JJMIE
Volume 10 Number 4, December.2016
ISSN 1995-6665
Pages 271-277
Jordan Journal of Mechanical and Industrial Engineering

Pad Cratering: Reliability of Assembly Level and Joint Level

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Received July, 24, 2016 *Accepted October, 24, 2016*

Abstract

The emergence of pad cratering has become an increasingly common failure mode for electronics manufacturing due to the transition to lead –free soldering. This phenomenon has become one of the first concerns between manufacturers of electronic equipment devices and other high reliability products who have focused on the failure in testing, handling or transport due to a single overload. Moreover, the number of manufacturers of servers and other electronic products report an early failure by pad cratering in thermal cycling, an occurrence practically unnoticed for SnPb soldered assemblies. There are many factors that affect pad robustness, including but not limited to design (pad size, solder mask, connecting trace, vias), stackup (resin content, glass style), resin material (filler, cure type). Preconditioning also has a significant effect on the long term reliability.

The aim of the present study is to evaluate several laminate materials with respect to pad pull strength, using accepted industry testing methods. Several different design variables, such as resin filler, resin content, fiber glass reinforcement and fabrication process, were studied. Data are presented to show the effects of the above, and to highlight the long term risk associated with latent damage mechanisms.

Keywords: *Epoxy Matrix, Composites, Various Ratios of Particles, TiC*.

1. Introduction

Pad cratering is one of the most problems that occurs in lead-free solder joints, the conversion from using tin-lead solder joint to lead-free soldering has raised many assembly and reliability issues in this field, the most prevalent one is the increased propensity for pad cratering on laminates through lead free soldering process or even right after reflow. The transition to lead free assembly comes to comply with the widely enacted environmental legislation which restricted the use of Hazardous Substances; this directive was adopted by the European Union in 2003 and took effect in 2006.This transition caused high requirement for the use of laminate materials with high glass transition temperature capable of withstanding higher temperature for Printed Wiring Boards (PWBs) and components substrates (Lee, 2006) but the use of these laminate materials are more liable to a mode of failure known as pad cratering (Mattila TT., 2006; Farris A., 2008; Newman, 2008; Vickers N., 2008).

Pad cratering is a crack initiation that occurs during the manufacturing process and propagates during work-service beneath the pad copper connection which occurs within the resin region which consequently leads to ripping off the contact pad from the laminate (the solder ball, the pad and with some ruptured material are lifted together) which is known as cratering (Mukadam M, 2005) as shown in Figure 1. This has been associated with stiffer solder joint and higher flexural modulus and hardness for the laminate included in the lead-free system (Long G, 2007). Furthermore, an increase of laminate hardness may occur in higher processing temperatures (Mukadam M., 2005; Shade F. G., 2006).

Figure 1. Pad cratering Failure mode

The most important characteristic of pad cratering is that cracks occur underneath pad copper and traces. This failure mode is getting an important issue after some stress tests, such as functional test, in-circuit test and mechanical assembly. The separation of the connecting pad from the

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circuit board leads to electrical failure and other issues that drastically decrease reliability. Therefore, efforts are continuously exerted to study cratering issues for a large number of electronic industries, but the majority of these efforts is completely empirical and based on the explanation of test outcomes and some failure analysis. Researches are still conducting to mitigate pad cratering. Under the conditions of high load-low cycle Jonnalagadda and Qi (Jonnalagadda K, 2005) conducted a study on pad cratering failures while Geng and McAllister (Geng P, 2005) focused on shock loads by one or two drops producing a failure of pad cratering mode. With different laminates the trends and behavior vary strongly, for example, the laminate which used lead-free had lower pad strength than a DICY-crude laminate (Mukadam M, 2005). On the other hand, the effect of temperature on pad strength for some materials was not significant (Ahmad M., 2009; Ahmad M., 2008), while for other materials an increase in temperature has a significant effect on both strengths and fatigue resistance in which both strengths and fatigue resistance decreased significantly (J., 2007; Roggeman B. R. V., 2011; Raghavan, 2010). A study conducted by Yang *et al*. (2010) for pad cratering resistance found that multiple reflows for printed Wiring Boards (PWBs) subjected to different thermal conditions tend to reduce pad strength, also the study had shown the significant impact of peak temperature on the pad strength resistance. Studies for various materials with multiple reflow showed a decrease in pad strength (J., 2007; M. Ahmad J. B., 2009; Roggeman*et al*., 2008; G., 2009). On other hand, a study by Parupalli*et al.* (2008) showed that the effect of multiple reflows did not have a significant effect on pad strength. Other studies showed a significant degradation in fatigue resistance with multiple reflows (J., 2007; Roggeman*et al*., 2008; Godbole G., 2009).

The resin system, filler particles, glass type, pad size and shape are factors make pad cratering a complex problem in which pad cratering is highly dependent on these factors (Roggeman*et al*., 2008; M. Ahmad J. B., 2009)**.** Furthermore, the prediction of pad cratering is much highly difficult due to complex interactions with a multiple degradation mechanismsthat work in conjunction (Roggeman*et al*., 2008). In addition**,** test results showed forstandard FR-4 boards tested for micro-hardness an increasing hardness for the case of as received, post eutectic reflow and post lead free reflow. These results have indicated that an increase in hardness dose not essentially interprets to an increase in the strength but dose inevitably translate to an increase of board brittleness making it more sensitive to pad cratering(Mukadam M, 2005)**.**

Crack initiation occurs for several reasons, these includes that the lead free solder balls are in general more stiffer than tin lead solder balls, so as a result of that they can transfer strain to the Printed Circuit Board (PCB), also the Phenolic-cured PCB materials that in general is used in lead free assemblies are more brittle than the conventional Dicy-cured materials, those two factors coupled together with the high reflow temperature that the lead free assemblies are subjected could lead to higher strain in the assemblies and consequently lead to crack initiation (Ahmad M., 2009.)**.**

The loading condition will also have an impact on the failure mode. Handheld and portable devices are much more likely to experience impact loading from dropping and other handling issues. The high strain rates associated with this type of loading apply more stress onto the connecting pads.

Many test methods have been made to characterize pad cratering and showed that pad performance and position of pads relative to underlying glass bundles are related (Roggeman*et al.*, May 27-30; Roggeman*et al*., 2008; M. Ahmad J. B., 2009; Ahmad M., 2008; D. Xie, May 27-30, 2008).

2. Test Methodology

Testing the resistance to pad cratering can be done as a board level test or joint level test. However, because of some of the inherent differences between two level tests that make correlation of these tests and hence the characterization significantly difficult (Roggeman*et al.*, 2008). In general, engineers rely on joint level testing because they are looking for easier and cheaper way of testing. As described by Roggeman*et al.* (2008), board level tests will give a more complete picture of the reliability of the system in that given scenario, but they are slow, costly and require full assembly and this requires several assemblies to develop good statistics. Some test methods, such as drop, vibration and bend testing, are the most employed methods for board level testing.Table.1 further details the investigation with sample numbers.

Table 1. Materials Characterized (Pad strength benchmarking)

Number	Material	Pad Size	Resin Percentage %	Filled / Unfilled	Process
1	IT 180-1	0.01756 in	0.53	Unfilled	Standard
2	IT 180A-1 B	0.01738 in	0.53	Filled	Advance
3	IT 180-2 B	0.0171 in	0.74	Unfilled	Advance
4	IT 180A-2 B	0.01708 in	0.74	Filled	Advance
5	IT 180-1-	0.01712 in	0.53	Unfilled	Advance
6	IT 180-2	0.01756 in	0.74	Unfilled	Standard
7	IT 180A-1	0.01764 in	0.53	Filled	Standard
8	IT 180A-2	0.01728 in	0.74	Filled	Standard

2.1. Joint Level Test

Joint level test requires only a few pads to gain a good understanding of the strength and fatigue resistance, therefore the number of circuit boards required is very small. In most cases, a single board can be used for several different pad test procedures. Individual solder balls are attached to the pads of interest.A Dagebondtester is used in Hot Bump Pull (HBP) method to pull solder balls attached to Non-Solder Mask Defined (NSMD) pads.At the joint level, a 30° angle fixture using a Hot Bump Pull (HBP) cartridge and a speed of 5 mm/s were used for conducting pad strength as shown in Figure2 below.

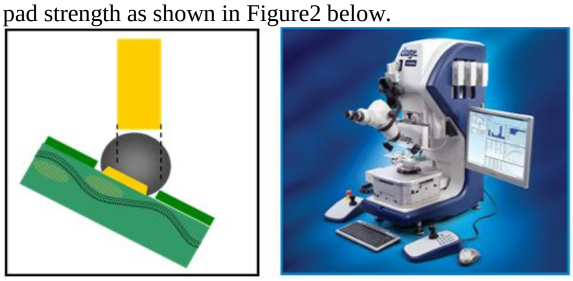

Figure 2. 30° angle at the right and Dage 4000 plus at the left

2.2. Assembly Level Test

An Instron Tensile Tester with a four-point bend fixture was used for assembly testing, the support and load span were 160mm and 76mm, respectively (Figures 3 and 4) . The test is done to determine the inflection strain which represent mechanical failure (pad cratering) for variation in filler which is used to reduce the z-axis expansion, and is predominantly used in multi-layer PCBs in high reliability applications, glass style or resin percentage which determine how thicker the PCBs, thinner glass results in higher resin content and allows easier drill for PTHs and Vias, and finally the lamination process which play a large role in PCB quality and reliability.

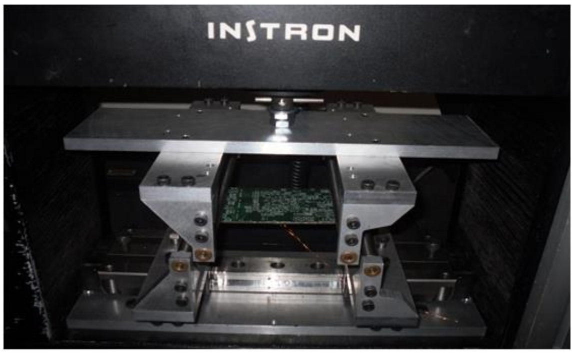

Figure 3.Instron

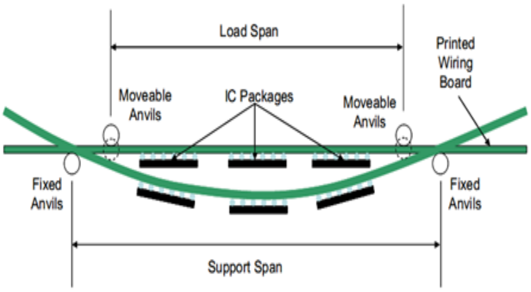

Figure 4. 4-point bending test

A target strain rate of 6000 µ-strain/second was chosen as it is a relatively high rate and is more likely to produce cracks under the pads than a lower rate.

3. Result and Discussion

Performing the test at the joint level yields faster results at cheaper cost; it can offer quantitative data on individual pads. Testing was done on the IT laminates with different design variables using the HBP test method at 30° to the substrate normal. Ten pads were tested under the test methodology for each laminate. Full factorial design has been conducted on the strength with three factors each factor with two levels and ten replicates. From the ANOVA in Table2 at 95% confidence level, it can be seen that the most significant factor is the process then the resin% and the filler is not significant, but the interaction between the filler and the process is the most significant among the main factors and their interaction as normal plot shows the thesameresults as shown in Figure 5.

Table 2. ANOVA

Source	DF	Adj SS	Adj MS	F-Value	P-Value
Model	4	1.570	0.392	25.48	0.00
Resin %	1	0.428	0.143	9.27	0.00
Filler	1	0.068	0.068	4.40	0.04
Process	1	0.271	0.271	17.56	0.00
Filler * Process	1	1.148	1.148	47.11	0.00
Error	35	0.539	0.015		
Total	39	2.109			
R-Square = 74.43%			R-Sqaure (adj) = 71.51%		

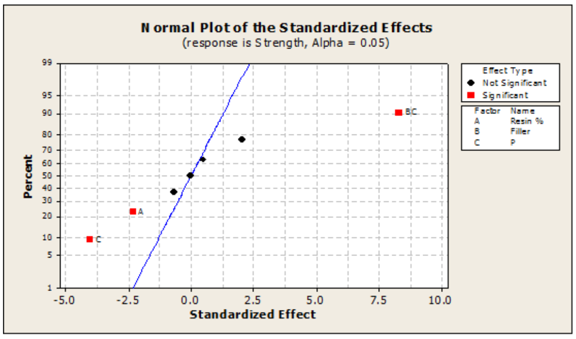

Figure 5…

Figure6 exhibits a comparison between different percentage of resin (53% Versus 74%), then a two sample t-test was conducted, the p-value (P-Value = 0.131) shows that the differences between the strengths obtained from 53% and 74% of resin is not statistically significant, but the trend shows that for 53% of resin is stronger and this is attributed to the thicker fiber glass in the laminate of 53% of resin. Another comparison is done between filled and unfilled laminate as shown in Figure 7. A t-test was conducted, the p-value (P-Value = 0.1390) shows that the differences between the strength from filled and unfilled laminate is not statistically significant, also the trend shows that for filled laminate is stronger than unfilled laminate. The presence of filler particles in laminate materials influences the pad performance. Inert filler particles inhibit the crack propagation resulting in higher fatigue resistance for filled materials as shown by Li (J., 2007) and Roggeman*et al.* (Brian, 2008). Both of them agree with the fact that though the differences in strengths of two materials that were tested are not statistically significant but the fatigue resistances are higher for the filled material.

The last comparison is done between standard and advance process in which the p-value that was resulted from t-test is P-Value = 0.243). From Figure8, it is obvious that the laminate that was manufactured by standard process is stronger than advance process. It can be seen from Figures 8, 9 and 10 that there is an increasing trend in the strength with the design variables of 53% of resin, filled laminate and standard process. However, from the two sample t-test, the p-value shows that the differences between the strength from filled versus unfilled, 53% versus 74% of resin and standard versus advanced process is not statistically significant.

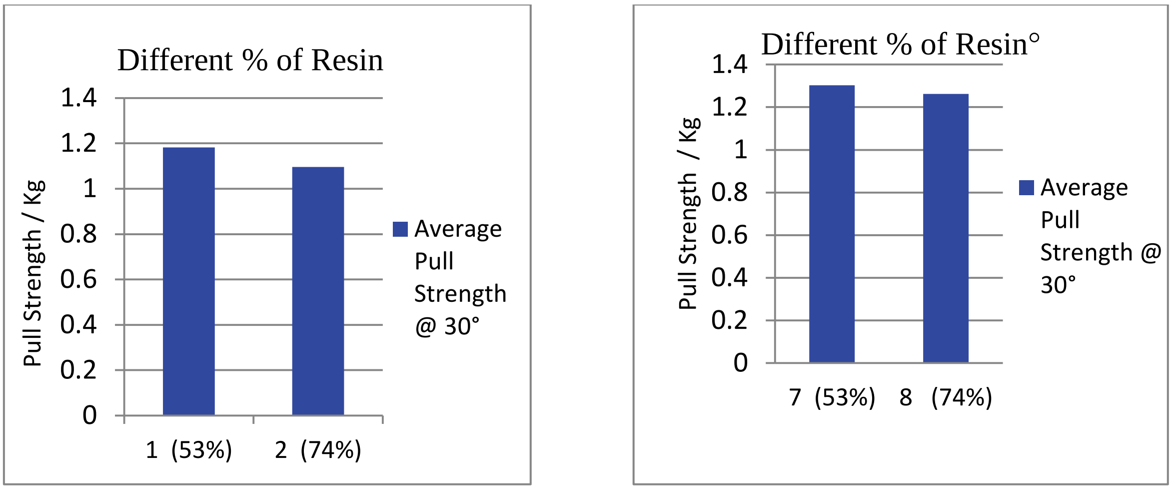

Figure 6. Comparison between different percentage of resin (for 1&2 P-Value = 0.131, for 7& 8 P-Value = 0.555)

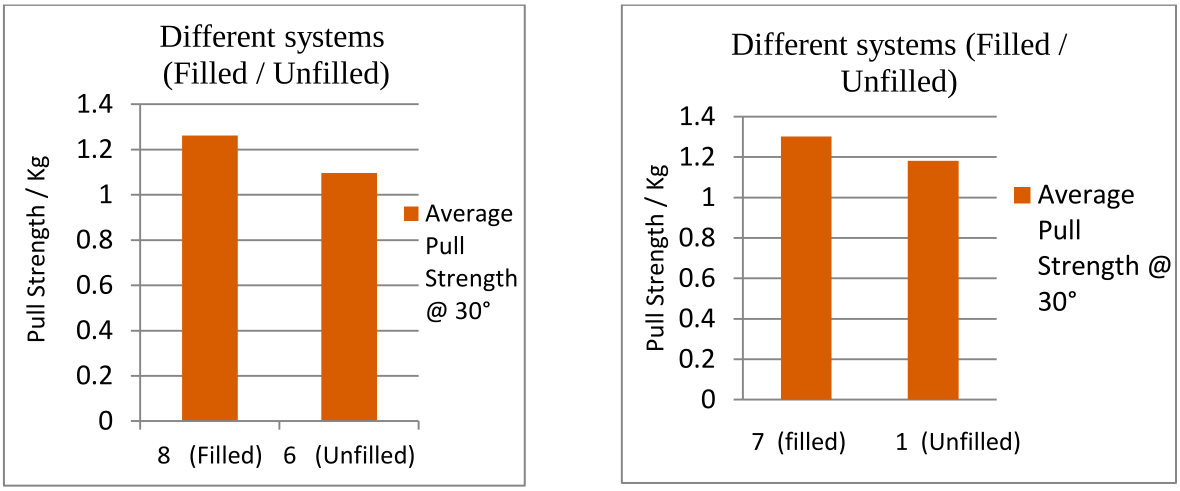

Figure 7. Comparison between different filler (for 7&1 P-Value = 0.139)

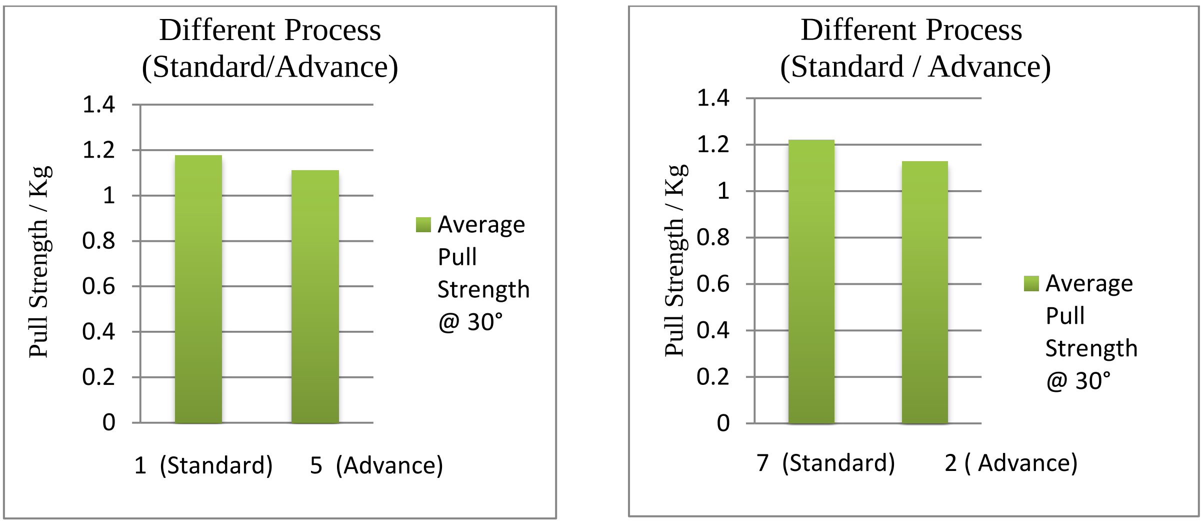

Figure 8. Comparison between different filler (for 1&5 P-Value = 0.243, for 7& 2 P-Value = 0.434)

The failure mode that was observed from the joint level test for the different design variables is a combination of adhesive and cohesive failures, with the cohesive faiure occuring within the resin and the adhesive failure ocurring at the resin-glass interface as it can be seen in Figure 9.

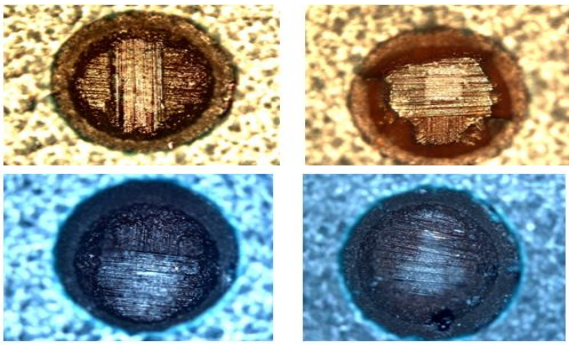

Figure 9. Failur modes top : filled at right ,unfilled at left. Bottom: process at right , advnce at left

Even though joint level testing provides for an easy method for testing, experiments need to be conducted at the assembly level, 4-point beiding test was conducted to creat board flexure using inflection stain approach which measure both PCB and component bending strain at the same time until a point at which the component is separating from the PCB where a mechanical failure will be observed. Figure10 shows the inflection stran mechanism.

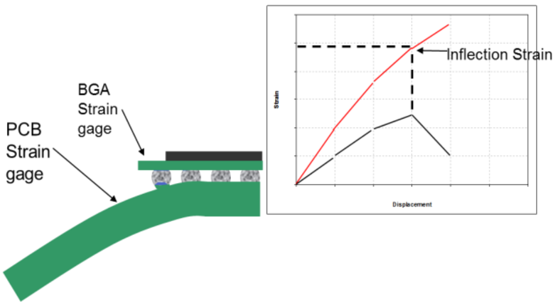

Figure 10.Inflection strain approach

Eight samples were first bent to break. The failed samples were then cross-sectioned and subjected to dye and pry to study the failure mode. The samples showed a good amount of dye penetration under the pads and the cross-sectioned samples showed cracks beneath the interconnecting pad indicating that all failures were by pad cratering. Figure 11 is one of the images that studied.

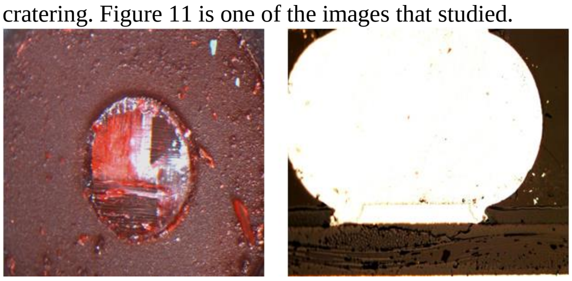

Figure 11.Right dye and pry left cross-sectioned for 1 (Unfilled)

To find the inflection strain which represents a mechanical failure (pad cratering), the data from the Instron and DASwere analyzed. A graph of six curves was drawn; the first two curves (red and blue) indicating the strain for the PCB and the other four curves indicating the strain for the component. A sudden change in the curve with respect to the time would appear as a downward in the graph, the time of occurrence of this gives the strain at which the component separate from PCB and a mechanical failure will occur which is known as pad cratering (Figures 12 and 13).

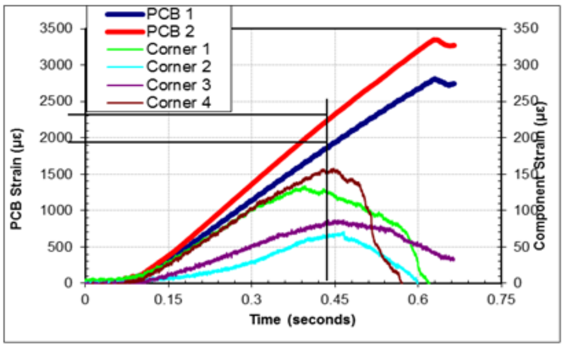

Figure 12.Inflection strain for 1 (unfilled)

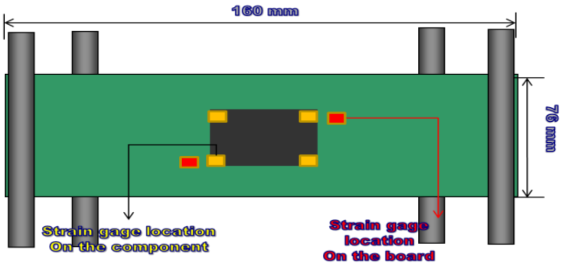

Figure 13.Test setup layout

Figure 14 shows another plot. Please keep in mind that the results for only seven assemblies were available because one of the assemblies had completely not analyzed and this is due to strain gage installation is not done perfectly. The plot shows the inflection strain for each board, it can be seen that for filled laminate and advance process is the strongest one. By comparing laminate 1 and 5 regarding process, it obvious that laminate 1 result in higher inflection strain (strong board) and the differences in the inflection strain is statistically significant at 95% confidence level since p-value=0.007, another comparison is done between laminate7 and 2 regarding the process, laminate 7 result in higher inflection strain but the differences is not statistically significant at the same confidence level since p-value=0.317, it is obvious that the standard process affects the inflection strain but to prove that it requires additional testing. Also a 53% of resin result in higher inflection strain (thicker fiber-glass) than 74% of resin by comparing laminate 7 and laminate 8, the differences between the two laminates is not statically significant since p-value= 0.71. However, by comparing laminate 1 and 6, 74% of resin result in higher inflection strain but the differences is not statistically significant since p-value =0.339. the last comparison is done between laminate 1 and 7 by comparing filled and unfilled laminate, it is clear that laminate 7 result in higher inflection strain, but the differences is not statistically significant since p-value=0.117. However, laminate 6 which is unfilled indicates higher inflection strain by comparing it with laminate 8 which is filled laminate, the differences between the inflection strain is statistically significant since p-value=0.022. So it is obvious that it requires additional testing to determine which design variable affect the inflection strain.

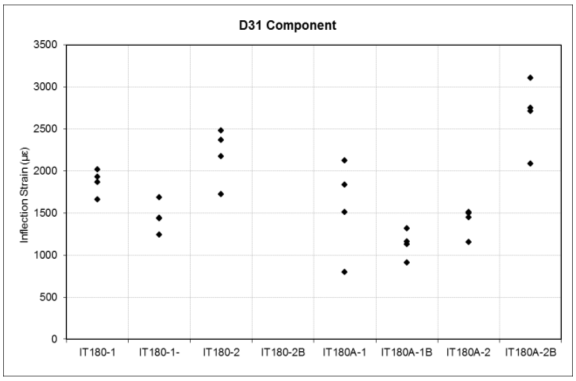

Figure 14.Inflection strain for the samples

4. Summery and Conclusion

Joint level test and assembly level test havebeen investigated here. Several key points of our observations are summarized as follows:

Jointlevel

- The filled resin is consistently stronger than unfilled, not statistically significant at 95% but requires additional testing to prove.
- Lower resin% (thicker glass) results in higher pad strength, not statistically significant at 95% but requires additional testing to prove.
- Standard process result in higher pad Strength, not statistically significant at 95% but requires additional testing to prove.

Assembly level

- Standard process result in higher inflection strain (strong board) but statistically significant at 95% for 1 & 5 but not significant for 7 & 2 requires additional testing to prove.
- Comparing 7 & 8 lower resin% result in higher inflection strain and 2 & 4 higher resin% result in higher inflection strain but requires additional testing to prove.

Failure Mode

- Failure mode for joint level is very similar to assembly level.

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