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A Comparison of PCB Adhesion Test Methods and Adhesion Promoters

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Introduction

Interest in the adhesive strength of PCBs has recently come to the forefront of the industry. This has been driven by the advent of lead free soldering processes that severely stress the mechanical properties of the board. For sometime, the accepted test method for measuring adhesion in the PCB industry has been the widely used peel strength test. At the same time, it has been common knowledge within the industry that this technique has been less than adequate in guarding against delamination failures during reflow and wave soldering. In recognition of this deficiency, a new test was recently introduced and the test method is now a part of IPC 650; the so called "T260 Method" in which a thermal event is imposed that causes a delamination of the test specimen.

This paper presents a statistical comparison of the two test methods. The correlation is found to be very poor indicating the failure mechanisms measured by the two tests are structurally dissimilar. An analysis is then carried out to mathematically define the stress fields created by the two tests. As suspected, the stress fields are significantly different. Finally, these two tests are used to compare the strength of two different copper adhesion promotion chemistries, the Black Oxide coating and an Alternative coating. Most empirical observations have found that the performance of the coatings is equivalent; however, only the T260 test agrees with this observation.

Measurement Techniques

The failure mechanism of interest is a rupture causing a breach within the PCB. Nearly always, this occurs between a copper layer and a layer of prepreg. When this failure is observed, it is normally the result of a thermal event such as reflow or wave soldering. The rupture is caused by the dissimilar lateral expansion between the copper and the adjacent glass-epoxy layer. This creates a shear stress between the two layers which if severe enough will cause a rupture, i. e. a delamination. An issue which has confronted the industry for some time is to define a quantitative measurement that will be a reliable index of the likelihood that a particular PCB structure will survive a thermal event.

The technique which has been used for many years is referred to as the peel strength. Several test methods are available for this measurement in IPC-650. The test is usually performed on an Instron. The test coupon is composed of a copper foil that is laminated to a PCB substrate. A small width of laminated copper foil is pulled vertically from the sample and the force required is measured. Often this test is performed at an elevated temperature in an attempt to account for the thermal effects of assembly.

A second index that is coming to the forefront is referred to as the "T260" test method and again the test method is found in IPC-650. In this case, a sample of an actual board is placed into a Thermal Mechanical Analyzer (TMA). The TMA chamber is quickly heated to 260^{o}C and held. A very sensitive probe is placed on the top of the sample which detects any vertical expansion of the test sample. When a sudden expansion is detected, as caused by a delamination, it is sensed by the TMA and the elapsed time recorded. The elapsed time is then the index of structural integrity of the sample. This technique has the advantage that it faithfully simulates the stress field associated with a thermal event. As a result, the T260 test method is rapidly becoming the measurement of choice.

The time required to generate a failure in the T260 test procedure is often in excess of 20 minutes and consequently some in the industry have elected to accelerate the test by using a higher equilibrium temperature, in cases up to 280^{0} C. The risk is the same as always; the higher the acceleration the greater the likelihood of triggering additional failure mechanisms. An abbreviated form of the T 260 test has also been defined by the IPC. In this case, the coupon is floated on a solder pot at 260^{0}C for a specified time. This stress is repeated until the coupon fails and the total time of exposure recorded.

In the analysis that follows, both techniques will be presented on common materials. The results are the statistically compared to see if there is a correlation between the test methods.

Statistical Analysis

Figure 1 presents a statistical investigation comparing peel strength measurements to T260 results. The figures below summarize these findings.

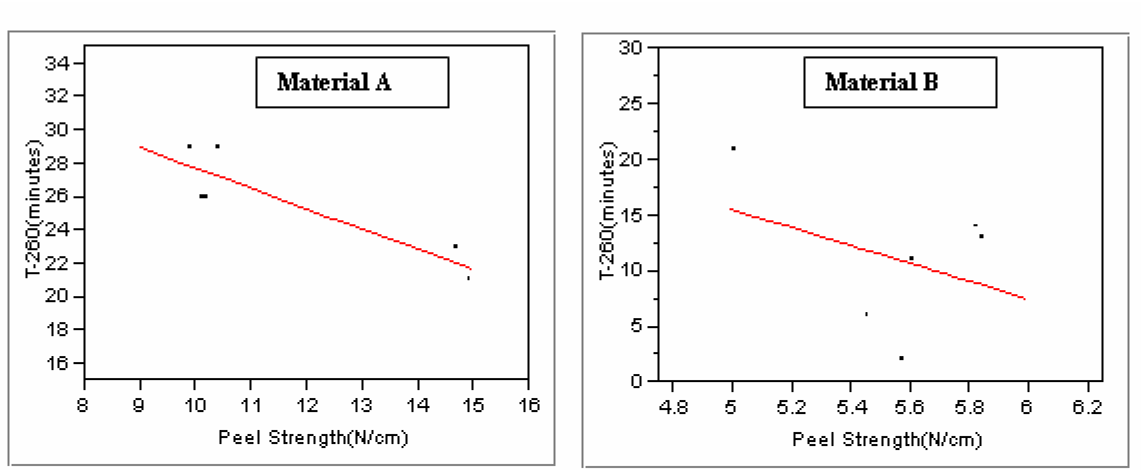

Figure 1 – Statistical Investigation comparing Peel Strength Measurement to T260 Results

The red line in these figures is the least squares fit. As seen the correlation is very poor and in fact negative. In both cases, increasing peel strength produces a declining T260 measurement. These results clearly indicated the two procedures measure two different and probably unrelated mechanisms. It is appropriate to question if either is a good index of the failure mode of interest, i.e. the susceptibility of a PCB to delamination during assembly. Consequently, a stress analysis is in order.

Stress Analysis T260 Test

The analysis considers a structure composed of two dissimilar components bonded together as shown in Figure 2:

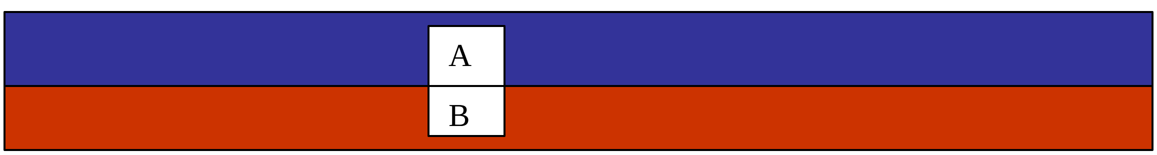

Figure 2 - Two Dissimilar Components Bonded Together

The structure is unrestrained and initially at a temperature T_1. The temperature is elevated to T_2. An equilibrium stress analysis of this phenomenon is given in Reference 2.

After temp erature T_2 is achieved the stress field can be described by the free body diagram in Figure 3.

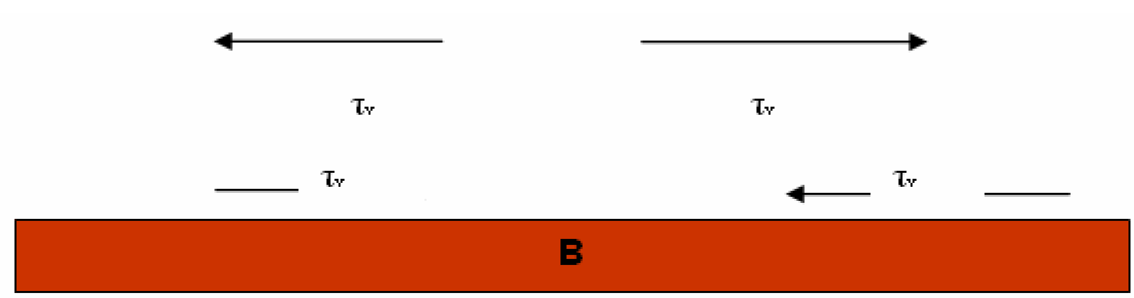

Figure 3 - Free Body Diagram

Rayleigh's Law Requires:

- ? $L{=}a\,L(T_2\text{-}T_1)$

And according Hook's Law

- $F/A = ($? $L/L)E$

Where

– a is the coefficient of thermal expansion (CTE)
– E is the modulus of elasticity

Consequently:

? $L_A = a_A\, L\, (T_2\text{-}T_1) + t_x\, L^2 / E_A t_A$
? $L_B = a_B\, L\, (T_2\text{-}T_1) - t_x\, L^2 / E_B t_B$
? L_A = ? L_B
Therefore:
$t_x =$? $T(a_B - a_A)\, E_A\, (t_A\, /L)/[1+(t_A E_A/t_B E_B)]$

If the strength of the bond between component A and B is less than t_x, rupture occurs.

It is important to realize this is the only stress generated in an unrestrained thermal expansion of two dissimilar materials. Consequently, this is the only stress generated in the T260 measurement and during PCB thermal excursions associated with most reflow and wave solder operations.

It is also interesting to note the scale factor t/L appears in the equation which is consistent with the observation that thicker copper is more susceptible to delamination.

Peel Strength
Attention is now given to the stress developed in the peel strength measurement depicted in Figure 4
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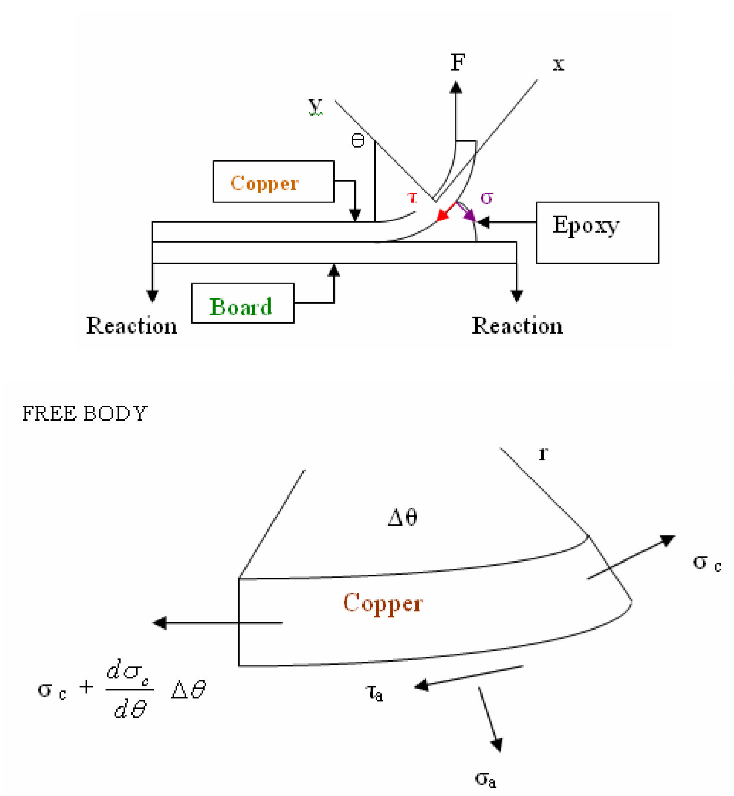

Figure 4 – Peel Test

Summing the forces orthogonal to the radius gives

$$t_a = -\frac{ds_c}{dq}\frac{t}{r}$$

And by definition

$$t_a = e_c G = s_c \frac{G}{E_c}$$

The tensile stress in the copper at the point that the force F is applied is $\frac{F}{tw}$

Then after integrating and applying the boundary condition

$$s_c = (\frac{F}{A})\exp[(q - p/2)\frac{G}{E_c}\frac{r}{t}]$$

It follows that the shear stress applied by the adhesive (t_a) is

$$t_a = (\frac{G}{E_c})\ (\frac{F}{A})\exp[(q - p/2)\frac{G}{E_c}\frac{r}{t}]$$

Summing forces in the radial direction shows that

$$s_a = s_c \frac{t}{r}$$

Or

$$s_a = \frac{t}{r}\frac{F}{A}\exp[(q - \frac{p}{2})\frac{G}{E_c}\frac{r}{t}]$$

It is interesting to note that the ratio of the two stresses is

$$\frac{t_a}{s_a} = \frac{G}{E_c}\frac{r}{t}$$

Where:
? is the polar position on the copper strip (measured in radians)
G is the shear modulus of elasticity of the adhesive
F is the peel force
E_c is tensile modulus of elasticity for copper
r is the radius of curvature of the copper strip
And t is the thickness of the copper

To an order of magnitude the ratio of $\frac{G}{E_c} = O\left(10^{-3}\right)$

And $\frac{r}{t} = O(10^3)$ or more

Consequently, both stresses are of the same order of magnitude and both play equally important roles in the peel strength measurement. The stress vector resulting from these two orthogonal stresses then causes a fracture in the plane defined by the stress vector. Also, the radius of curvature, which generally is uncontrolled, is seen to play a strong role in the peel strength measurement.

In a thermal event, the fracture is parallel to the copper glass/epoxy interface and only the shear component is present. The peel strength measurement is then at best problematic from two aspects; it interjects a superfluous tensile stress as well as incorrectly identifying the plane of failure. Consequently, the measurement is suspect.

Comparative Adhesive Measurements

The above analytical results are now compared to an empirical study involving different adhesion promoters. The evaluation considered the peel strength of both a Black Oxide and an Alternative Coating. The results are presented in the Table 1. Clearly, the Black Oxide coating has the higher peel strength. In assembly, however, the two coatings have been found to perform equally as well which is contrary to the peel strength measurements.

Table 1 – Results of the Evaluation both a Black Oxide and an Alternative Coating

Prepreg	Alternative Coating		Oxide	
	Lbs/in	N/cm	Lbs/in	N/cm
High speed material	2.6	4.5	4.0	7.0
High speed material	2.2	3.8	3.1	5.4
FR402/2116	5.4	9.4		
FR404/2116	6.2	10.9		
FR404/7628	6.7	11.7		
FR406	3.3	5.7	5.5	9.7
FR408	3.0	5.3		
G200	3.0	5.3	3.2	5.6
P 25	2.7	4.7		
MLF/113/2113	6.0	10.5		
MLF/116/2116	5.9	10.3		
4205-2/2116	6.2	10.8		
N4000-13	2.7	4.7	3.5	6.1
N4000-6	3.3	5.8	5.1	8.9
N6000	1.4	2.4	1.0	1.7

This inconsistency has recently been pursued by another study that compared the adhesive strength of coupons using the Black Oxide coating and an Alternative coating. The conventional T260 test was modified. In this case the coupons were floated for multiple cycles of ten seconds each in solder at 260^0C in the manner defined by IPC 650. The results are presented in the Figure 5.

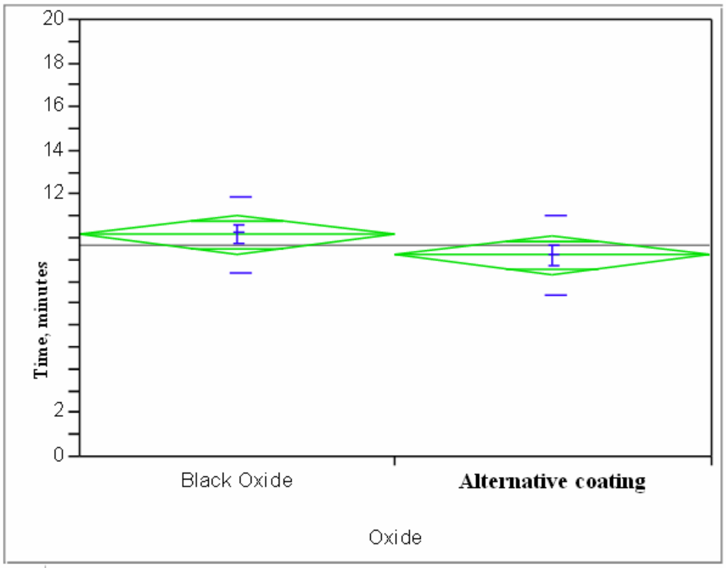

Figure 5 – Results of the Modified Conventional T260 Test

As shown the T260 test finds the adhesive strength of both coatings to be equivalent, which is the expectation based upon past experience. This again shows the T260 test to be superior.

Summary

A stress analysis was carried out for both the peel strength and T260 tests. This analysis clearly showed the T260 test to be a superior choice for measuring the adhesion performance of PCBs during thermal excursions such as experienced in assembly. The utility of the T260 measurement was then demonstrated by comparing the adhesive strength of two sets of coupons using these two adhesion promoting coatings. While the peel strength measurement normally finds the Black Oxide coating to be superior to the Alternative Coatings, the comparison using the T260 measurement finds the strength of the coatings to be equivalent which is in keeping with most observations.

References

1. Oxide Alternative Qualification, A Case Study; Brooks, Patrick; Roberts, Hugh; Johal, Kuldip; Atotech Corporation; 2003
2. Gatewood, B. E.,Ph D, Thermal Stresses, McGraw-Hill Book Company, Inc. 1957