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Novel Approaches for Minimizing Pad Cratering

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Abstract
With the electronic industry moving towards lead-free assembly, traditional SnPb-compatible laminates need to be replaced with lead-free compatible laminates that can withstand the higher reflow temperature required by lead-free solders. Lead-free compatible laminates with improved heat resistance have been developed to meet this challenge but they are typically more brittle than SnPb laminates causing some to be more susceptible to pad cratering. In this paper, two novel approaches for minimizing pad cratering will be discussed. Preliminary results which validate the two approaches will also be presented.

Introduction
Pad cratering is defined as laminate fracturing that may occur under the Cu pads of a surface mount component. Typically, the fracture initiates within the laminate during a dynamic mechanical event. The initial crack propagates in the laminate under external stress and eventually into adjacent Cu conducting lines, resulting in an electrical open circuit. (The term "pad cratering" has been widely adopted for this defect since the extent of fracturing may be sufficient in severe cases for the pad to be pulled from the laminate during normal processing leaving a crater.) Though not a common issue, pad cratering is more often experienced in lead-free assemblies than in those using SnPb solder due to the use of different laminate materials and has been extensively studied in the electronic industry [1-8]. Identified mitigation approaches are based upon either reducing the stress on the laminate or using a stronger and more pad cratering resistant material.

Several methods have been used to reduce stress on the laminate, including increasing the effective pad size through use of solder mask defined pads, corner glue on the components, and strict limitations on board flexure during circuit board assembly operations such as ICT testing. The idea is that, with reduced stress on the laminate, pad cratering will be minimized or its onset significantly delayed.

The second approach is to use laminates with improved pad cratering resistance. Increasing the strength and pad cratering resistance of the laminate material has proved difficult and very little progress has been achieved in this regard with the most popular epoxy based lead-free laminates. Polyimide has higher pad cratering resistance than epoxy based laminates due to its higher intrinsic strength and can be used for mitigating pad cratering. However, polyimide is more expensive and difficult to process compared to the widely used epoxy based laminates. As a compromise, polyimide has been used as the external layer (in the form of Zeta™ Cap) for minimizing pad cratering in epoxy-based laminates [9]. The hybrid structure formed by using epoxy laminate as inner layers and polyimide as cap layers improves the pad cratering resistance of the board compared to boards using epoxy laminates only [10].

In this paper, we propose two approaches for mitigating pad cratering issues. The first approach uses a pad cratering resistant material for the external layers in a hybrid structure and falls into the second category of mitigation strategies (see above). The second approach is based on minimizing defects (the initiation site for pad cratering) and forms a new and third category of mitigation strategies. Some preliminary testing result will be presented to demonstrate the viability of these two approaches.

Concept 1:

Due to the higher reflow temperature required for assembly process using lead-free solder alloys than that using SnPb solder, many laminates used in SnPb assembly would suffer from delamination issues if they were used for lead-free assembly. Typically, delamination occurs within the inner layers rather than the outer layers due to the uneven stress distribution among the layers during the assembly process. Fig. 1 shows a distribution of delamination location in a 20-layer circuit board [11], where the number of samples with delamination is plotted versus the location of delamination. This distribution summarizes results for 153 samples from 32 different laminates with two different resin contents (58% and 69%) [11]. Figure 1 clearly shows that most delaminations occurred in the layers close to the center of the stack-ups.

No delamination was observed in the external layers. Due to the high propensity for inner layer delamination under lead-free assembly conditions, lead-free compatible laminates with improved heat resistance have been developed to meet this challenge. With the improved heat resistance, lead-free compatible laminates are typically also more brittle than SnPb laminates. The brittleness of lead-free compatible laminates has contributed to the increased occurrence of pad cratering in lead-free PWB assemblies.

In contrast to delamination being located within the inner layers, pad cratering occurs only on the surface layers. This difference is illustrated in Fig.2. Due to this distinct difference in the failure locations of delamination and pad cratering, it is proposed to use different laminate materials at these two locations to mitigate the two different failure mechanisms:

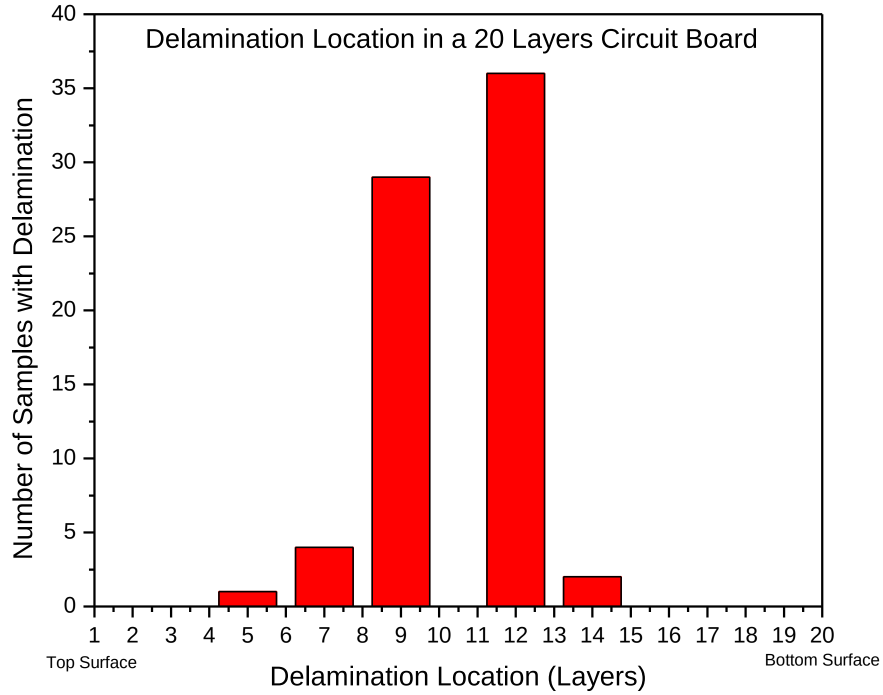


Fig.1. Distribution of delamination location in a 20 layers board

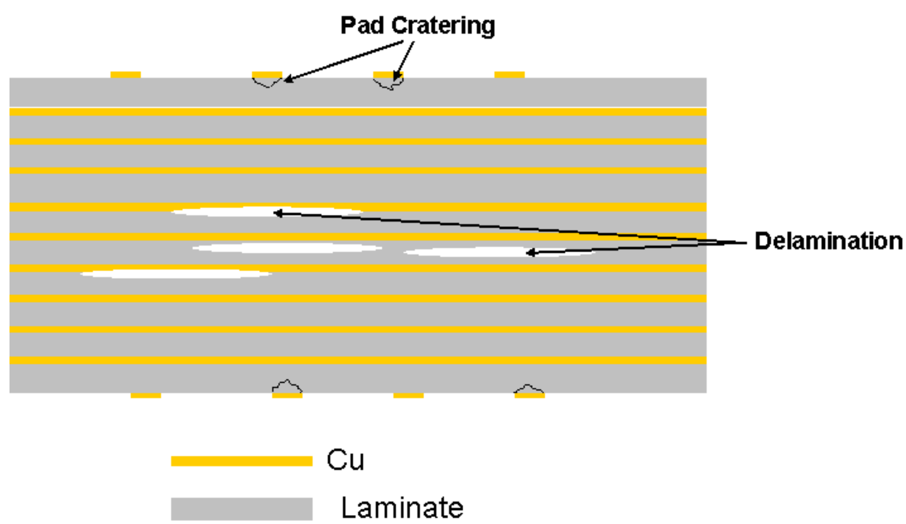


Fig.2. Illustration of typical location of delamination and pad cratering

1. Thermally stable lead-free compatible laminates, which may be prone to pad cratering, should be used in the 2 to n-1 layers of a PWB board to minimize/eliminate delamination issues during lead-free assembly.

2. Pad cratering resistant laminates, which may be susceptible to delamination during lead-free assembly, should be used for the two outer layers (1 and n layers) for preventing pad cratering.

Figure 3 illustrates the proposed new stack-up. Using this stack-up, less heat resistant but more ductile and less brittle laminates could be used as outer-layer materials for lead-free assembly to minimize pad cratering without promoting delamination.

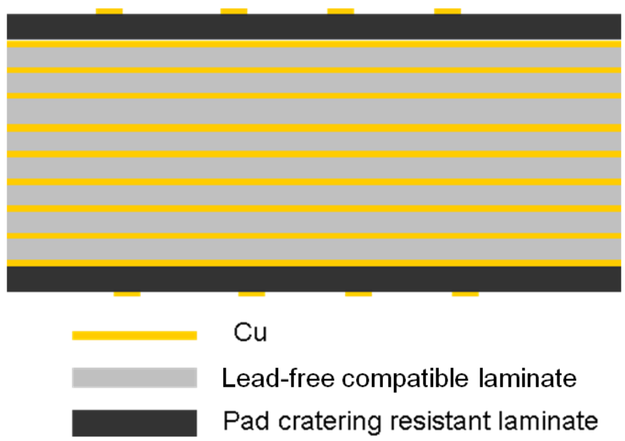


Fig.3. Proposed PWB stack-up for dealing with delamination and pad cratering issues.

There are many possible combinations for utilizing pad cratering resistant materials for the external layers and lead-free compatible materials for the inner layers. As an example of this hybrid structure, one may use dicy-cured epoxy laminate, which is generally more pad cratering resistant but prone to inner layer delamination [3], as the external layers, while phenolic-cured epoxy laminate, which is generally compatible with the lead-free assembly process but prone to pad cratering [3], may be used for the inner layers. This combination would mitigate pad cratering in the external layers and delamination in the inner layers. The other obvious advantage of this combination is that dicy-cured epoxy and phenolic-cured epoxy have very similar chemical and electrical properties and hence, unlike the polyimide and epoxy combination, do not have compatibility issues.

Concept 2:
Pad cratering is generally believed to be due to brittle fracture of the laminate under external mechanical (including thermal mechanical) stresses. The failure mechanism is governed by fracture mechanics instead of the classical mechanics of materials. Figure 4 compares classical mechanics and fracture mechanics. In classical mechanics, a material's ability to survive a stress condition is determined by the balance between applied external stress and intrinsic material properties such as yield or tensile strength. In fracture mechanics, a third parameter, physical defects, also needs to be considered in addition to the external stress and intrinsic material property. The second approach is based on the importance of defect sites in brittle fracture mechanics and attempts to minimize pad cratering by reducing the initiation sites.

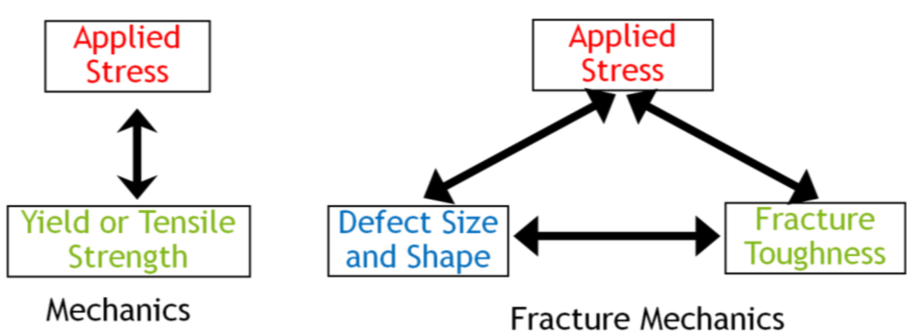
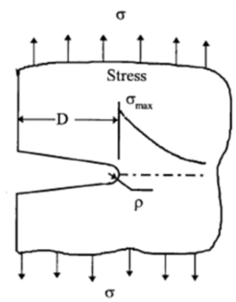


Fig.4. Mechanics vs. fracture mechanics

The presence of defects can drastically increase the stress concentration at the defect site, allowing brittle fracture to occur at much lower external stress than in a defect-free state. For instance, for a notch type of



$$K_T = \frac{\sigma_{max}}{\sigma_{nom}} = 1+2\sqrt{\frac{D}{\rho}}$$

Fig.5. Stress concentration near a notch defect

defect, the maximum stress σ_{max} at the root of the notch is related to the nominal applied external stress σ using the equation in Fig. 4, where D and ρ are the notch depth and the notch root radius, respectively [12]. Only in a defect-free state does the maximum stress σ_{max} at the root equal the applied external stress σ. Depending on the size and shape of defects, the maximum stress σ_{max} at the root can be much larger than the nominal applied external stress σ. The stress σ_{max} at the root of the notch is critical to crack propagation (brittle fracture) and allows the brittle fracture to occur at a much lower nominal applied external stress than that for a defect-free state. An everyday example of this behavior is found in the process of glass cutting. Glass is a strong but brittle material and is very susceptible to brittle fracture. The easiest way to cut a piece of glass is to first create a defect site in the glass (for instance by scratching the glass). The glass can then be easily broken along the defect site by applying a minimal stress.

In PCB fabrication, copper foils are laminated to dielectric materials (such as epoxy laminate). Due to the intrinsically weak interaction between copper and typical laminates, the chemical adhesion is rather weak between Cu foil and laminates. To improve the adhesive strength between copper foils and laminates, the copper surface is pretreated with adhesion promoters to increase chemical adhesion and also etched to form a rough surface for added mechanical adhesion. Fig. 6 illustrates the rough profile of the Cu surface at the Cu-laminate interface. When copper is removed in a print-and-etch process to form the desired printed circuit features, permanent defects due to the rough copper surface are imprinted into the laminate surface. These defect sites around the perimeter of a pad could serve as the initiation site for pad cratering and promote its occurrence. In order to determine how the copper surface roughness affects pad cratering, test vehicles were prepared with identical materials and lamination process but different copper surface roughness and were subjected to pad cratering testing.

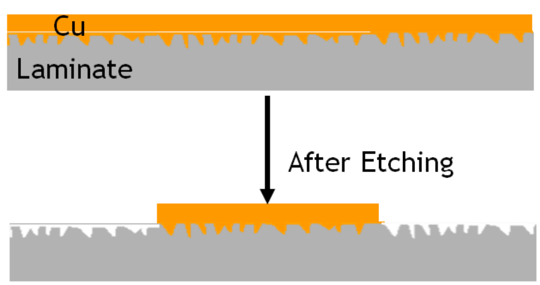


Fig. 6. Defect in the laminate surface due to rough copper surface

Experimental:

The test vehicle used for pad cratering testing, shown in Fig. 7, is a 10 layer board with 7 different sizes of non solder mask defined copper pads and with an organic solderability preservative as final finish. Results of testing on both 18 and 22 mil diameter pads are reported in this paper.

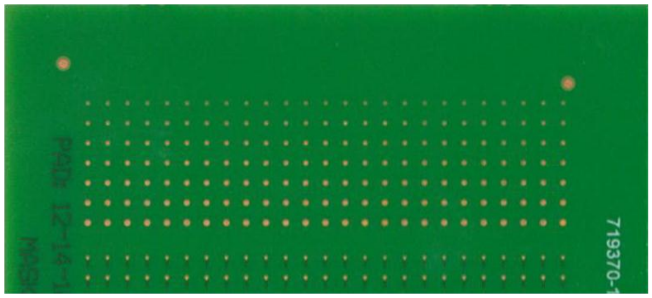


Fig.7. Test vehicle for angled Hot Bump Pull testing

The Angled Hot Bump Pull (HBP) testing of individual pads was performed with the DAGE 4000Plus bump tester shown in Figure 8. The tester is configured with a stage inclined at 30º and fitted with the Hot Bump Pull cartridge. In HBP testing, a copper pin is heated through its holder until it is soldered to the pad. The sample is then allowed to cool down to room temperature before the pin is pulled upwards for the pad cratering test.

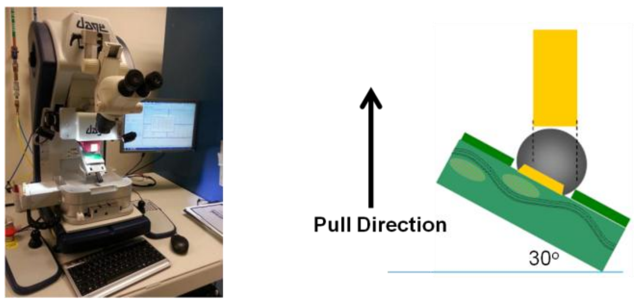


Fig.8. Setup for Angled Hot Bump Pull testing

Results and Discussion

Concept 1: Hybrid Structure for Minimizing Pad Cratering

For demonstrating the concept of using a hybrid structure to minimize pad cratering, a test vehicle was fabricated using pad cratering resistant laminate (dicy-cured epoxy) in the external layers (layers 1 and 10) and pad cratering susceptible lead-free compatible laminate (phenolic-cured epoxy) in the inner layers (layer 2 to layer 9). Test vehicles using dicy-cured epoxy alone and using phenolic-cured epoxy alone were also prepared as reference samples. Figure 9 compares 22 mil pad pull strength for the dicy+phenolic hybrid board with both the dicy board and phenolic board. Two types of failures were observed: pad cratering in the laminate and intermetallic failure in the solder joint. According to the failure mechanism, pull strength results are segregated into curves due to pad cratering (left in Figure 9) and intermetallic failure (right in Figure 9). Consistent with the previous published results in the literature [3 and 10], the dicy board (green curve) shows much higher pull strength than the phenolic board (black curve).

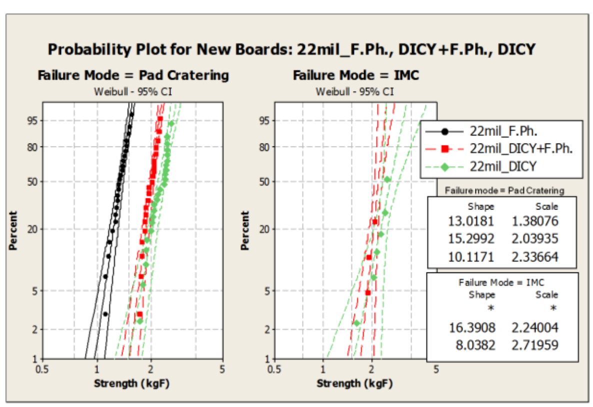


Fig.9. 22mil pad pull strength comparison between phenolic board (black), dicy board (green) and dicy+phenolic hybrid board (red). The data points are segregated according failure mechanism: pad cratering (left) and intermetallic failure (right)

All failures in the phenolic board are due to pad cratering. The high propensity for pad cratering in phenolic-cured epoxy laminates is a result of the brittle nature of highly cross-linked phenolic-cured epoxy. For the dicy board, some of the failures have shifted to intermetallic failure in the solder joint due to the higher pull strength of the dicy-cured laminate than the phenolic-cured laminate. Figure 9 clearly shows that the dicy+phenolic hybrid board (red curve) has very similar pull strength to the dicy board (green curve) and is much more pad cratering resistant than the phenolic board (black curve). Similar to the dicy board, some of the failures in the dicy+phenolic hybrid board have also shifted to intermetallic failure in the solder joint due to the high pull strength.

Similar behavior, summarized in Fig. 10, has been also observed for 18 mil pads. The phenolic board again shows only failure due to pad cratering, while the dicy board and dicy+phenolic hybrid each show one solder joint intermetallic failure. Only pull strength data associated with pad cratering are provided in Fig. 10. Consistent with the result for 22mil pads, the 18mil pad shows similar pull strength for the dicy and dicy+phenolic hybrid boards which are much more pad cratering resistant than the phenolic board.

These results clearly demonstrate that the pad cratering resistance of a board is mostly determined by the nature of the laminate used in the external layer. The type of materials used for the inner layer has little effect on the pad cratering of the multilayer board. Additional experiments are planned to determine the hybrid board’s compatibility with the typical higher temperature lead free soldering process.

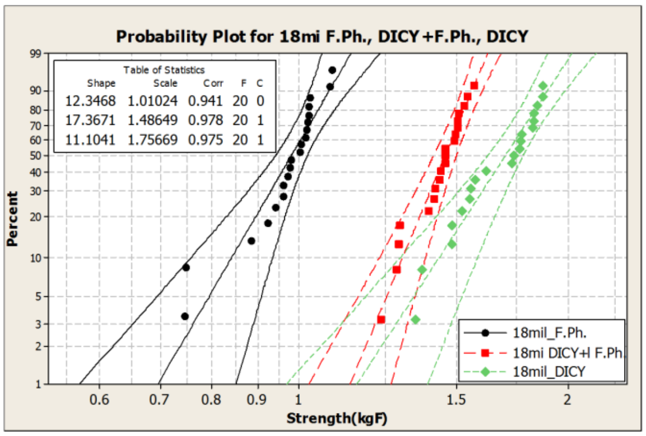


Fig.10. 18mil pad pull strength comparison between phenolic board (black), dicy board (green) and dicy+phenolic hybrid board (red).

Concept 2: Effect of Defects on Pad Cratering

Test vehicles were prepared using pad cratering prone phenolic-cured lead-free compatible laminate with two different types of copper foil: standard copper foil and the so-called “low profile” ultra smooth copper foil. Fig.11 shows cross sections of the samples fabricated with smooth and rough Cu foils. Unfortunately, both samples showed very similar copper surface roughness at the Cu-laminate interface in the cross sectional view, making the comparison between smooth and rough copper surface more difficult. However, it is assumed that a careful measurement of the surface roughness on the top side of the copper surface should still reveal a difference in the surface roughness between the two samples, although the difference may be minor.

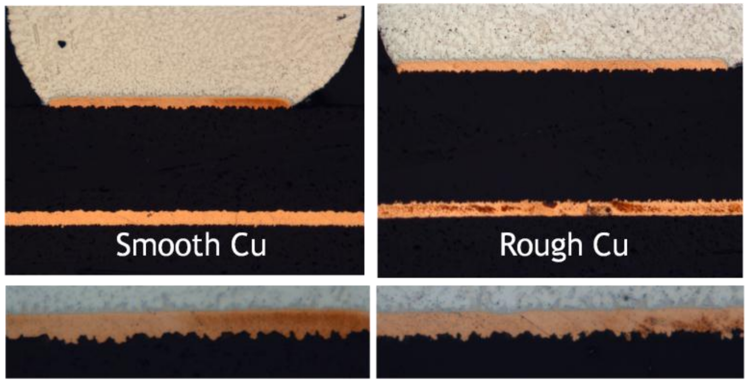


Fig.11. Cross section view of samples with smooth and rough copper

In Fig. 12, the pull strength results are summarized for 22mil pad samples with both rough and smooth Cu foils. There is a clear difference in pull strength between the smooth and rough copper samples. From the adhesion point of view, the smooth sample should have weaker adhesion than the rough sample, which would lead one to predict lower pull strength for the smooth sample than the rough sample. However, the pull strength result in Fig.12 shows the opposite trend with the smooth sample (red curve) having significantly higher pull strength than the rough sample (black curve). This seemingly surprising result is likely due to the difference in the defect density between the two samples. The smooth sample is expected to have fewer and smaller defects in the laminate surface around the perimeter of the pad than the rough sample (see Fig. 6) and hence fewer initiation sites for pad cratering. The higher density of defects in the sample with rough copper compared to that with smooth copper would result in higher stress concentration in the defect areas and hence increased probability for pad cratering.

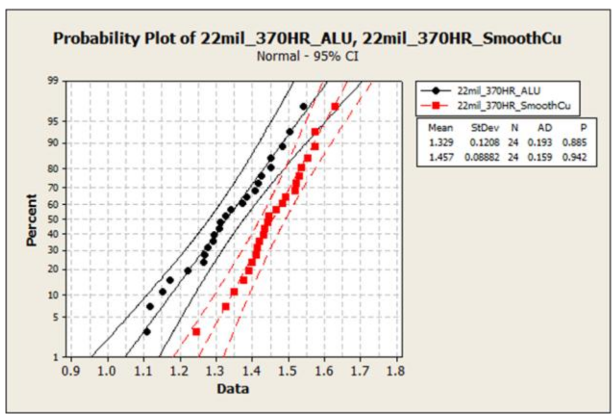


Fig.12. 22mil pad pull strength comparison between sample with rough copper (black) and sample with smooth copper (red).

Similar but less pronounced results were also seen for samples with 18 mil pads and are summarized in Fig. 13. In this case, only at 85% confidence interval, the sample with smooth Cu (red curve) shows higher pull strength than the sample with rough Cu (black curve) in strength testing. Further testing with an even smoother copper surface than that used in this work is planned to better understand the effect of the defect density on pad cratering. It is also understood that the adhesion between Cu and laminate may become the dominant factor preventing further reduction in copper surface roughness. An optimal Cu roughness for balancing between reducing defect density and achieving adequate adhesion needs to be determined. Some of the new ultra smooth Cu foils, developed for extra low loss in high speed RF application, may be useful candidates for minimizing defect sites in the laminate surface.

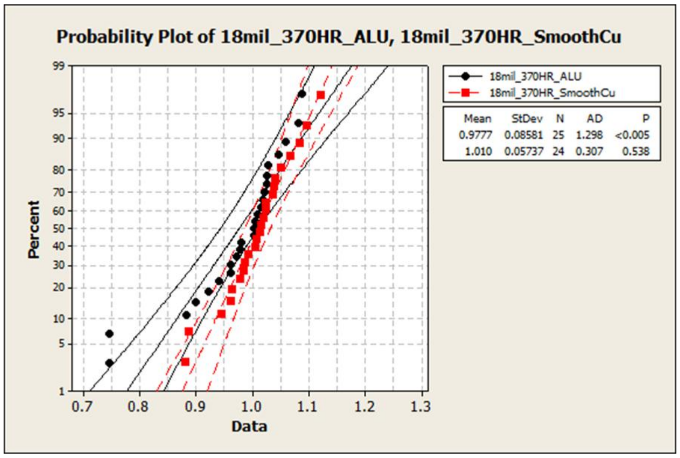


Fig.13. 18mil pad pull strength comparison between sample with rough copper (black) and sample with smooth copper (red).

Conclusion

Two novel approaches for mitigating pad cratering are presented. The first approach, based on the realization of distinctly different locations of pad cratering (in the external layer) and delamination (in the inner layer), uses pad cratering resistant material in the external layers and lead-free compatible material for the inner layers. The second approach is based on the importance of defect sites in brittle fracture mechanics and attempts to minimize pad cratering by reducing the initiation sites. Future work is planned to determine the lead-free compatibility of the hybrid structure and the optimal Cu surface roughness for minimizing pad cratering.

Acknowledgements

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