR-4. Key: ■ = comb 1, ● = comb 2, ▲ = comb 3, ▼ = comb 4

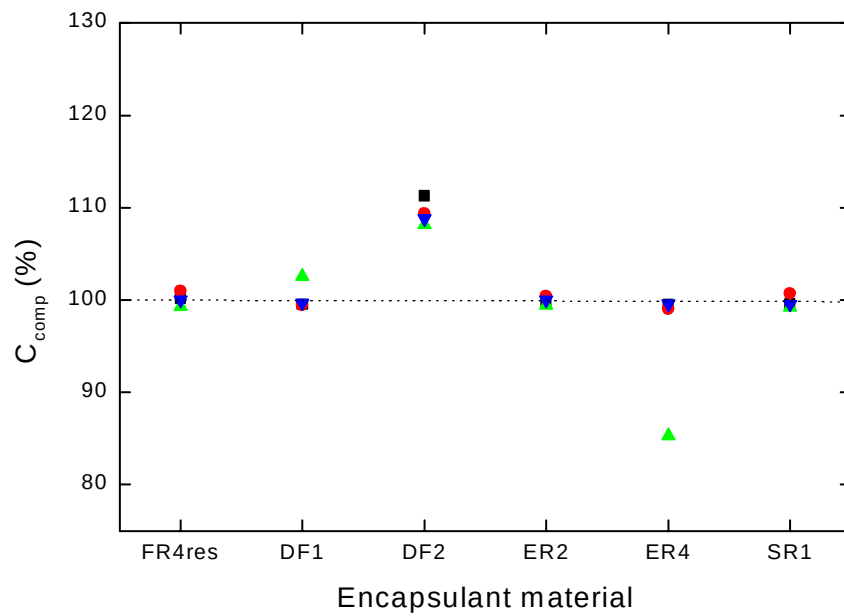


Figure 12: A comparison of capacitances measured before and after thermal cycling following equation 2 for un-coated and coated double combs deposited on FR-4 coated with resist. The symbol key can be found in the legend to figure 11.

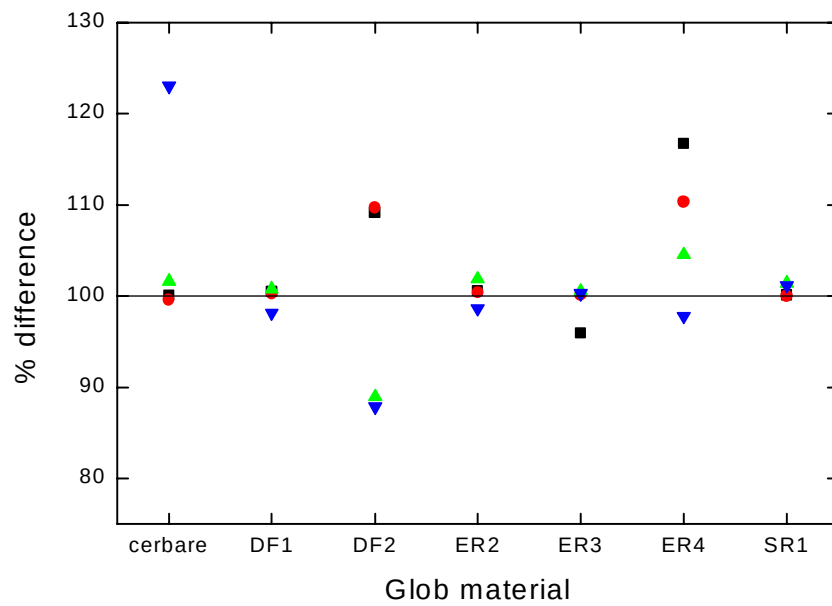


Figure 13: A comparison of capacitances measured before and after thermal cycling (following equation 2 for un-coated and coated double combs deposited on ceramic. The symbol key can be found in the legend to figure 11.

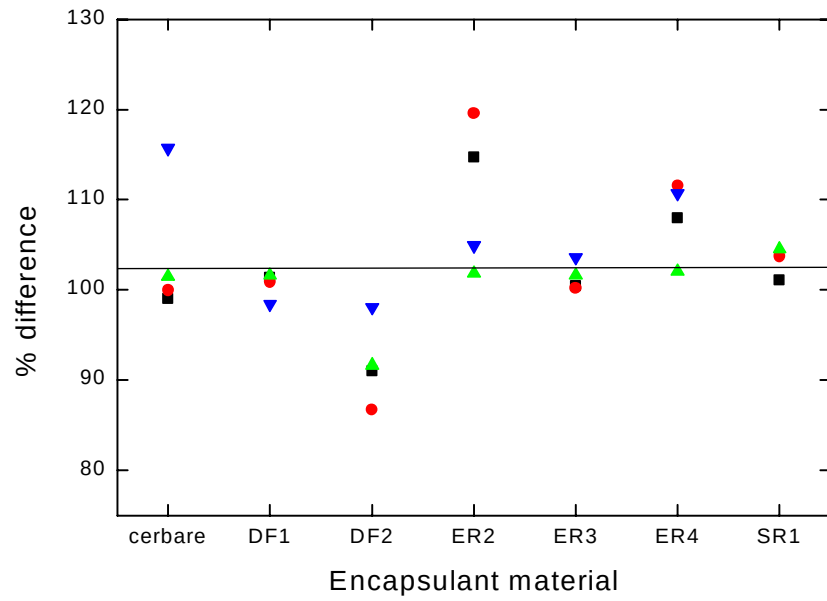


Figure 14: A comparison of capacitances measured before and after thermal cycling (following equation 2 for un-coated and coated double combs deposited on ceramic coated with resist. The symbol key can be found in the legend to figure 11.

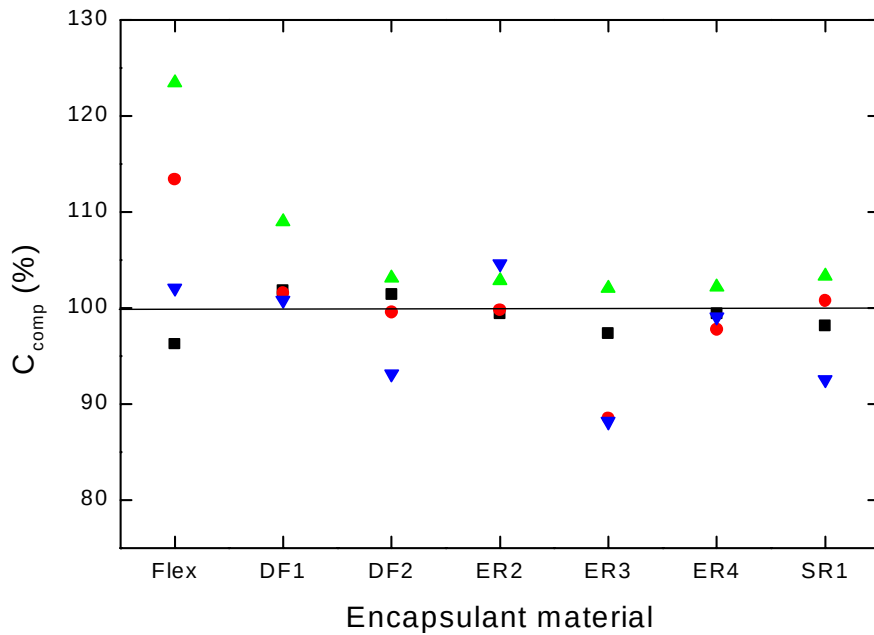


Figure 15: A comparison of capacitances measured before and after thermal cycling (following equation 2 for un-coated and coated double combs deposited on flex. The symbol key can be found in the legend to figure 11.

Visual inspection shows that all of the SR1 encapsulants became detached from the ceramic boards after thermal cycling, but this is not apparent from the capacitance data obtained under standard laboratory conditions.

Data obtained from encapsulants attached to flexible substrates are shown in Figure 15. The variation of approximately 10% in the capacitance of the bare board and one where the combs are encapsulated by ER3 appears to be uncorrelated with the degree of adhesion.

3.4 BUTT TENSION TEST MEASUREMENTS

Butt tension tests were conducted on each of the encapsulated double combs wherever possible. The results from these tests show that the force required to detach the pull stub from the substrate is independent of the area of the encapsulated region (see Tables A1 and A2 of Appendix 2). For this reason the force data for each encapsulant/substrate combination have been averaged. Figure 16 shows that thermal cycling has a negligible effect on the force required to detach the pull stub from encapsulated SIR patterns deposited on FR-4 with the possible exception of coating SR1.

This pattern is repeated in Figures 17 to 19 for ceramic substrates as well as for resist coated FR-4 and ceramic. These results show that there is excellent adhesion between the encapsulants and their underlying substrates with the possible exception of SR1 which although weaker lies close to the industry benchmark of 3 Nmm^{-2} .

The reduced tensile strength of silicone resins has been reported elsewhere¹ and attributed to the weakness of the silicone network compared with epoxies or acrylics. In a similar study of epoxy and silicone based encapsulants Khoo and Liu¹⁰ detected a decline in the shear modulus of these materials after a period of thermal cycling (1000 cycles) between -55°C and 125°C in an uncontrolled humidity environment. Khoo and Liu¹⁰ also report changes in the loss factor ($\tan \delta$) which suggests that there is some degradation of the samples. However whether such changes will adversely affect the electrical performance of the encapsulants was not addressed.

Measuring the force required to detach different encapsulants from different substrates assumes that the substrate is stiff enough not to buckle under the tensile load applied during the test. This requirement obviously prevents the test from being used to measure adhesion of encapsulants to the flexible substrate. A second more demanding requirement of this test method is to find an adhesive to securely attach the pull stub to the surface of the encapsulant such that the joint is able to tolerate high loads without failing at the interface between the pull stub and the encapsulant.

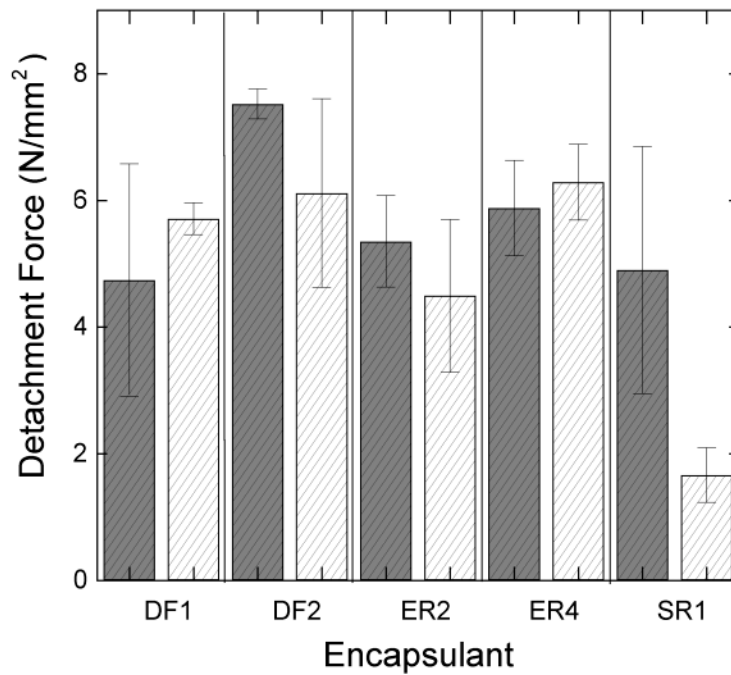


Figure 16: A comparison of the detachment force required pre and post thermal cycled (pre- thermal cycled is highlighted as the darker regions of the bars).

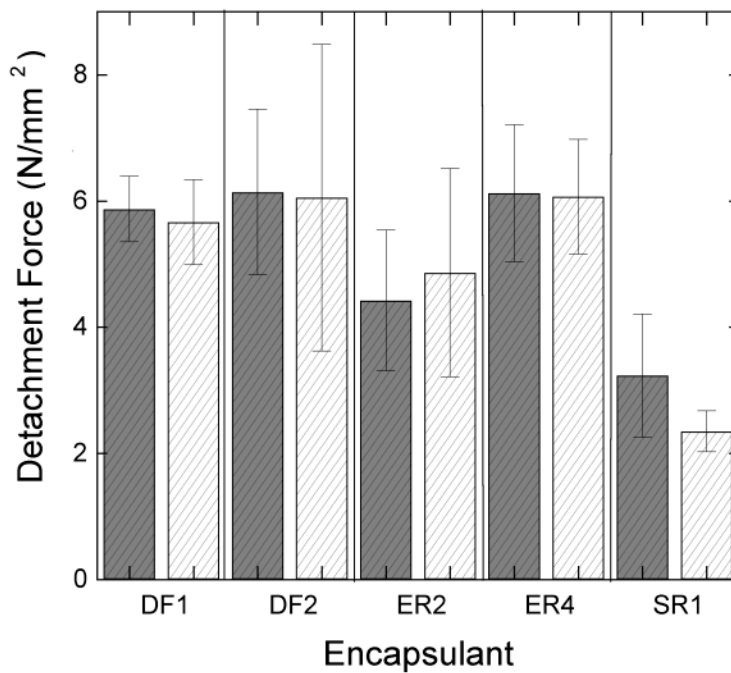


Figure 17: The figure above relates to boards produced with FR-4 substrate with resist. Pre and post thermal cycling is represented as shown in Figure 16. Once again the only difference of some magnitude seen is with the SR1 encapsulant where post thermally cycled boards produced a lower detachment force.

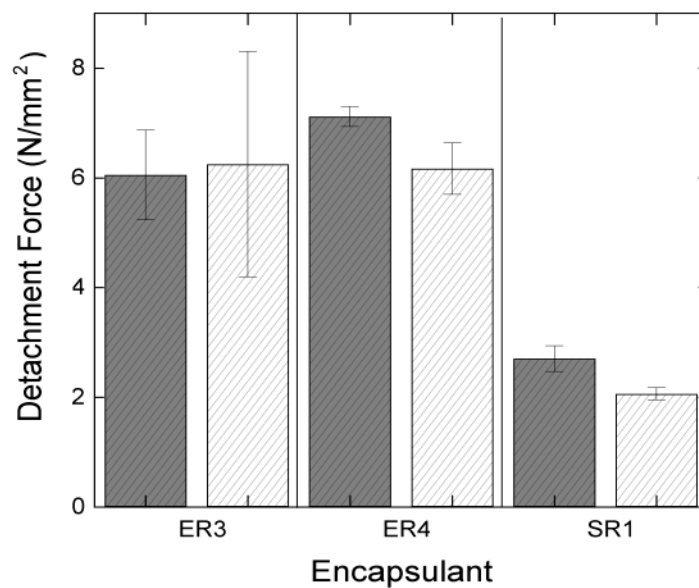


Figure 18: This graph represents results obtained from the testing of encapsulants on ceramic boards. Once again the areas representing the pre-thermal cycled results are shaded.

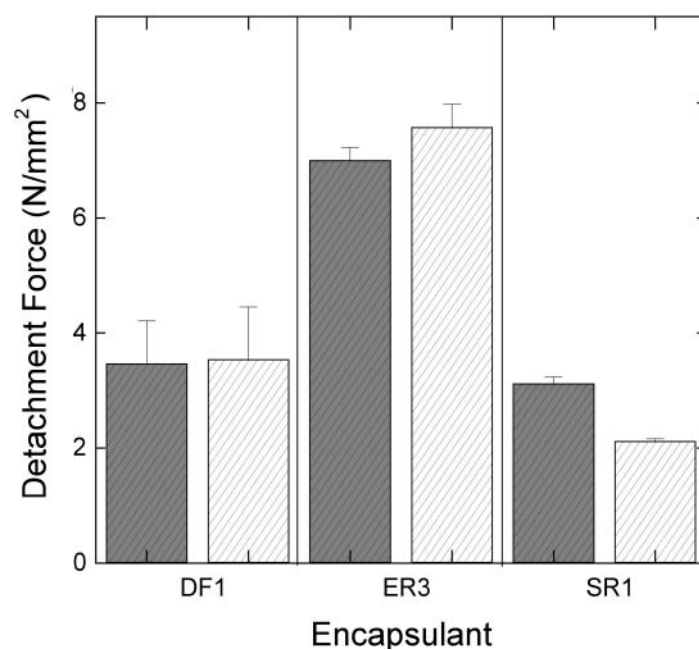


Figure 19: This graph represents results obtained from the testing of encapsulants on ceramic and resist boards. Once again the areas representing the pre-thermal cycled results are shaded.

Figure 20 shows the sites where the pull-stub – adhesive – encapsulant – substrate assembly can fail. In most instances failure of the assembly occurred adhesively at the interface of the substrate and the encapsulant (Tables A1 and A2 of Appendix 1). Examples of some of the fracture surfaces are shown in Figures 21 and 22.

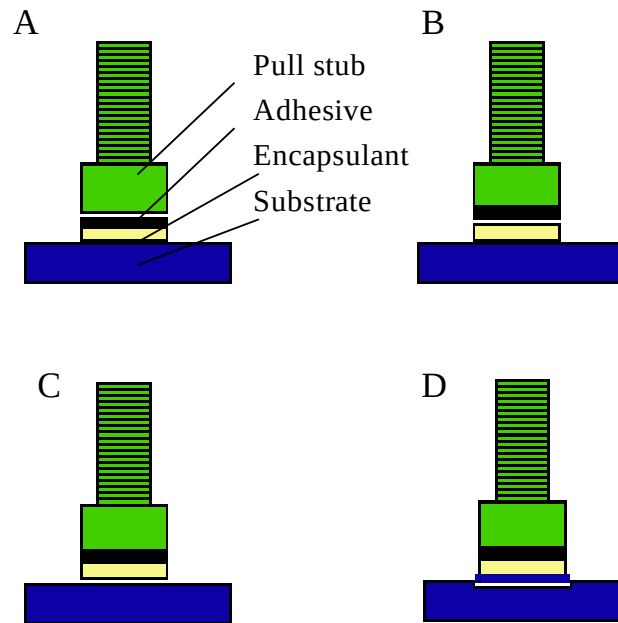


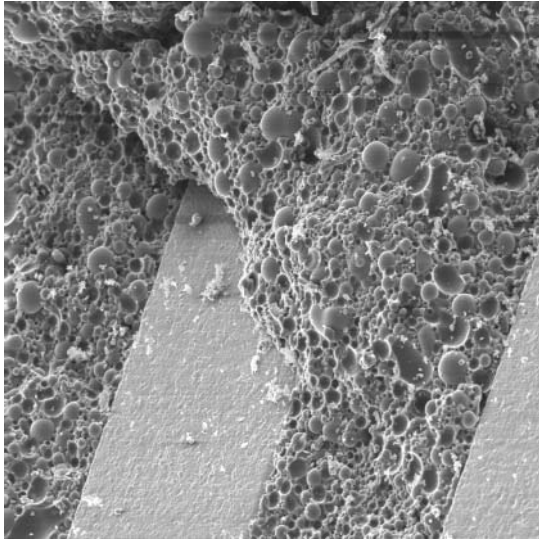
Figure 20. Various sites where pull stub failure can occur.

Figure 20: Failure of the encapsulant material can occur at:

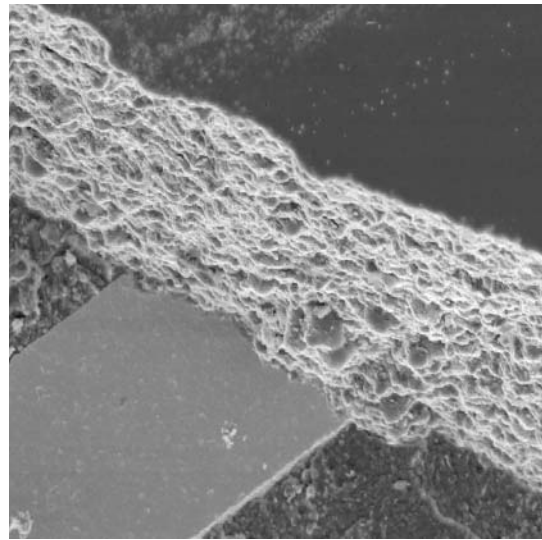
- The interface between the pull stub and the adhesive system (A).
- The interface between the adhesive system and the encapsulant material (B).
- The interface between the encapsulant material and the substrate (C).
- Or within the substrate material (D).

Figure 21 shows that the encapsulants appear to be at least two phase systems, particularly sample DF2 which consists of a range of differently sized globular objects embedded in a polymer matrix. The encapsulants show poor adhesion to the gold finished track that subsequently acts as a weak point within the assembly. No differences were seen between the fracture surfaces of samples that had been thermally cycled and those that had not.

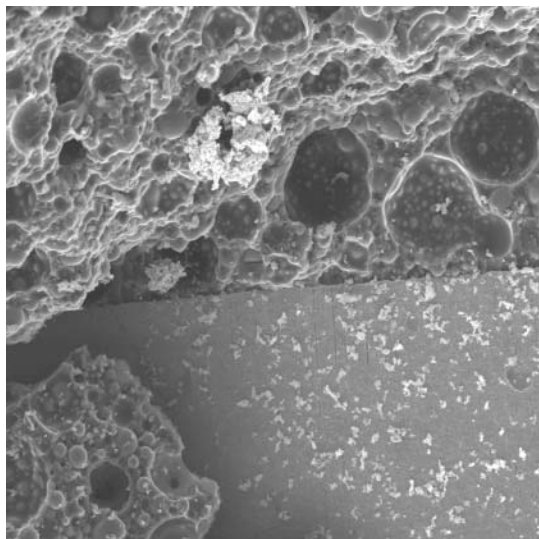
The fracture surfaces shown in Figure 22 are quite different to those shown in Figure 21 in that there are few remnants of the encapsulant remaining on the ceramic substrate after failure. The gold track also appears to be quite porous in contrast to that deposited over copper on FR-4. The results suggest that van der Waals interactions or the respective surface energies of the encapsulant and substrate are much more important for ceramic substrates than for FR-4 where mechanical retention plays a more significant role.



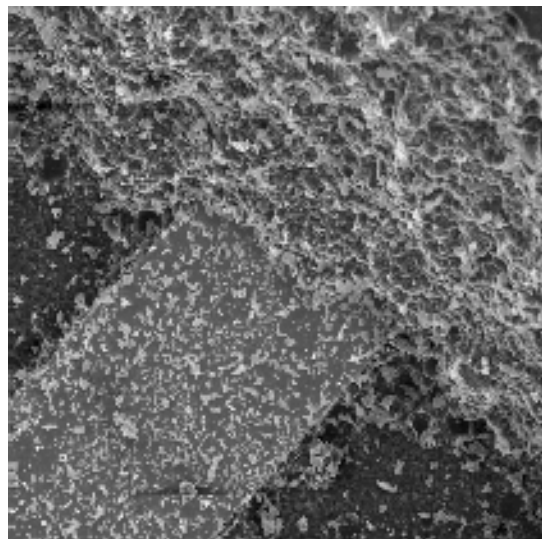
DF2 on FR-4 (x55)



ER4 on FR-4 (x80)

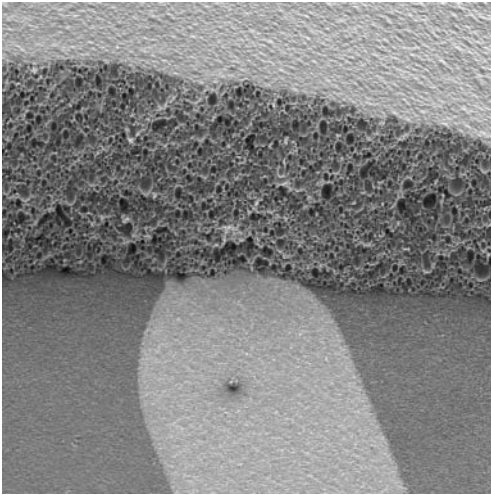


ER3 on FR-4 (x150)

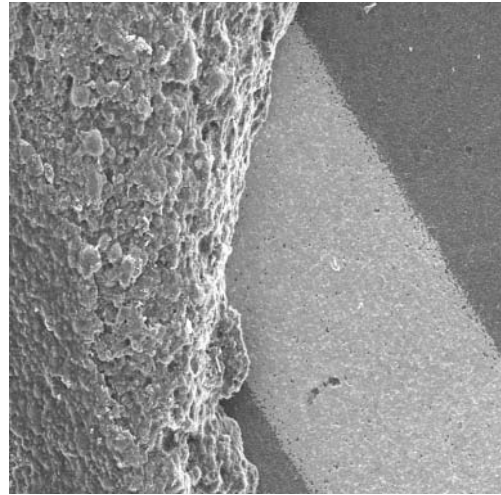


ER2 on FR-4 (x80)

Figure 21: Typical fracture surfaces of encapsulated material deposited onto ceramic PCB.



ER3 (ceramic) (x80)



ER4 (ceramic) (x80)

Figure 22: Typical fracture surfaces of encapsulated material deposited onto ceramic PCB.

4 Conclusions

- Delamination of encapsulants from ceramic substrates can occur during the period of cooling following cure at elevated temperatures (150°C).
- The accuracy of resistance measurements of double comb patterns made under typical laboratory conditions depends on the size of the double comb pattern, the nature of the substrate and time.
- Neither measurements of the resistance or capacitance of double comb patterns are sensitive to the degree of adhesion between encapsulants and the substrate under typical laboratory conditions.
- Butt tension test results show that excellent bonding occurs between a wide range of generically different encapsulants bound to both FR-4 and ceramic substrates.
- Where thermal cycling does induce delamination of the encapsulant failure occurs at the interface between the encapsulant and the substrate.
- Mechanical retention of encapsulant plays a more significant role for FR-4 substrates than for ceramic PCB's.

From this study it is apparent that the bond formed between a range of generically different types of encapsulants and substrates is durable and able to tolerate an extensive period of thermal cycling.

5 Acknowledgements

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6 REFERENCES

- 1) M. Bartholomew, 'An Engineers Handbook of Encapsulation and Underfill Technology', Electrochemical Publications, Isle of Man, 1999.
- 2) J. Liu, K. Gustafsson, Z. Lai and C. Li, 'Surface characteristics, reliability, and failure mechanisms of tin/lead, copper and gold metallizations', IEEE Transactions on Components, Packaging and Manufacturing Technology – Part A, **20**, March 1997.
- 3) T.M. Moore and R.G. McKenna, 'Characteristics of integrated circuit packaging materials', Butterworth-Heinemann, 1993.
- 4) C.G.L. Khoo and J. Liu, 'Temperature cycling effects in some glob top polymer materials', Circuit World, **24**, 11, 1998.

Substrate	Thermal cycling	Mean ratio (standard deviation)
FR-4	No	1 : 0.279 (6.57E-3) : 0.0762 (3.56E-3) : 0.0665 (5.21E-3)
FR-4	Yes	1 : 0.278 (6.62E-3) : 0.0780 (5.61E-3) : 0.0648 (1.59E-3)
Ceramic	No	1 : 0.269 (9.59E-3) : 0.0697 (1.94E-3) : 0.0701 (6.90E-3)
Ceramic	Yes	1 : 0.269 (1.07E-2) : 0.0701 (5.00E-3) : 0.0708 (2.33E-2)
Flex	No	1 : 0.299 (1.58E-2) : 0.0884 (7.49E-3) : 0.0682 (3.77E-3)
Flex	Yes	1 : 0.302 (3.45E-2) : 0.0830 (5.99E-3) : 0.0700 (5.55E-3)

Table A1: The ratio of the capacitances measured for each of the four double comb patterns (1:2:3:4) is unaffected by thermal cycling. These data are the mean values for each batch of test boards. The figures in brackets represent the standard deviation. Note that these data have been derived from all encapsulated boards irrespective of the variation in the chemical composition of the encapsulants.

Substrate	Encapsulant	Pattern 1 (N/mm ²)	Pattern 2 (N/mm ²)	Pattern 3 (N/mm ²)	Pattern 4 (N/mm ²)	Failure point
FR-4	DF1	5.95	6.64	5.56	6.56	C
	DF2	7.64	7.29	7.69	7.11	C
	DF2	7.65	7.71	7.74	7.35	D
	ER2	4.76	5.98	4.84	5.54	C
	ER3	7.42	6.49	6.28	6.18	C, D
	ER4	5.54	6.39	6.68	4.29	C
	ER4	6.14	6.01	6.38	5.58	C
	SR1	3.52	-	-	6.28	B
	DF1	2.81	3.15	-	2.53	B
	ER2	6.59	5.51	4.32	5.28	C
Ceramic	ER3	5.91	5.38	7.12	6.85	C
	ER3	6.31	4.58	6.44	5.83	A,C
	ER4	7.14	7.29	6.86	7.18	C, D
	SR1	2.87		2.54		B
Fr-4 + resist	DF1	5.2	6.45	6.0	5.84	C
	DF2	7.31	7.21	5.29	4.75	C
	ER2	4.41	5.85	4.3	3.13	C
	SR1	2.31	2.49	3.89	4.24	B
	ER4	6.59	7.44	5.13	5.33	C
Ceramic + resist	DF1	2.99	3.53	4.8	2.44	C
	DF1	3.59	4.15	3.28	2.98	C
	ER3	7.21	6.85	7.18	6.78	
	SR1	3.03	-	-	3.07	B
	SR1	-	3.13	3.28	-	B

Table A1: Failure of the pull stub – encapsulant – substrate assembly occurred either at the interface between the encapsulant and the pull stub (pull stub), at the interface between the encapsulant and the substrate (Enc. int) or within the interface (Coh. Ceramic). Pre-thermal treatment

The failure point shown refers to the failure points as described in Figure 20.

Substrate	Encapsulant	Pattern 1 (N/mm ²)	Pattern 2 (N/mm ²)	Pattern 3 (N/mm ²)	Pattern 4 (N/mm ²)	Failure point
FR-4	DF1	5.63	5.84	5.4	5.97	C
	DF2	5.66	4.5	3.88	6.02	C
	DF2	7.78	7.87	7.43	5.78	C, D
	ER2	5.2	3.97	2.94	5.87	C
	ER3					
	ER4	6.87	5.91	6.24	5.08	C
	ER4	6.97	6.62	6.29	6.31	C
	SR1	1.97		1.36		B
	DF1					
	ER2	5.2	3.97	2.94	5.87	C
Ceramic	ER3	7.86	7.2	6.68	3.25	C
	ER3					
	ER4	6.78	6.28	5.77	5.84	C, D
	SR1	2.14			1.98	A
Fr-4 + resist	DF1	6.64	5.53	5.11	5.38	C
	DF2	7.78	7.43	6.5	2.5	C
	ER2	6.64	4.65	5.45	2.71	C
	SR1	2.12	2.58			B
	ER4	6.99	5.61	6.64	5.03	C
Ceramic + resist	DF1	3.8	2.98	2.7	4.71	C
	DF1					
	ER3	7.78	6.98	7.78	7.78	
	SR1	2.15	2.1	0	0	B
	SR1					

Table A2: Failure of the pull stub – encapsulant – substrate assembly occurred either at the interface between the encapsulant and the pull stub (pull stub), at the interface between the encapsulant and the substrate (Enc. int) or within the interface (Coh. Ceramic). Post-thermal treatment.

The failure point shown refers to the failure points as described in Figure 20.