Lead Free Processing and other Thermal Challenges for Flexible Printed Circuits

John Coonrod, David Guo, Carlos Barton, Duane Mahnke
Rogers Corporation

ABSTRACT
In this paper, factors that influence the ability for a flex circuit, especially a multilayer flex circuit, to survive the lead-free soldering and other thermal processes during the circuit fabrication processes will be discussed. Results and discussion will be given to demonstrate that the main factors that determine the robustness of a multilayer flex circuit to survive lead-free soldering include: (a) the intrinsic thermal stability of the flex circuit materials used to build the circuit; (b) the multilayer construction of the circuit and related processes making it; and (c) the design of the circuit patterns.

INTRODUCTION
There are several issues that influence the ability for a flex circuit to survive lead-free soldering and other thermal processes. Most of the current cell phone circuits are multilayer and by the nature of the air-gap design, they require multiple lamination cycles. Many flex circuit adhesive systems, are not thermally robust after multiple laminations and have difficulty passing the lead-free soldering requirements.

Through the development of Rogers new Halogen Free flexible circuit adhesive system (R/flex JADE, hereafter called RJ), there have been many lessons learned in regards to adhesive performance with multiple lamination cycles and elevated temperature exposures. Some ideas held to be true in the past are now debatable, such as the effect of moisture and peel strength on thermal performance.

RESULTS AND DISCUSSION
(1) Material Thermal Stability
The first major factor that determines whether a flex circuit can be robust in surviving lead-free soldering processes is the intrinsic thermal stability of the materials used to build the circuit. A typical air-gap multilayer circuit normally contains following materials: copper clad laminates, adhesive bonding films, and adhesive based cover films. In such a multilayer circuit, the inner layer adhesive bonding films and cover films are normally the weak link in regards to thermal stabilities at elevated temperatures. If the adhesive layers are not thermally stable, degradation can take place under lead-free solder conditions to generate volatiles, which in turn can cause delamination.

During our development of a halogen free and lead-free soldering capable epoxy based adhesive system, significant amount of work was performed to understand the thermal stability of the resin systems and the testing methods.

In our study, one way to evaluate the thermal stability of an adhesive system is to measure the weight loss of the adhesive resins during heating by using a TGA. Figure 1 show TGA weight loss results of a new halogen free adhesive from Rogers (RJ) and two other commercial products (RC, KH). The data show that when heating from room temperature to 500°C at a rate of 10°C/min in air, both KH and RC had much more weight loss than RJ, and the weight loss started at temperatures much lower than 288°C. The weight loss is caused by volatiles generated by degradation of the resin components in the adhesive. Such volatiles can lead to delamination during soldering. In this TGA, RJ shows the best thermal stability of the three samples tested.

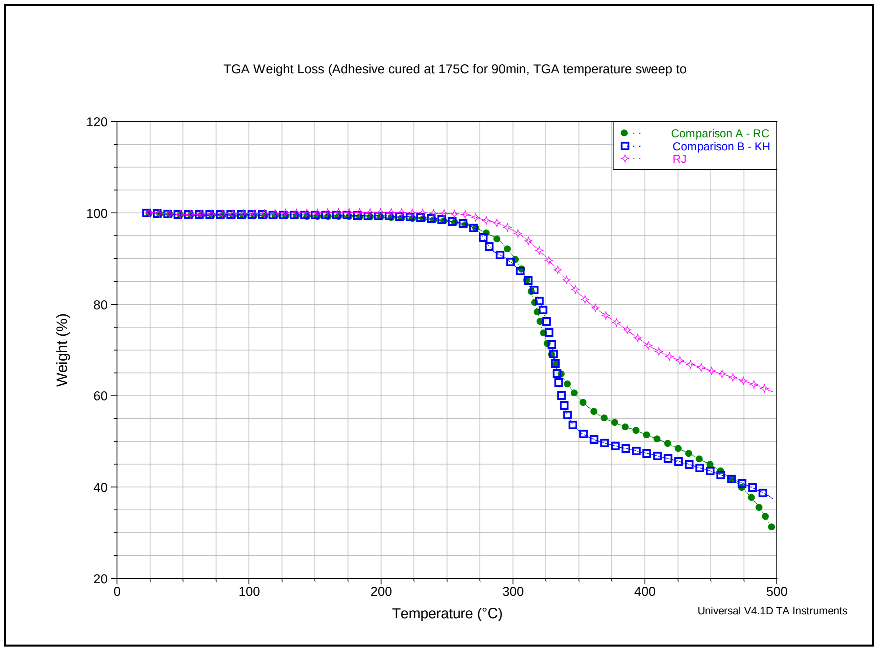


Figure 1 - TGA Wt Loss During Heating of Different Adhesive Systems

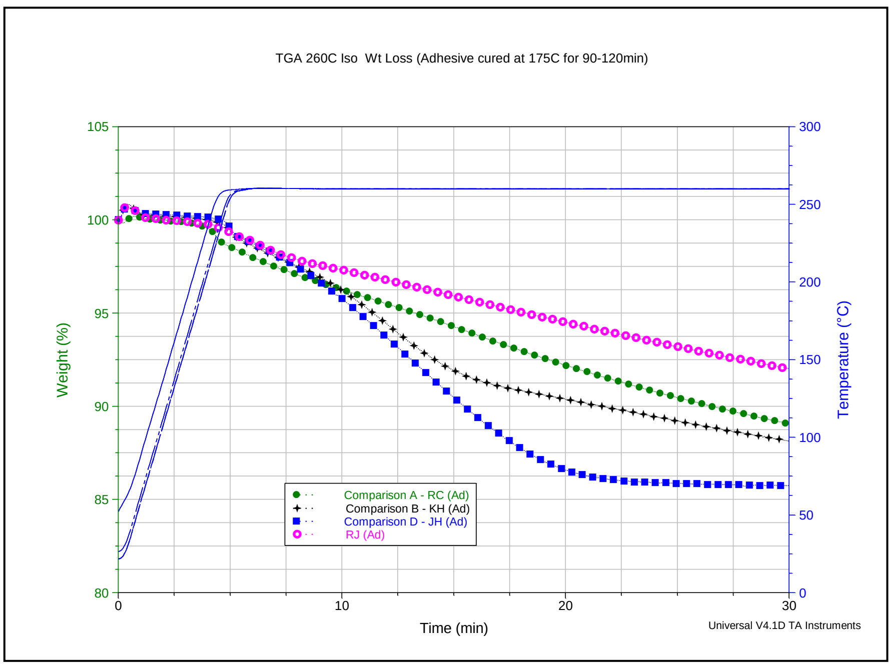


Figure 2 - TGA Wt Loss at 260°C of Different Adhesive Systems

Another test used in our study to evaluate thermal stability of an adhesive system is to measure its weight loss when the TGA temperature is held at 260°C for an extended time, which is the peak temperature of the typical lead-free solder reflow profile. The test is run normally in air. Less weight loss in such a test normally suggests better stability. Figure 2 shows weight loss results of several commercial adhesive based products, where RJ is a new halogen free and lead-free capable adhesive system. Again, the results show that RJ is the best thermally stable product among these four products.

Also in this work, thermal stability of adhesive based double-sided copper clad laminates were evaluated by using a TMA. The test was performed by putting a double sided laminate in the TMA furnace, as shown in Figure 3. The temperature was quickly increased to 288C, and then held there for an extended time. This test is called T-288 test. If a sample exhibits a significant dimensional change during the test, it indicates that the sample delaminates due to poor thermal stability.

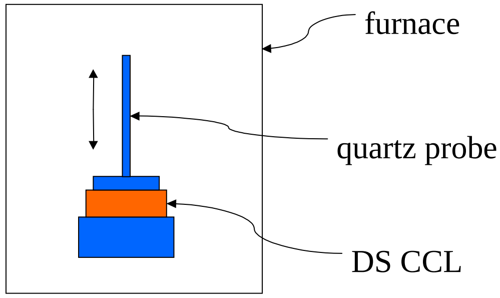


Figure 3 - TMA probe and sample setup in the furnace.

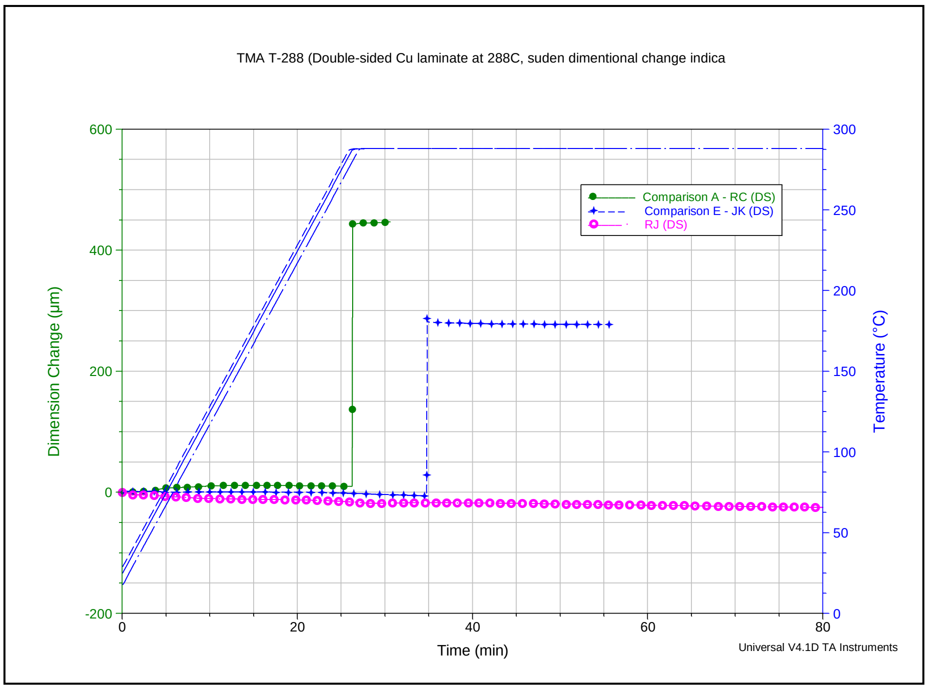


Figure 4 - TMA T-288 Test Results of Different Adhesive Based Double sided Cu Clad Samples

Figure 4 shows T-288 results of several commercial products. As shown by the data, there was no delamination taken place during the T-288 test for the RJ sample. It should be expected that this material will perform well and survive long times in 288C solder float test as well in a lead-free soldering process.

Solder float tests were conducted to compare two of the above tested samples: RC and RJ. Both were epoxy adhesive based products, while RC is brominated and RJ is halogen-free. The tests were done using double-sided laminate coupons, which had both sides copper remained and no etched patterns. This was the worse case scenario because with solid Cu plains on both sides, any volatiles generated at elevated temperatures would have no place to escape but lead to delamination. Results in Table 1 indicates that RJ is a much more thermally stable material than RC. The solder results agree with previous thermal results conducted by TGA and TMA. The results show that an adhesive resin system with high thermal stability that shows minimum weight loss at elevated temperatures will in general benefit performance in lead-free soldering.

Table 1 - 288°C Solder float results of two epoxy adhesive based double sided laminates

Sample	Time without Delamination
RC	< 2 min
RJ	> 10 min

(2) Multilayer Construction and Process Related Influence

The flex circuits that are used in the cell phone industry are typically multilayer. A recent complex hinge flex design is a 5 layer, air-gap with buried vias. There are several methods that could be used to build this circuit however a more standard process would go through 6 lamination cycles and several bake cycles. After the circuit is built, then it must also go through lead free soldering 2 times. A simplified process flow chart is shown below in Figure 5.

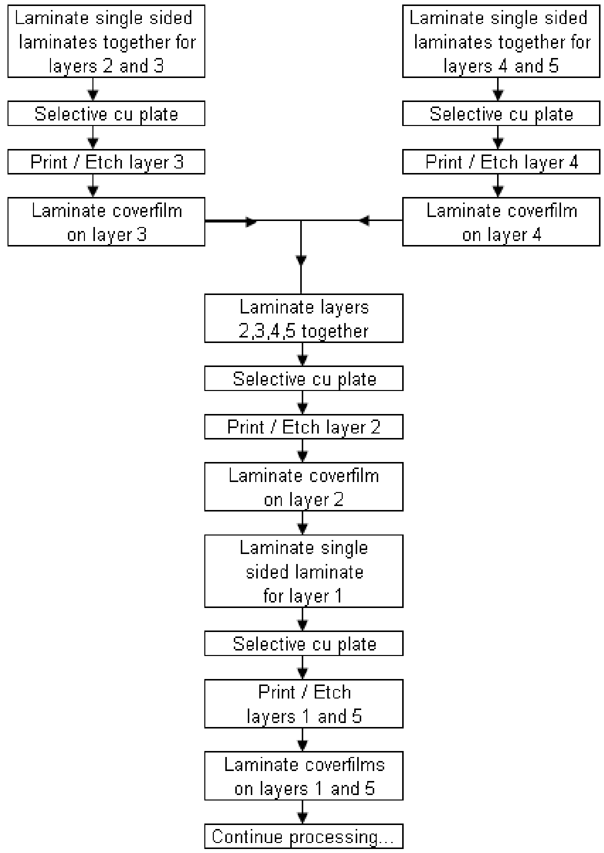
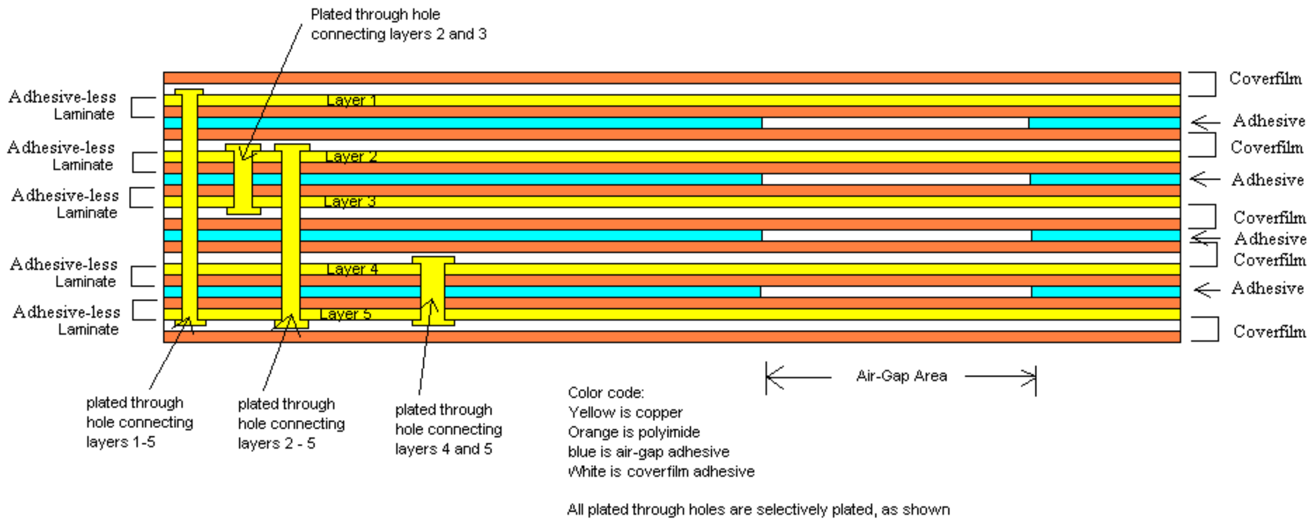


Figure 5. Simplified five layer flow chart

In Figure 6 a cross-sectional view of the 5 layer hinge flex circuit is shown.



Figures 6 - Cross-sectional view of a 5 layer cell phone hinge flex circuit

The weak interface in the flex circuit construction in regards to elevated temperature exposure is typically the adhesive – copper interface of the inner layer coverfilms. Those layers are bonded to shinny copper and they will have to endure multiple lamination cycles. The shinny rolled copper surface is very smooth, so there is little mechanical bonding at this interface. The thermal performance of some adhesive systems will degrade after just 2 or 3 lamination cycles. Data for a typical epoxy based adhesive system, RC, is shown below in Table 2. This study was done using a simple coverfilm lamination to raw shinny rolled copper. Each lamination cycle was done at 166°C (330°F) for 60 minutes.

Peel Strength (lb)

1st lamination	2nd Lamination	3rd Lamination	4th Lamination	5th Lamination	6th Lamination	
9.8	9.6	9.2	7.5	7	6.5	
	2.04%	6.12%	23.47%	28.57%	33.67%	< percent decrease

Time to failure at 288C (seconds)

28	23	12	3	<3	<3

Table 2 - Multiple laminations using a modified epoxy adhesive

Although the solder resistance degraded very rapidly, it is interesting to note that the peel strength remained relatively good. The percentage change was significant, however the minimum value of 6.5 lb is still considered acceptable.

In addition to the multiple lamination cycles there are often several bake cycles. The baking can be to cure a legend ink, soldermask or prior to a soldering operation. These bake cycles can also influence the ability for the adhesive to withstand elevated temperature exposures. There is also the possibility of circuit fabrication chemistries being entrapped within the flex circuit and later volatilizing at elevated temperatures. The last area of processing where elevated temperatures are encountered is the solder reflow process. A typical solder reflow process is shown in Figure 7.

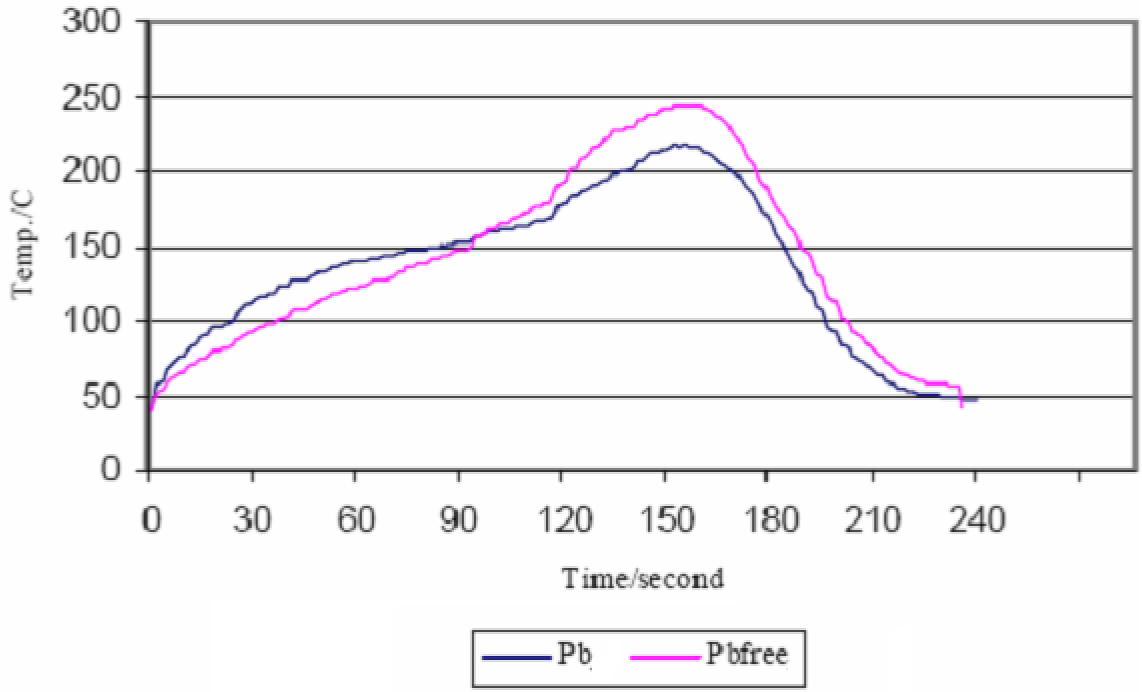


Figure 7 - Typical Solder Reflow part temperature Profile for Eutectic (Pb) and Lead Free solder (Pbfree)
In flex circuit evaluations, the circuit will often be exposed to multiple exposures to the lead free process or multiple solder float exposures. Some fabricators will want the finished circuit to endure 5 repetitions through the lead free solder process, without any signs of degradation. Other fabricators will perform solder float tests at 260°C. The solder float will typically be done for 10 seconds and repeated 3 to 5 times.

(2) Circuit Pattern Design and Its Influence

Another major influence in the thermal robustness of the flex circuit is the circuit construction and design. A circuit pattern with large copper planes will be more problematic for high temperature exposures. This has been well known in the flex circuit industry for years and many times the large copper areas will have a crosshatched pattern to minimize this concern. A worse case scenario for design would be a multilayer with large copper planes aligned directly in the z-axis. A crosshatched ground plane is shown in Figure 8. The ground plane is the top plane and it is possible to see the conductors on the plane just beneath.

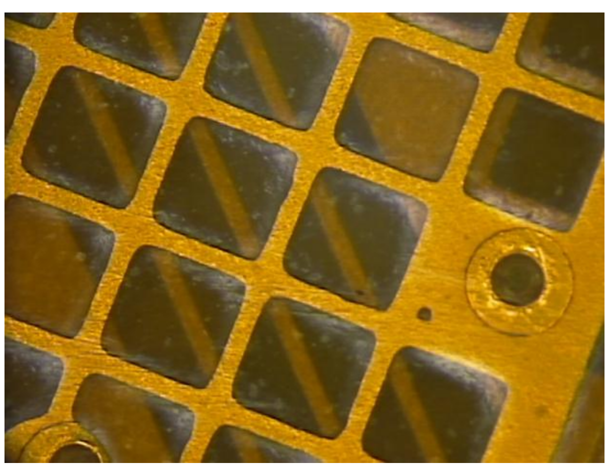


Figure 8 - Crosshatched ground plane

In this work, experiments were performed to investigate the effects of circuit designs and pre-solder conditions to the solder resistances of a variety of flex circuit materials. Table 3 shows a matrix of the study and the results. One of the major contributors to delamination during solder exposure is the test vehicle design and construction. As an example, the chart in

Table 3 shows a variety of testing done on several different materials with no circuit image. These were adhesive based laminates, some single sided and other double sided copper laminates. The double-sided laminates proved to be less robust for thermal exposures. It should be here pointed out that the new halogen-free and lead-free adhesive system was not included in this matrix. However, a different study (Table 1) demonstrated that the double-sided laminate based on this adhesive survived 288°C solder for more than 10 minutes without failing (delamination and blistering).

There are some amounts of volatiles trying to escape during solder reflow and solder float testing. These volatiles could be from related to moisture absorption, processing chemistry or degradation of the adhesive. The double-sided laminates will have copper that is entrapping the polyimide and adhesive layers, which will limit the diffusion of these volatiles during the solder exposure. A similar analogy can be given to a multilayer circuit with large copper planes.

			135°C 1 hour									21°C/50% RH 24 hours									85°C/85% RH 24 hours							
TEMP	Seconds		1	2	3	4	5	6	7	8		1	2	3	4	5	6	7	8		1	2	3	4	5	6	7	8
260ºC																												
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	60						C		C							C		C							C		C	
	90						C		C							C		C							C		C	
	120						C		C							C		C							C		C	
	240						C		C							C		C							C		C	
	360						C		C							C		C							C		C	

Table 3 - Solder float testing of various laminates with different pre-conditioning

Material ID #	Adhesive Type	Polyimide Type	Double Sided ?
1	Phenolic Butyral	HN	N
2	Phenolic Butyral	ACPI	N
3	Modified Acrylic	NP	N
4	Modified Acrylic	NP	Y
5	Modified Epoxy	AV	N
6	Modified Epoxy	AV	Y
7	Modified Epoxy	NP	N
8	Modified Epoxy	NP	Y

CONCLUSIONS

There are many factors that influence the ability for a flex circuit, especially a multilayer flex circuit, to survive the lead-free soldering and other thermal processes during the circuit fabrication processes. The thermal stability of the adhesive system used in the circuit plays an important role. In general, an adhesive system with high thermal stability normally will benefit the robustness of the resulting circuits to survive soldering. However, this robustness is also strongly influenced by the multilayer construction, and the thermal processes related to build the multilayer circuits, such as multiple baking and lamination cycles. To a certain degree, the curing characteristics of an adhesive system are closely related to these thermal exposures. Finally, the soldering performance of a multilayer circuit is strongly related to the conductor patterns of the circuit. A circuit with overlap large solid conductor planes is least robust in a soldering process.

Lead Free Processing and other Thermal Challenges for Flexible Printed Circuits

John Coonrod, David Guo, Carlos Barton, Duane Mahnke
Rogers Corporation

Presented by: John Coonrod

Lead Free Processing and other Thermal Challenges for Flexible Printed Circuits

- Intrinsic thermal stability of flex materials
- Multilayer flex constructions and relating processing
- The effects of the circuit pattern

Lead Free Processing and other Thermal Challenges for Flexible Printed Circuits

- Intrinsic thermal stability of flex materials

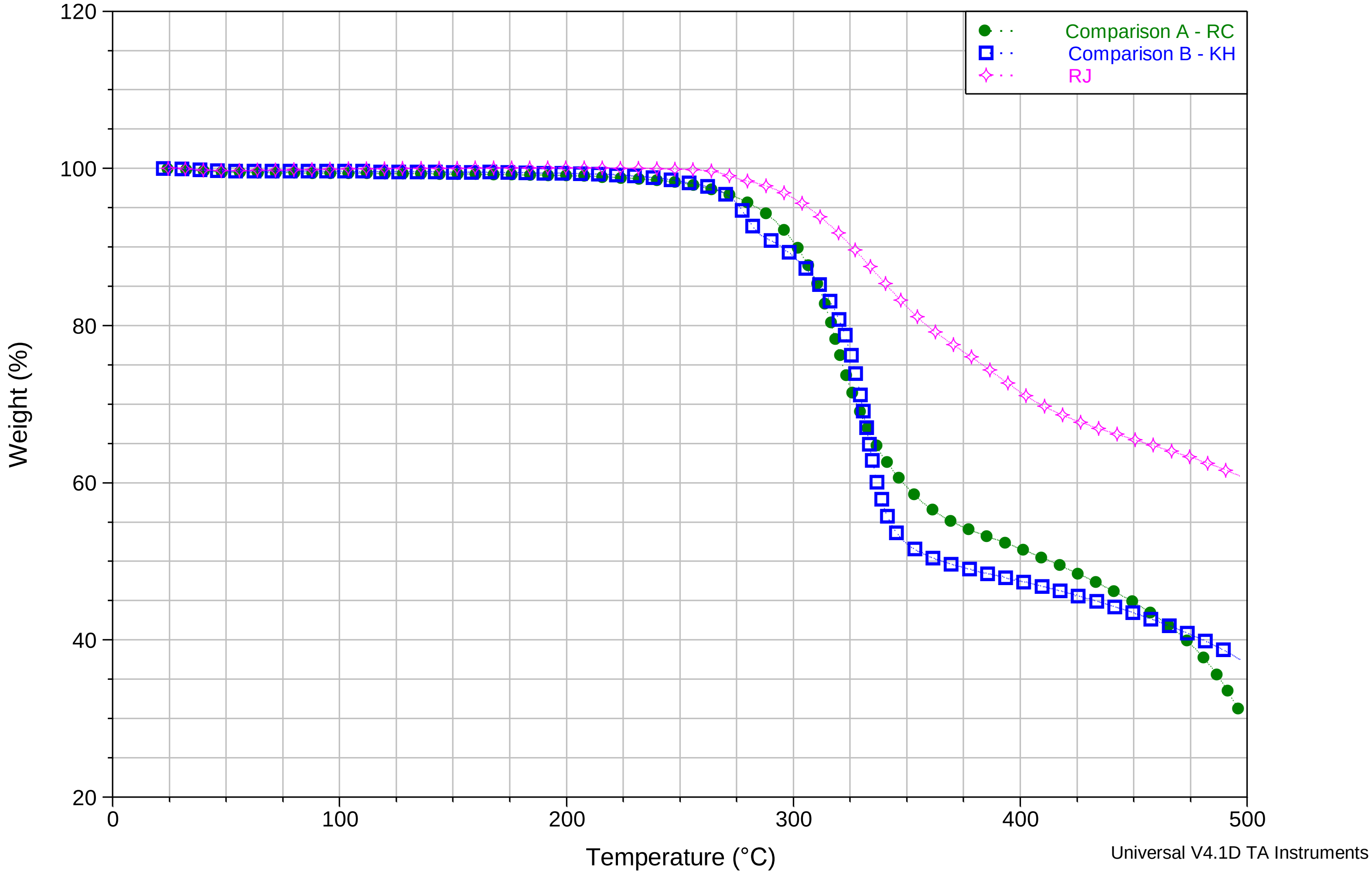
    - Many issues related to flex materials / circuits having good thermal performance; surviving lead-free soldering, multilayer processing, etc.
    - Many new flex designs are multilayer, air-gap designs
    - The circuit fabrication can degrade the thermal stability of some flex adhesive systems
    - Some intrinsic properties of flex materials make them more or less susceptible to thermal degradation
    - Many lessons learned in developing a new Rogers Halogen Free flex adhesive system, R/flex JADE
    - Materials used to make a flex:
        - copper clad laminates, adhesive bonding film, coverfilm
    - Weak link for thermal stability is typically inner layer bonding film and coverfilms

Lead Free Processing and other Thermal Challenges for Flexible Printed Circuits

- Intrinsic thermal stability of flex materials
  - During the development of our new adhesive system (RJ), work was done to understand resin systems stability and testing methodology
    - TGA was used to understand weight loss during heating
    - TMA was used to understand delamination at 288°C
    - Solder float testing at 288°C
    - Other well established commercially available flex adhesives were used for comparison
    - Double sided adhesive based laminates were used, with no copper etched off for TMA
    - Comparisons of pre-conditioning single and double sided laminates were done using 288°C Solder Float testing

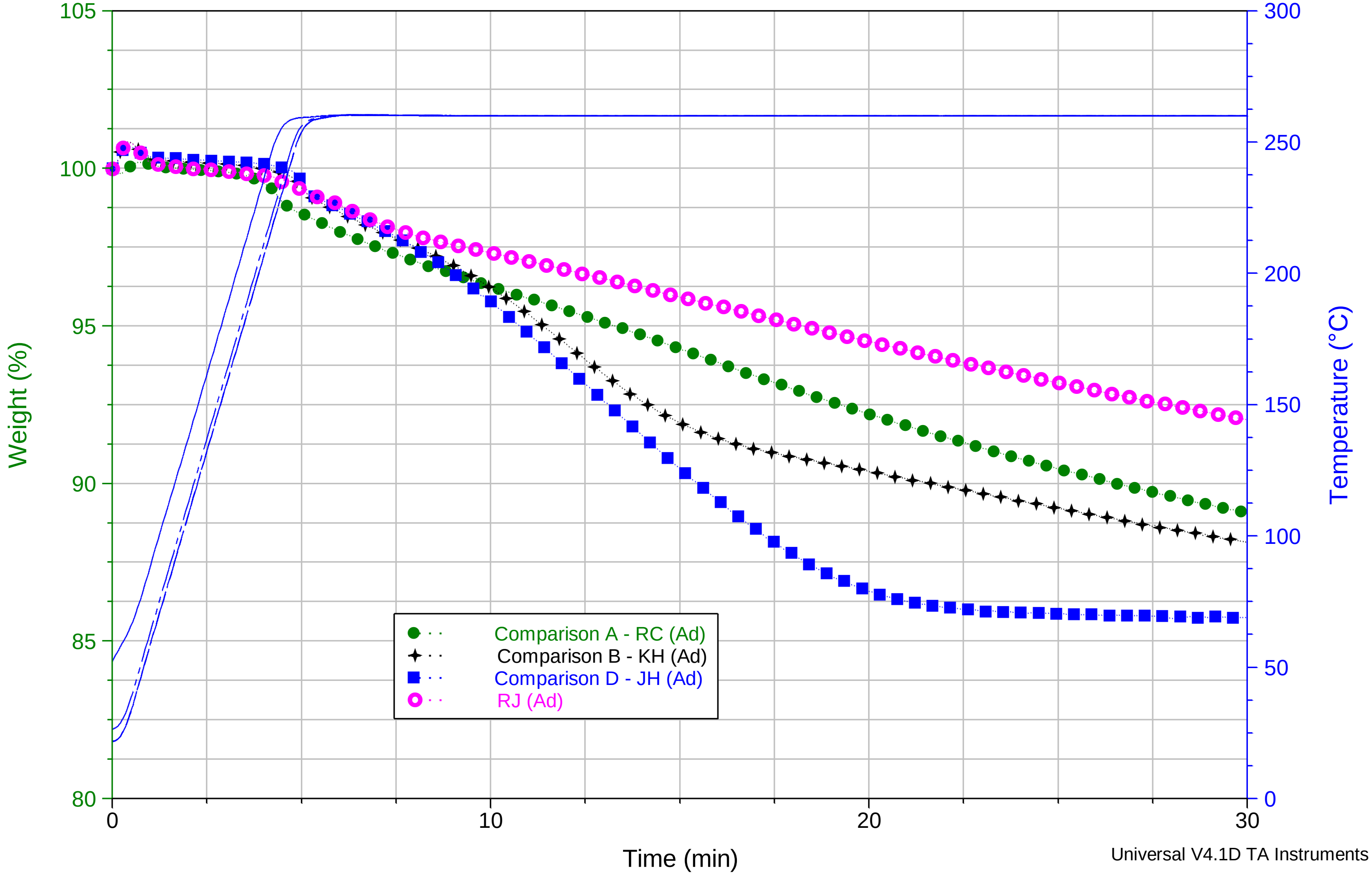
Lead Free Processing and other Thermal Challenges for Flexible Printed Circuits

- Intrinsic thermal stability of flex materials
  - TGA Weight Loss (adhesive cured at 175°°C for 90 min.), sweep to 500°C



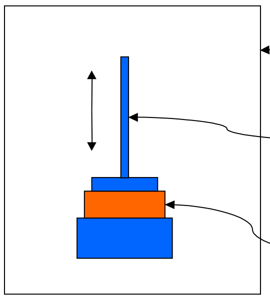
Lead Free Processing and other Thermal Challenges for Flexible Printed Circuits

- Intrinsic thermal stability of flex materials
  - TGA Weight Loss (adhesive cured at 175C for 90 min.), held at 260°C



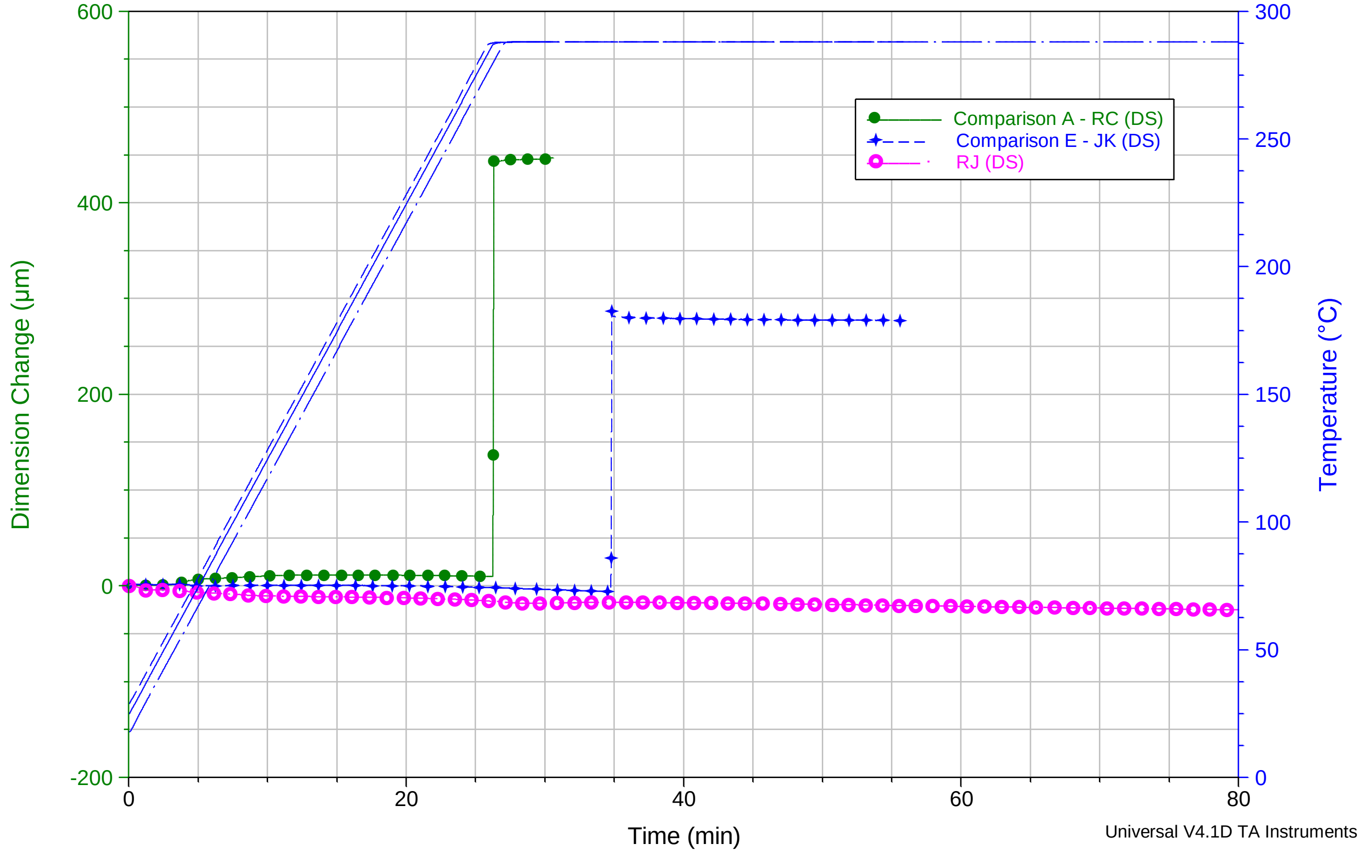
Lead Free Processing and other Thermal Challenges for Flexible Printed Circuits

- Intrinsic thermal stability of flex materials



DS CCL – Double Sided Copper Clad Laminate, no copper removed

- TMA T-288, Sudden Dimensional change indicates delamination



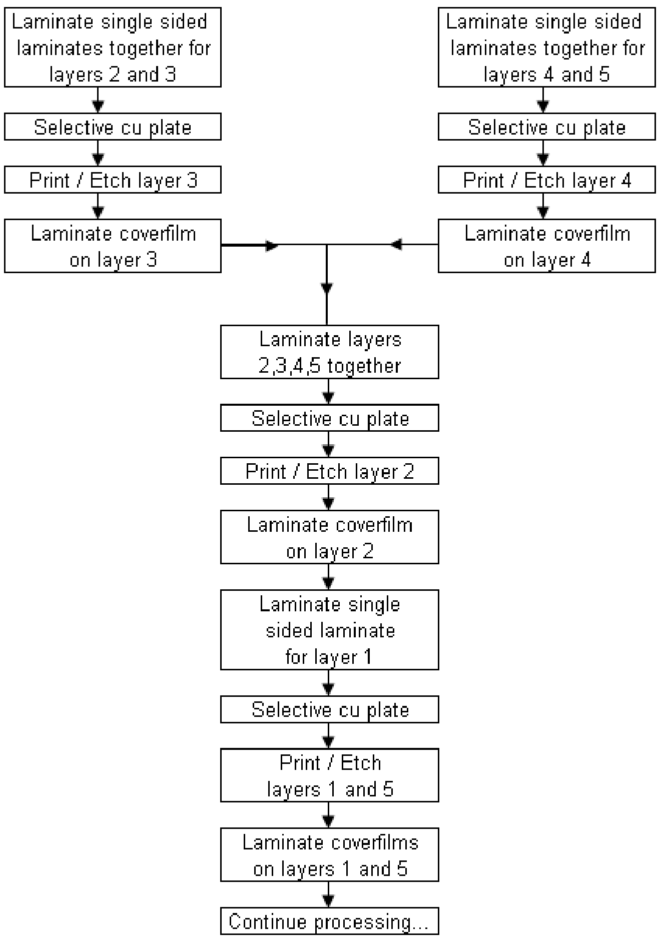
Lead Free Processing and other Thermal Challenges for Flexible Printed Circuits

- Intrinsic thermal stability of flex materials
    - 288°C Solder Float testing, DS CCL

Sample	Time without Delamination
RC	< 2 min
RJ	> 10 min

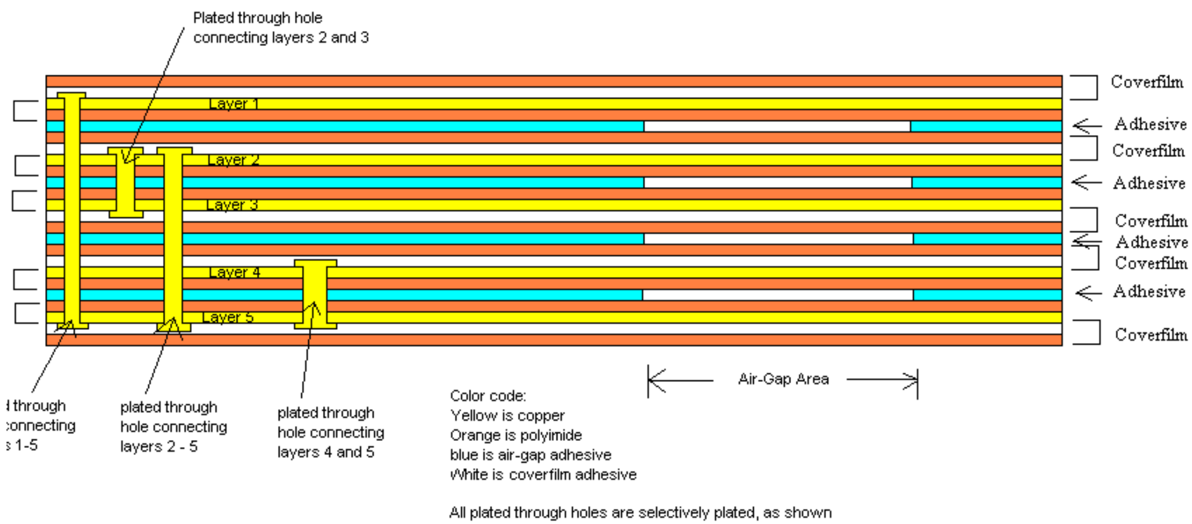
Lead Free Processing and other Thermal Challenges for Flexible Printed Circuits

- Multilayer flex constructions and relating processing
  - Example of a 5 layer, air-gap, buried via, large volume flex circuit



Simplified Fabrication Flow Chart

Depending on Fabrication methods, the inner layer coverfilms may go through 5 lamination cycles



Cross-sectional View

Lead Free Processing and other Thermal Challenges for Flexible Printed Circuits

- Multilayer flex constructions and relating processing
  - Multiple lamination cycles may degrade some adhesive systems thermal stability
  - After the multiple lamination cycles there are commonly more bake cycles and other thermal exposures
  - After fabricating the 5 layer circuit shown, then it must be able to survive going through a lead-free soldering 2 times
  - A beta site evaluation using the 5 layer, buried via, air-gap circuit:
    - A standard well established modified epoxy based system (RC) had low yields prior to lead-free soldering and didn’t survive the 2nd pass
    - Rogers newly developed halogen free (thermally stable) adhesive system (RJ):
      - Had excellent yields prior to lead-free soldering
      - Passed lead-free soldering 2X
      - Same circuits passing lead-free for 2x then passed 10 minutes at 288°C solder float

Lead Free Processing and other Thermal Challenges for Flexible Printed Circuits

- Multilayer flex constructions and relating processing
  - A well established commercially available epoxy based system (RC) has data shown below for the effects of multiple lamination cycles

Peel Strength (lb)

1st lamination	2nd Lamination	3rd Lamination	4th Lamination	5th Lamination	6th Lamination	
9.8	9.6	9.2	7.5	7	6.5	
	2.04%	6.12%	23.47%	28.57%	33.67%	< percent decrease

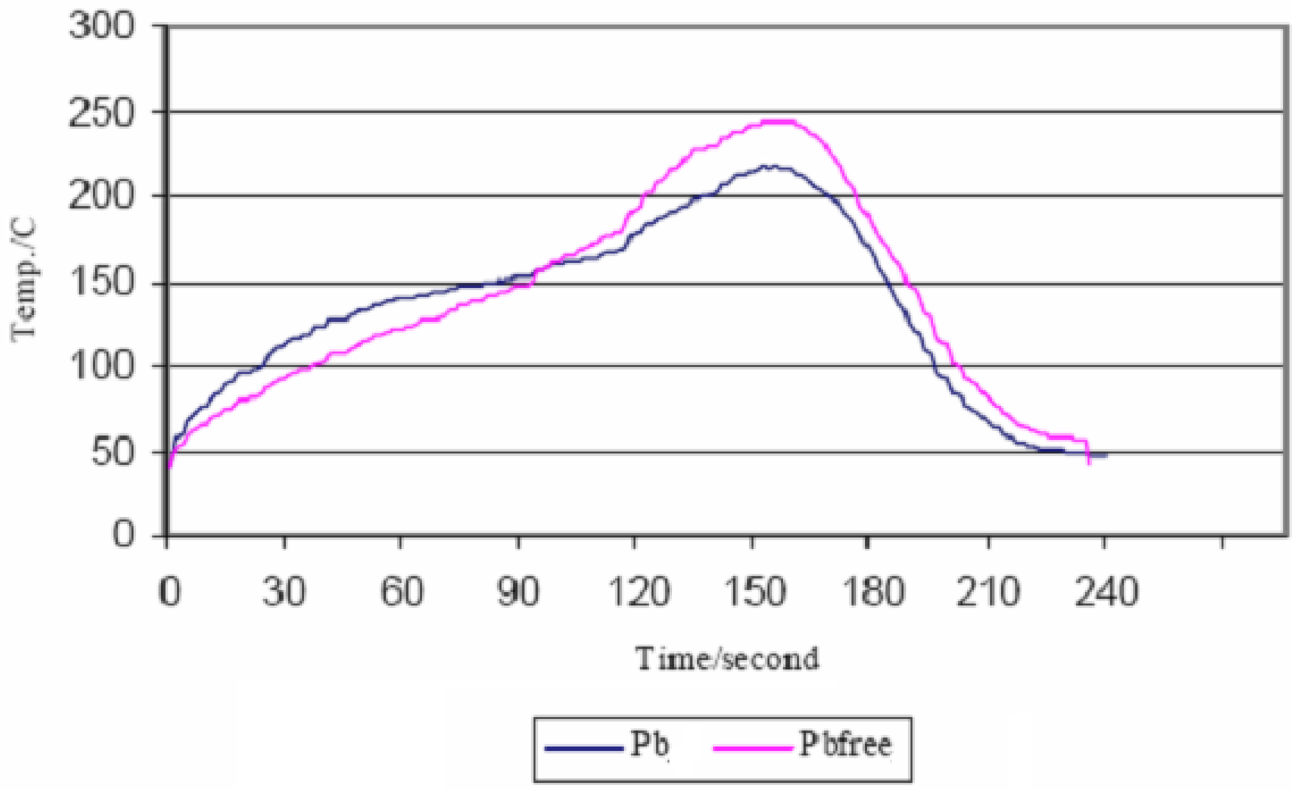
Time to failure at 288C (seconds)

28	23	12	3	<3	<3

  - Interesting to note that the peel strength degradation was not as pronounced as the thermal stability

Lead Free Processing and other Thermal Challenges for Flexible Printed Circuits

- Multilayer flex constructions and relating processing
    - After the multiple laminations and fabrication processes, the circuits will need to survive two lead-free soldering passes.
    - Typical part temperature profile of Eutectic (Pb) and Lead-Free (Pbfree) soldering process



Lead Free Processing and other Thermal Challenges for Flexible Printed Circuits

- Multilayer flex constructions and relating processing
  - In the evaluation process of a new circuit design and / or flex materials fabricators will often require the circuit to pass:
    - Lead-free soldering 3 to 5 times
    - Solder float at 260°C for 10 seconds for 3 to 5 times

- The effects of the circuit pattern
  - Large copper planes more problematic
  - Buried large copper planes in a multilayer are very problematic
  - Buried coverfilms on large copper planes in a multilayer are worse case

Lead Free Processing and other Thermal Challenges for Flexible Printed Circuits

- The effects of the circuit pattern
  - Laminate testing of single sided vs. double sided, adhesive base laminate

			135°C 1 hour									21°C/50%RH 24 hours									85°C/85%RH 24 hours							
TEMP	Seconds		1	2	3	4	5	6	7	8		1	2	3	4	5	6	7	8		1	2	3	4	5	6	7	8
260°C																												
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	60						C		C							C		C							C		C	
	90						C		C							C		C							C		C	
	120						C		C							C		C							C		C	
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4	Modified Acrylic	NP	Y
5	Modified Epoxy	AV	N
6	Modified Epoxy	AV	Y
7	Modified Epoxy	NP	N
8	Modified Epoxy	NP	Y

All copper clad laminates had no copper removed

- Adhesive type had little effect
- Pre conditioning had some minor effect
- Major influence is single sided copper clad vs. double side copper clad

Lead Free Processing and other Thermal Challenges for Flexible Printed Circuits

- Conclusions
  - Thermal stability of the adhesive plays an important role in the ability for the circuit to withstand lead-free soldering and other thermal processes
  - Adhesives with good thermal stability will have better yields through elevated temperature processes
  - Circuit construction plays an important role
  - The circuit design / construction interaction plays a very important role
  - Degree of adhesive cure can be a significant factor for thermal stability
  - Peel strength is not a major contributor
  - Pre-conditioning has some influence, however not a major contributor