An Analytical Characterization and Comparison of Adhesion Test for PCBs

J. Lee Parker, Ph D
JLP Consultants
Richmond, VA

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 which 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. The purpose here is to compare the stress field associated with a board delamination to that generated by the peel test and the T260 test.

This analysis will initially give attention to a first principals characterization of the stress field associated with a uniform, free expansion of a PCB, such as in the reflow process. If severe enough, this will result in a delamination. The stress fields produced by the Peel and T260 tests are then analyzed and compared to that of a free expansion. As suspected, the stress fields of the two test methods are significantly different. The stress field created by the T260 test has the same geometry as the free expansion, but a scale factor is required for a total correlation.

Finally a novel technique is suggested for characterizing the layer-to-layer structural integrity of a PCB does not suffer these drawbacks.

Fundamentals

According to first principals, the stress field of a differential cube at equilibrium is uniquely defined by three shear stresses acting along each of the faces of the cube and three normal stresses acting normal to each of the faces. For a two dimensional problem which will be the case here, this reduces to two normal and two shear stresses as shown in Figure 1. When these four stresses are known, the applied stress is uniquely defined regardless of the nature of the stimulus (e.g. a thermal, mechanical etc).

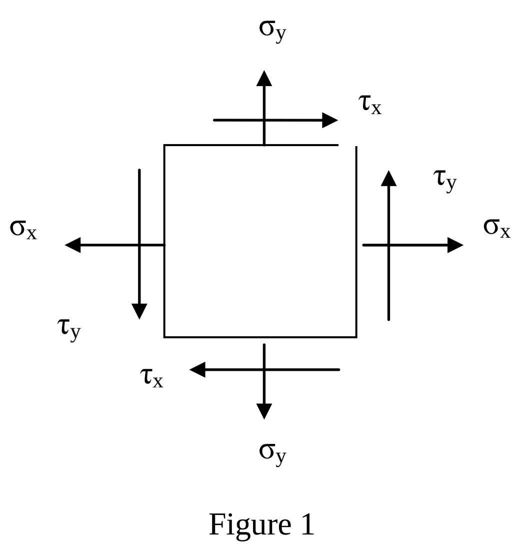


Figure 1

Unfortunately, the peel strength alone, does not uniquely define the stresses shown in Figure 1 and consequently the measurement is not definitive. That is, the peel strength along with some other variables (not yet discussed) must be defined in order to reduce the measurement to the fundamental variables of Figure 1. It follows, the peel strength causing a rupture may vary if these additional variables are not same. Later, these additional variables will be identified.

<u>Stress Field at Delamination</u>

The failure mechanism of interest is a rupture causing a breach within the PCB. Most often, this occurs between a copper layer or feature 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.

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

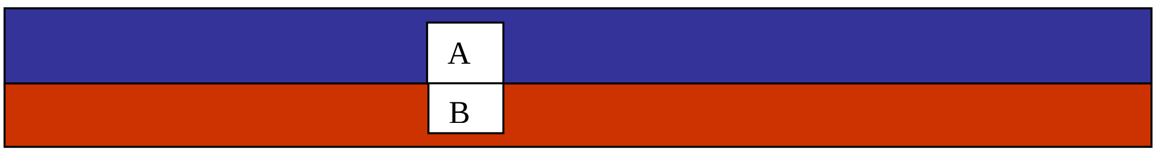


Figure 2

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 temperature T_2 is achieved the stress field can be described by the free body diagram below

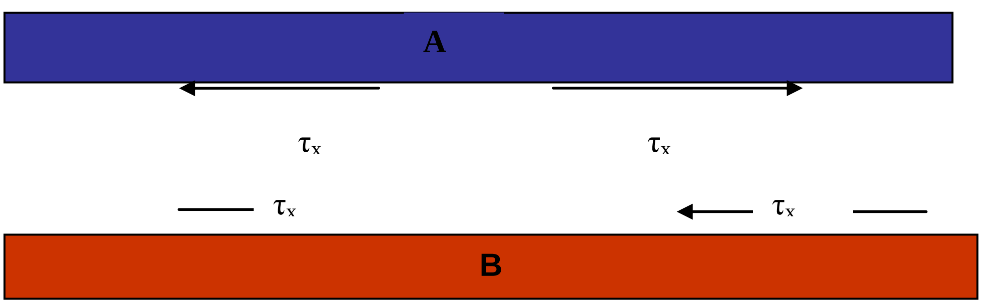


Figure 3

Rayleigh's Law Requires:

- $\Delta L = \alpha L (T_2 - T_1)$

And according Hook's Law

- $F/A = (\Delta L/L)E$

Where

- α is the coefficient of thermal expansion (CTE)
- E is the modulus of elasticity
- L is the length of the sample

Consequently:

$\Delta L_A = \alpha_A L (T_2 - T_1) + \tau_x L^2 / E_A t_A$

$\Delta L_B = \alpha_B L (T_2 - T_1) - \tau_x L^2 / E_B t_B$

$\Delta L_A = \Delta L_B$

t is the thickness of the component, A or B

Therefore:

$\tau_x = \Delta T(\alpha_B - \alpha_A) E_A (t_A / L)/[1 + (t_A E_A / t_B E_B)]$ (1)

Since there are no normal forces applied, both normal stresses (σ) are zero. It is important to realize that τ_x is the only stress generated in an unrestrained thermal expansion of two joined dissimilar materials. If the strength of the bond between component A and B is less than τ_x, rupture occurs.

It is interesting to note scale factors t_A /L (geometry) and t_AE_A/t_BE_B (structural) appear in the equation which is consistent with the observation that thicker copper is more susceptible to delamination. Obviously, for a laboratory simulation of the delamination of an actual board using a scaled coupon, the test specimen must reflect these two parameters as they occur in practice.

Peel Strength

The technique which has been used for many years to characterize the adhesion between layers 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.

Attention is now given to the stress developed in the peel strength measurement depicted below.

Peel Test

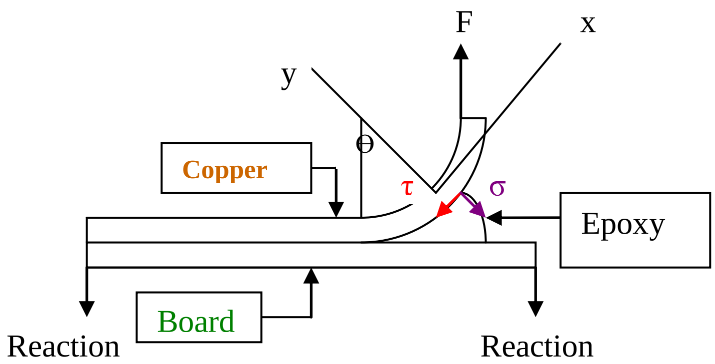


Figure 4

FREE BODY

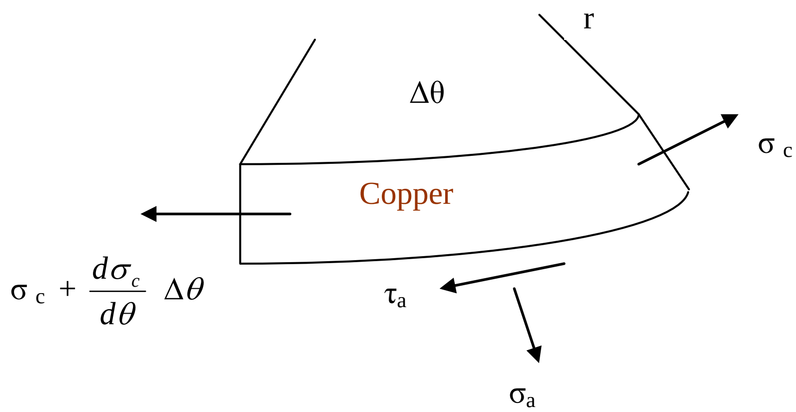


Figure 5

Summing the forces orthogonal to the radius gives

$$\tau_a = -\frac{d\sigma_c}{d\theta}\frac{t}{r}$$

And by definition

$$\tau_a = e_c G = \sigma_c \frac{G}{E_c}$$

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

$$\sigma_c = (\frac{F}{A})\exp[(\theta - \pi/2)\frac{G}{E_c}\frac{r}{t}]$$

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

$$\tau_a = (\frac{G}{E_c})\ (\frac{F}{A})\exp[(\theta - \pi/2)\frac{G}{E_c}\frac{r}{t}]$$

Summing forces in the radial direction shows that

$$\sigma_a = \sigma_c \frac{t}{r}$$

Or

$$\sigma_a = \frac{t}{r}\frac{F}{A}\exp[(\theta - \frac{\pi}{2})\frac{G}{E_c}\frac{r}{t}]$$

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

$$\frac{\tau_a}{\sigma_a} = \frac{G}{E_c}\frac{r}{t}$$

Where:
ϴ 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. The peel strength measurement is not germane to the issue of interest.

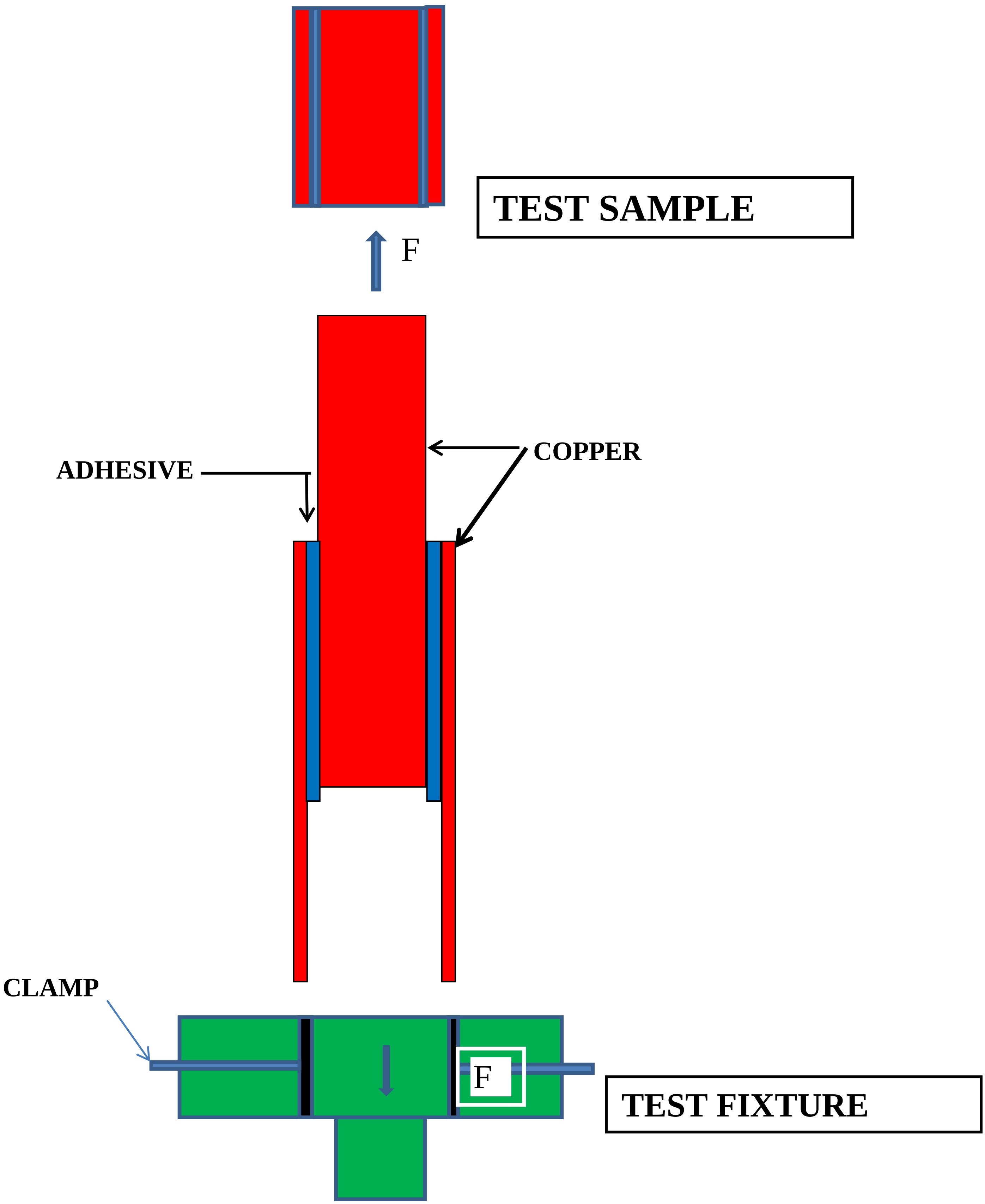
T260 Test Method

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 access 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.

Unfortunately, the end point metric (time) is an indirect measurement of the shear strength. The major disadvantage of the T260 test is that the failure occurs at a temperature some where in between ambient and the temperature of the test chamber. Most likely there are uncontrolled thermal gradients in the test sample which enhance the shear stress. There is no convenient way to relate the endpoint measurement, time to failure, to the shear stress. Although this procedure has some obvious advantages over the peel strength measure, it is far from perfect.

The Lap Joint

A proposed option to overcome the disadvantages of the previous techniques is the lap joint in Figure 6.



LAP JOINT Figure 6

Lap joint is formed by laminating copper between two pieces of laminate. The copper is segmented and overhangs at the ends of the specimen. It is essential that the rear vertical surface of the copper not be bonded to the laminate since this will add an undesirable element of structure. The ends of the overhang are placed in jaws of an Instron and pulled until failure occurs. As indicated by the free body, the shear stress at the copper laminate interface is
$\tau = (F/2)/(Xd)$

where d is the thickness of the sample.

The stress is independent of the thickness of the copper and the laminate. To insure a fracture along the copper laminate boundary, the thickness of the copper and laminate should be large. After failure, the sample should be inspected to insure that the failure occurred along the copper/laminate interface. If not, the sample should be redesigned. This test can be conducted at temperature using a heated chamber such as often used in Instron testing to measure material properties at elevated temperatures.

Summary

The analysis shows that the stress field generated by the peel test is poor reflection of that caused by a free expansion such as in reflow. The T260 Test generates the desired stress field, the measurement is indirect. A third option, a double lap joint is shown to overcome these issues, but the design and fabrication of the test sample is critical.

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

3. Parker, J. L., Brooks, Patrick, A Comparison of PCB Adhesion test Methods and Adhesion Promoters, IPC EXPO, February, 2005

AN ANALYTICAL CHARACTERIZATION AND COMPARISON OF ADHESION TESTS FOR PCB'S

BY
J. LEE PARKER, PH D
JLP CONSULTANTS
MECHANICSVILLE, VA
LEEP001@MSN.COM

AGENDA FOR DISCUSSION

Fundamentals of adhesion measurements

Analysis of stress field at delamination

The peel strength measurement

The T260 test

A new approach, the lap joint

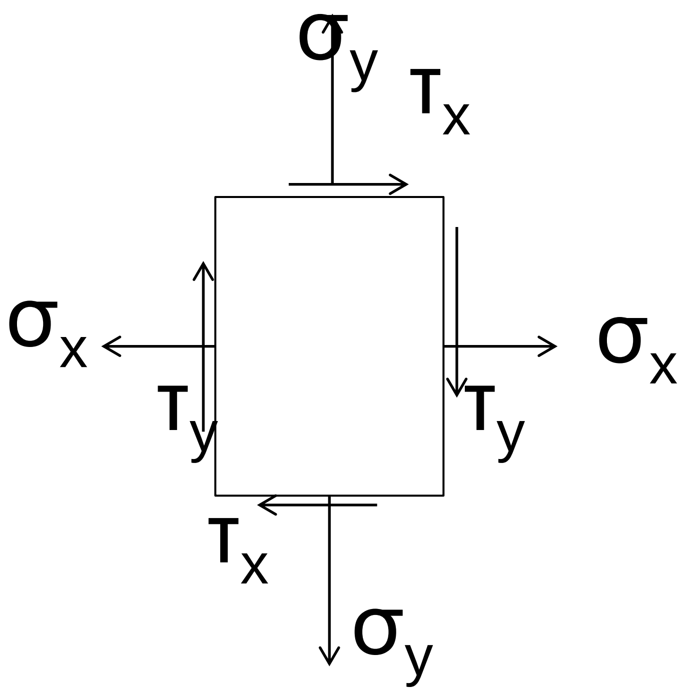
Summary

FUNDAMENTALS

According to first principals:

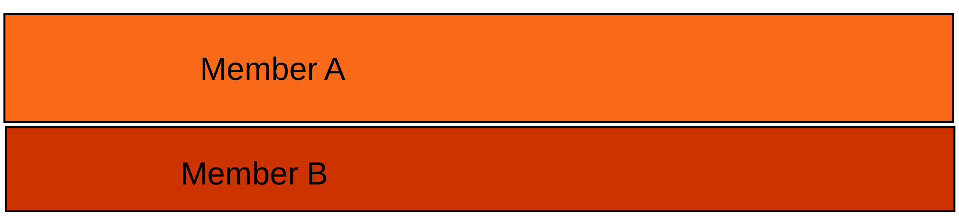
- The stress field of a two dimensional free body is completely defined by the shear stress and normal stress acting on each face of the element.
- With this information the forces and stress acting in any direction can be determine.
- No additional information is required
- Any other description will require additional information

FUNDAMENTAL STRESS FIELD



DEFINING THE PROBLEM

- Two dis-similar components
- Components bonded at interface
- Structure is unrestrained
- Structure is initially at a uniform temperature of T_1
- Structure is uniformly heated to temperature T_2
- Structure then expands unevenly, creating a shear stress at the interface,



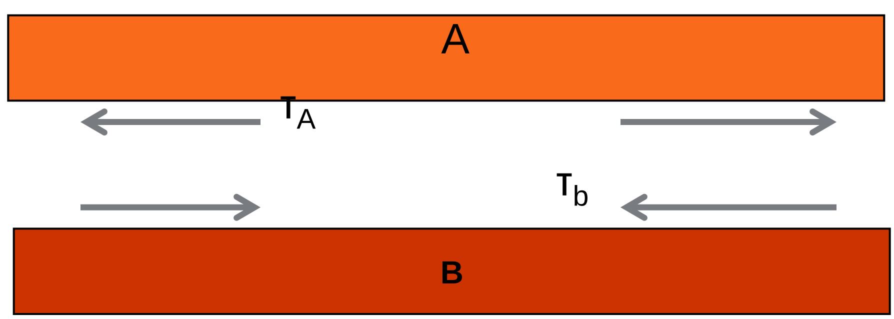
INTENT OF MEASUREMENT

Determine the likelihood of delamination during a thermal event (reflow, wave solder etc.)

Reproduce the stress field and stress vectors created in a thermal event

Provide an index of performance

The free body diagram is shown below



GOVERNING EQUATIONS

- **Rayleigh's Law (see Gatewood, Thermal Expansion, McGraw-Hill)**
- $\Delta L = \alpha L(T_2 - T_1)$
- **Hook's Law**
- $\tau = (\Delta L/L)E$
- **Where:**
  - **α is the coefficient of thermal expansion (CTE)**
  - **E is the modulus of elasticity**

FREE THERMAL EXPANSION STRESS ANALYSIS

The deformation of free-bodies A and B are

$\Delta L_A = \alpha_A L\,(T_2 - T_1) + L^2 / E_A t_A$

$\Delta L_B = \alpha_B L\,(T_2 - T_1) - L^2 / E_B t_B$

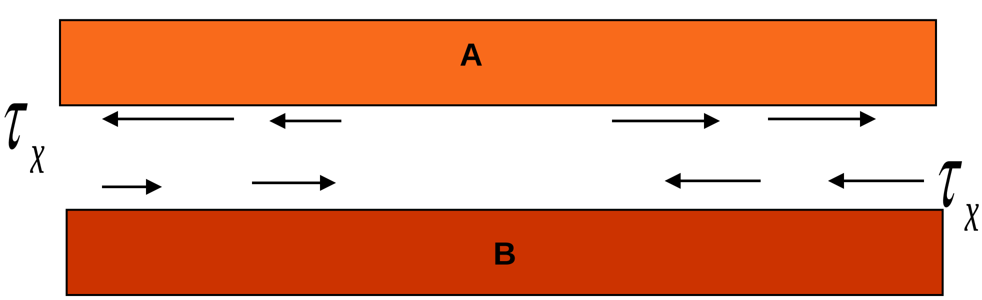
$\Delta L_A = \Delta L_B$

Therefore:

$$\tau_\chi = \Delta T(\alpha_B - \alpha_A)\, E_A\, (t_A / L)/(1 + (t_A E_A / t_B E_B))$$

This is the sole stress resulting from an unrestrained thermal expansion

e.g.:Reflow,T 260 test



OBSERVATIONS

Physical interpretation of stress equation

- **Scale factor: t_A /L**
- **Thick copper or laminate aggravates delamination**

$$\tau = \Delta T(\alpha_B - \alpha_A)\, E_A\, (t_A / L)/(1+(t_A E_A / t_B E_B))$$

QUALITATIVE COMPARISON OF ADHESION TEST METHODS

Candidates

- Peel test
- T 260 test
- A shear lap joint

Topics to be discussed

- Details of the test method
- Historical background
- Advantages/Disadvantages

CURRENT ADHESION TEST METHODS

Peel Test

- Defined in IPC 650
- Normally performed on an Instron Universal testing machine
- Sample composed of copper foil laminated to a substrate
- Copper is peeled from substrate and force measured

T260

- Defined in IPC 650
- Test normally performed on a TMA
- Test sample similar to Peel Test vehicle or a portion of a PCB
- Sample is quickly heated to 260^{o}C and the time to delamination recorded

PEEL STRENGTH

Advantages

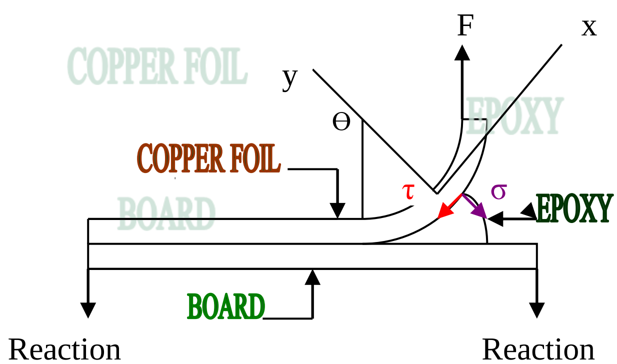
- Traditional measurement
- Present technique of choice
- Historical data base

Liabilities

- Results not always consistent with practice
- Results vary with copper thickness & peel rate
- Test method is not associated with a thermal event

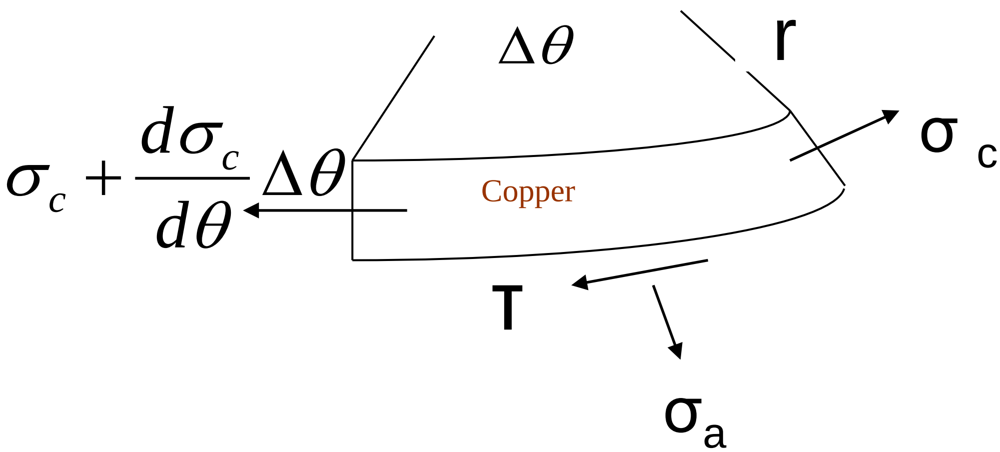
STRESS ANALYSIS
PEEL STRENGTH

PEEL TEST



F
x
COPPER FOIL
y
EPOXY
θ
COPPER FOIL
τ
σ
EPOXY
BOARD
BOARD
Reaction
Reaction

FREE BODY DIAGRAM



SUMMING FORCES ON FREEBODY

Sum of stresses in the transverse direction

$$\sigma_a = \sigma_c \frac{t}{r}$$

Sum of stresses in the radial direction

$$\tau_a = -\frac{d\sigma_c}{d\theta}\frac{t}{r}$$

Conservation of strain at the copper adhesive boundary

$$\tau_a = e_c G = \sigma_c \frac{G}{E_c}$$

STRESS VECTORS

Copper tensile stress

$$\sigma_c = \left(\frac{F}{A}\right) \exp\left[(\theta - \pi/2)\frac{G}{E_c}\frac{r}{t}\right]$$

Epoxy shear stress

$$\tau_a = \left(\frac{G}{E_c}\right)\left(\frac{F}{A}\right) \exp\left[(\theta - \pi/2)\frac{G}{E_c}\frac{r}{t}\right]$$

Epoxy tensile stress

$$\sigma_a = \frac{t}{r}\left(\frac{F}{A}\right) \exp\left[(\theta - \pi/2)\frac{G}{E_c}\frac{r}{t}\right]$$

Where

- A is the cross sectional area of the copper
- F is the applied force

MAGNITUDE OF TENSILE STRESS

Ratio of adhesive stresses

$$\frac{\tau_a}{\sigma_a} = \frac{G}{E_c}\frac{r}{t}$$

$$\frac{G}{E_c} = O\left(10^{-3}\right)$$

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

Consequently

$$\tau_a O \sigma_a$$

OBSERVATIONS
PEEL TEST

- **Stress field composed of a shear and tensile component**
- **Shear component and tensile component are of the same order of magnitude**
- **Rupture force is skewed to the plane of rupture**
- **Rupture force is very sensitive to radius of curvature at point of contact**
- **Radius of curvature is uncontrolled**

OBSERVATIONS
T 260

- Simulates stress field caused by a thermal event
- Is dependent upon test vehicle layer count and size
- Index of failure is an indirect measurement of adhesion strength

T 260 TEST

Advantages

- Test method is associated with a thermal event

LIABILITIES

- Very little historical data

CURRENT ADHESION TEST METHODS

COMMON ISSUES

- There is currently no analytical justification for either test method

- The induced stress fields are not commonly understood

CRITIQUE
OF
TEST ADHESION TEST METHODS

T 260

- Simulates stress field caused by delamination
- Results correlate with field experience
- Results sensitive to coupon size
- Test can be preformed on PCB structure
- Indirect performance index

Peel Test

- Poor simulation of delamination stress field
- Results often contrary to field experience
- Test usually performed on unique coupon
- Direct performance index

CONCLUSIONS

- Very poor agreement between test methods
- Increasing peel strength appears to produce poor T 260 results
- The correlation between the two techniques is negative

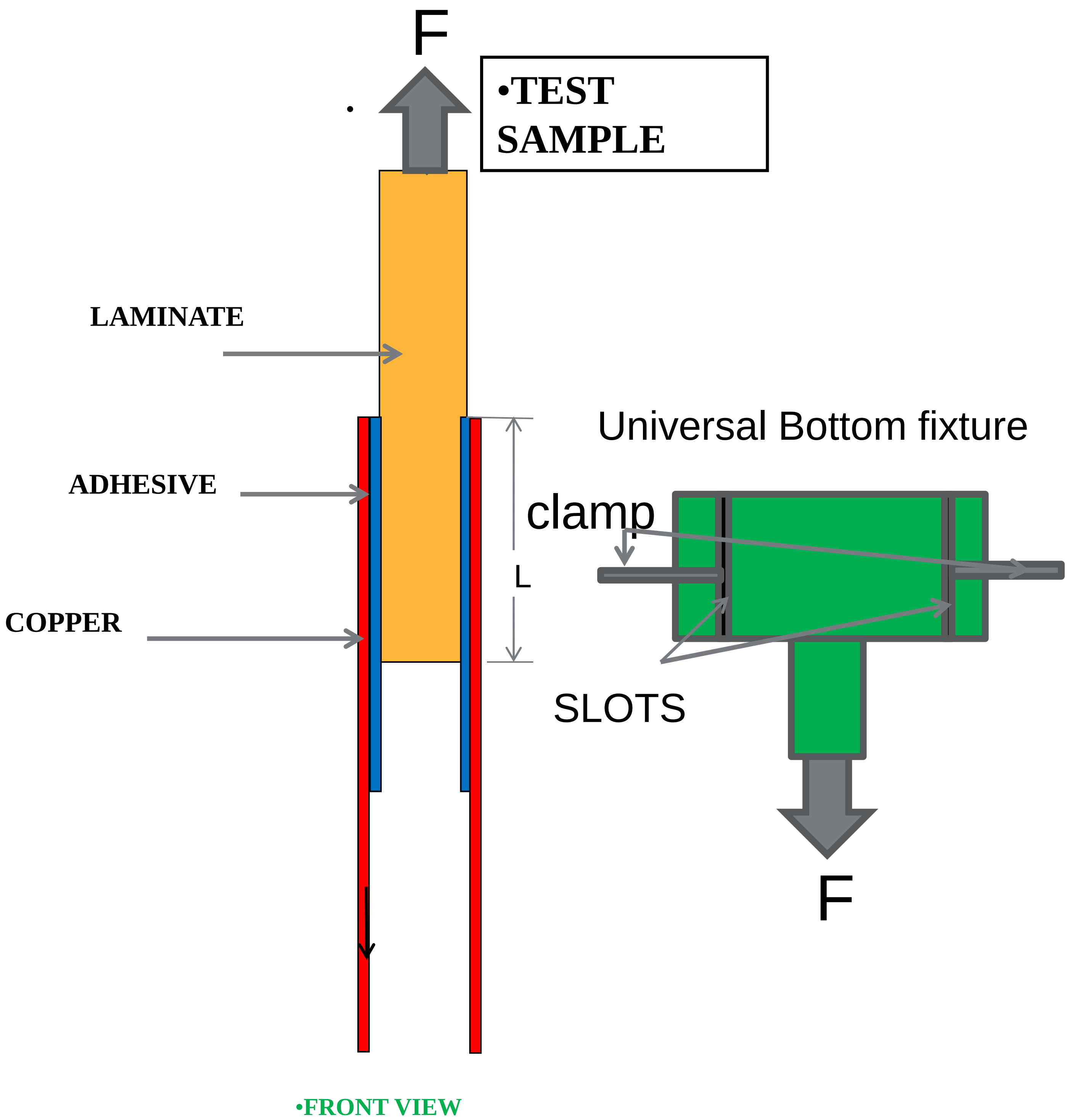
Conclusion:

- The physical mechanisms measured by these tests must be different
- An explanation is essential before either test can be justified
- A stress analysis of both test methods is required to explain discrepancies

THE LAP JOINT ADHESION TEST

- **The adhesion joint is in shear, <u>only</u>**
- **The test coupon is composed of five members bonded together**
- **Test sample is composed of two material members**
  - Normally copper and laminate
  - Or laminate to laminate
- **Test is performed on Instron**
- **Both strain and stress can be measured**
- **A simple special universal fixture is required to interface between lower jaw of the instron and test sample**

Adhesion Lap Joint Test Sample



ADHESION AND STRESS CALCULATIONS

The strain generated by this test is;

$\varepsilon = \Delta L/L$

where ε is the stress

ΔL is elongation

L is the length of the bond

The stress generated by this test is

$\tau = F/(2LR)$

where F is the applied force

R is the depth of the bond

SUMMARY

- **Both the Peel Test and the T260 Test have serious drawbacks**
- **The Lap Joint Test avoids these issues by**
  - Placing the adhesive joint in pure shear
  - Directly measuring the adhesive strength
  - An elevated temperature environment can be created

THANK YOU