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Ultrasonic Evaluation of Artificial Kissing Bonds in CFRP Composites

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Abstract
The primary aim of this paper is to create artificial inter-laminar kissing bond-like defects in CFRP panels for ultrasonic inspection. Carbon fibre reinforced polymer structures pose a unique problem, as unlike metal-to-metal bonds (single bond line) carbon fibre reinforced polymer composites have multiple bond lines (between each laminate layer and between the individual carbon fibre bundles). This increases the number of locations for kissing bonds and other defects to lie. Published works look at bonding defects in joints (lap joints, and solid-solid bonding). This paper looks at inter-laminar bonding. A number of samples are created and attempts are then made to detect these kissing bonds using ultrasonic techniques. Further investigation into contaminants for artificial defect creation is advised and destructive verification of the kissing bond samples is still required.

Keywords: NDT, Kissing Bond, CFRP, Carbon Fibre Composite, Ultrasound Inspection

1. Introduction

The primary aim of this paper is to create artificial inter-laminar kissing bond-like defects in CFRP panels. Literature is researched to investigate methods used to artificially create kissing bond type defects in other material bonds. These methods are then applied to manufacture CFRP kissing bond samples. The samples are then tested in an immersion tank using the pulse echo method.
A kissing bond is a bond line defect where two surfaces are in intimate contact, but are not glued, or have greatly reduced bond strength. A number of bond line defects exist, including cracks, voids, delaminations, and porosity. These defects are all detectable using current non-destructive test methods. However, no method is currently available for detecting kissing bonds in CFRP composites. The danger with kissing bonds is that from the outside they appear to be solidly bonded, but the bond strength between the two adherends is of very low or no strength. These weakened bonds can deteriorate due to in-service loading or environmental conditions, leading to catastrophic failure. This research contributes the following to the collective scientific knowledge base:

1) Creation of kissing bonds in CFRP composites for ultrasonic inspection

The creation of kissing bonds or kissing bond-like defects is a very difficult process, and an artificial defect for one inspection method may not be suitable for another method. For example PTFE inserts are used to simulate delamination in composites for ultrasound inspection. However, a shearography camera would see the surface deflection caused by the insert even before a vacuum load was applied. Similarly, methods used to create artificial kissing bond defects in other bonds may not be suitable for CFRP, due to the type of adhesive or the material itself.

2) C-Scan evaluation of inserted contamination

A clean, defect free CFRP sample is ultrasonically C-Scanned in an immersion tank to record baseline readings. The series of manufactured defect samples is then ultrasonically C-Scanned in the immersion tank. The time of flight data is then analysed. Any detection of a defect will mean that the attempted creation of a kissing bond has failed. Although no indication of a defect does not necessarily confirm the production of a kissing bond.

2. Problem Definition

2.1 Kissing Bond Definition

Kissing bonds are most often found in adhesively bonded structures, but they have also been found in metal-to-metal structures such as friction stir welds. There are many different definitions of a kissing bond, with similar properties, but no unified definition, as the mechanics of a kissing bond cannot be agreed upon. There appears to be some disagreement as to where poor adhesive bonding becomes a kissing bond. Some believe that only zero strength bonds where the surfaces are contacting can be classed as kissing bonds, whereas others believe that bonds which fail at less than 20% of their nominal strength are kissing bonds. “This form of poor adhesion can be thought of as lying somewhere between the poor adhesion case and the wholly disbonded case”[1].

In [2], Nagy describes a kissing bond as a bond having "intimate mechanical contact between the counterparts without an actual bond. Besides some weak sticking effects, such a 'bond' has practically no strength at all". Whereas in [3] a kissing bond is described as a disbond with the two surfaces still in contact, which fails under very low stress compared to nominal stress, and are “identical to perfect joints in all respects but with low adhesion strength”. A further description is given by Roach et al [4] where a kissing bond is described as a bond where there is intimate contact between the adherend and the adhesive, but reduced bond strength. The paper goes on to state that kissing bonds are created due to inadequate surface preparation, contamination, adhesive degradation, or environmental aging, such as corrosion and moisture intrusion. In simple terms, a kissing bond is like two slices of frozen bread stuck together. The surfaces are touching and the structure appears to be stuck together, but it has little or no bond strength. Once the slices are separated it is seen that there is not 100% coverage of ice which bonds the two together.

2.2 Defect Sample Creation

In order to test for defects, samples with defects must first be created. This in itself creates a difficulty, for the defect is within the sample, thus not visible on the outside. There is also no reliable method for finding kissing bonds, so it is not possible to discover whether or not a kissing bond has been successfully created without destructively testing the samples. In [3], to be classified as a kissing bond defect the samples had to meet three criteria 1) the bond strength must be 20% or less of the nominal strength 2) the failure must be purely interfacial and 3) they must not be detectable with ultrasonic C-Scans. Published works look at bonding defects in joints (lap joints, and solid-solid bonding). This paper looks at inter-laminar bonding.

In [2], Nagy used selected spots of release agent to create artificial kissing bonds in aluminium-epoxy bonded plates. Marty et al [3] states that kissing bond “formation is linked to one or a combination of problems at the surface such as the introduction of contaminants, e.g. fuel and hydraulic or de-icer fluids”. However, it was noted that only silicone based contaminants weaken the bond strength. Silicone contamination and electro release epoxy were used to create kissing bonds in aluminium-to-aluminium epoxy bonds. Whilst electro release epoxy was used, the authors noted that despite careful control of the applied voltage and the duration of the applied voltage, it was difficult to determine the percentage of bond strength lost from sample to sample. In [5], Yan also used electro-release epoxy and lubricating oil to simulate kissing bonds in bonded aluminium samples and along with

Amerini et al [6] used two compressively loaded specimens to create varying levels of contact force between the two surfaces to simulate imperfectly contacting surfaces (kissing bond simulation). As the applied force is reduced, the interface between the two surfaces weakens and is allowed to vibrate, creating a 'clapping' motion between the surfaces.

Roach et al [4] created reduced strength bonds (such as kissing bonds) using a variety of different contaminants. These included grease, water, wax, sand, vaseline, oil, baking powder, and mould release agents (pure and diluted). Silicon-based release agent was also used by [7] to form kissing bonds. Contaminants were uniformly applied across the bond area, with the distribution controlled by applying the contaminant through screens to ensure specific surface area coverage. Kissing bonds were also created using less than 100% adhesive coverage. However, as pre-preg carbon fibre is to be used this option will not be possible. [8] Created kissing bonds by adding 25-50mm diameter flat bottom holes into the rear of a carbon fibre covered aluminium honeycomb panel. This would indeed show areas of weak bonding using Shearography. However, UT would pick this up as a near surface back wall similar to a delamination, so this method is not appropriate for ultrasonic application. [9] Created kissing bonds using ETFE [ethylenetetrafluor-oethylene] based, fluoro-polymer release film. Release film may allow sound reflection for ultrasonic testing. However, this will depend on the thickness of the film, and the test frequency used.

3 Experimental Work

3.1 Sample Manufacture

A number of contaminants from the reviewed literature are trialled in order to see which will work for inter-laminar CFRP. A defect template will be used to apply the contaminants, similar to [7] to both control the location of the contaminants, and also to protect the material in the uncontaminated regions.

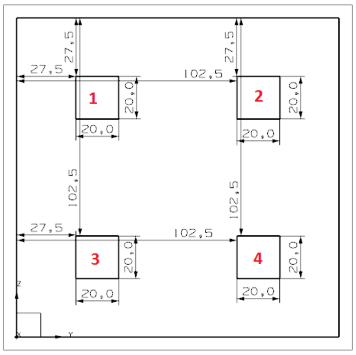

Figure 1~ Defect Layup Template

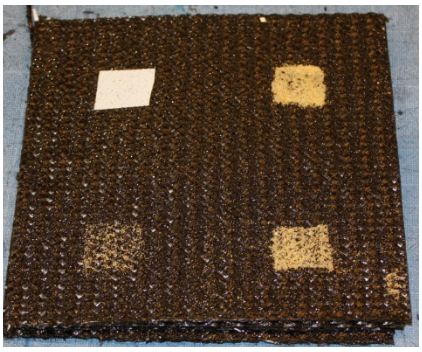
Figure 2 ~ Sand Contamination

A Clean Sample was created to record baseline setting for comparison. Using an identical layup procedure, samples were then created with a PTFE delamination reference and various levels of inserted contaminants (680 heavy weight oil, Frekote release agent, baking powder, sand and wax). Following the curing process, a visual examination of the panels was carried out, revealing the oil and wax samples to have released much of the inserted contaminant, and thus failing to create the kissing bonds.

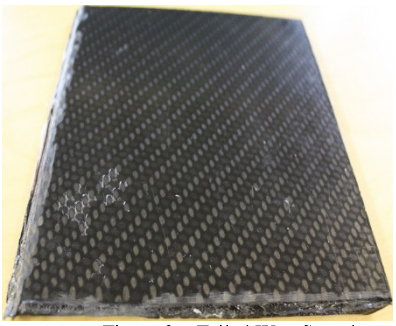

Figure 3 ~ Failed Wax Sample

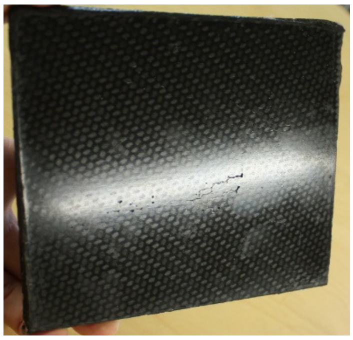

Figure 4~ Failed Oil Sample

3.2 C-Scan Inspection

After the visual inspection, the samples were ultrasonically C-Scanned using the immersion tank setup at TWI, using the pulse-echo technique. A 5MHz focused transducer was used for all tests. Four gates were set up on the sample. Gate one is the interface signal, gate two covers the back wall, gate three covers the area in the centre of the sample where the defects were inserted, and gate four covers the entire sample signal. Gate two utilised the DAC setting in the software to raise the back wall signal. The setup can be seen in figure 5.

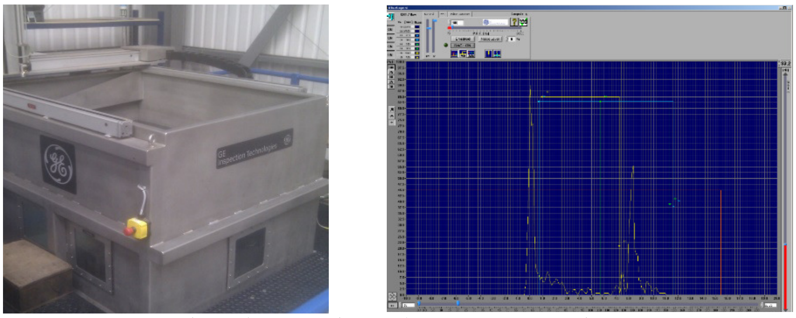

Figure 5 ~ Immersion Tank Set Up & Gate Settings

3.3 C-Scan Results

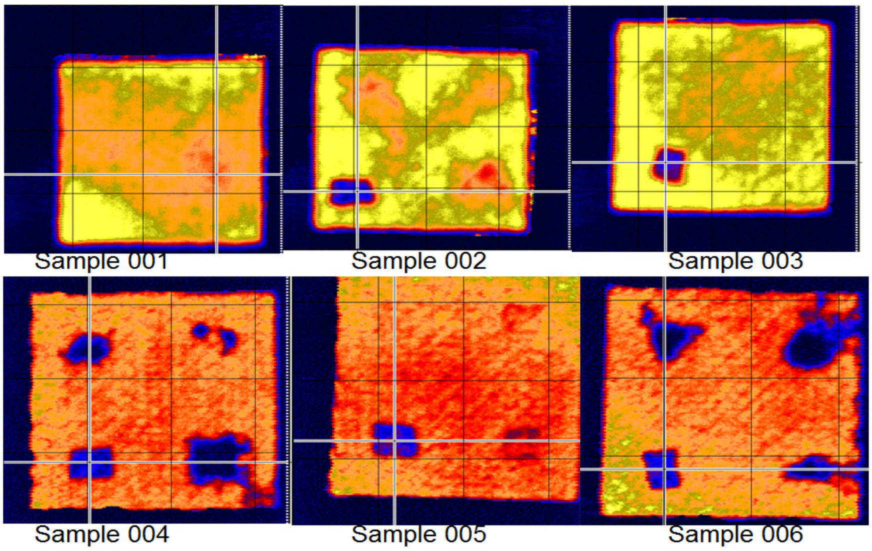

Figure 6 ~ C-Scan Images of Samples (Clean sample 001, Oil Sample 002, Release Agent Sample 003, Baking Powder Sample 004, Sand Sample 005, & Wax Sample 006)

As given in the figures above, the clean sample showed no visible defects, just amplitude variations within accepted limits for composies. The results show that all but two of the contaminated samples defects were visible in the C-Scans. Sample 003 (release agent) and part of sample 005 (sand) still look promising as artificial kissing bond defects. It is interesting to note that the smaller amounts of sand contamination were visible in the c-scans, though the largest level of contaminant was not.

3.4 Ritec Ram Time of Flight Analysis

Ultrasonic A-Scans were captured with a Ritec Ram 5000 Snap system and a LeCroy Oscilloscope. A-Scans are exported in CSV format for analysis. 2.5MHz and 5MHz unfocused transducers were used.

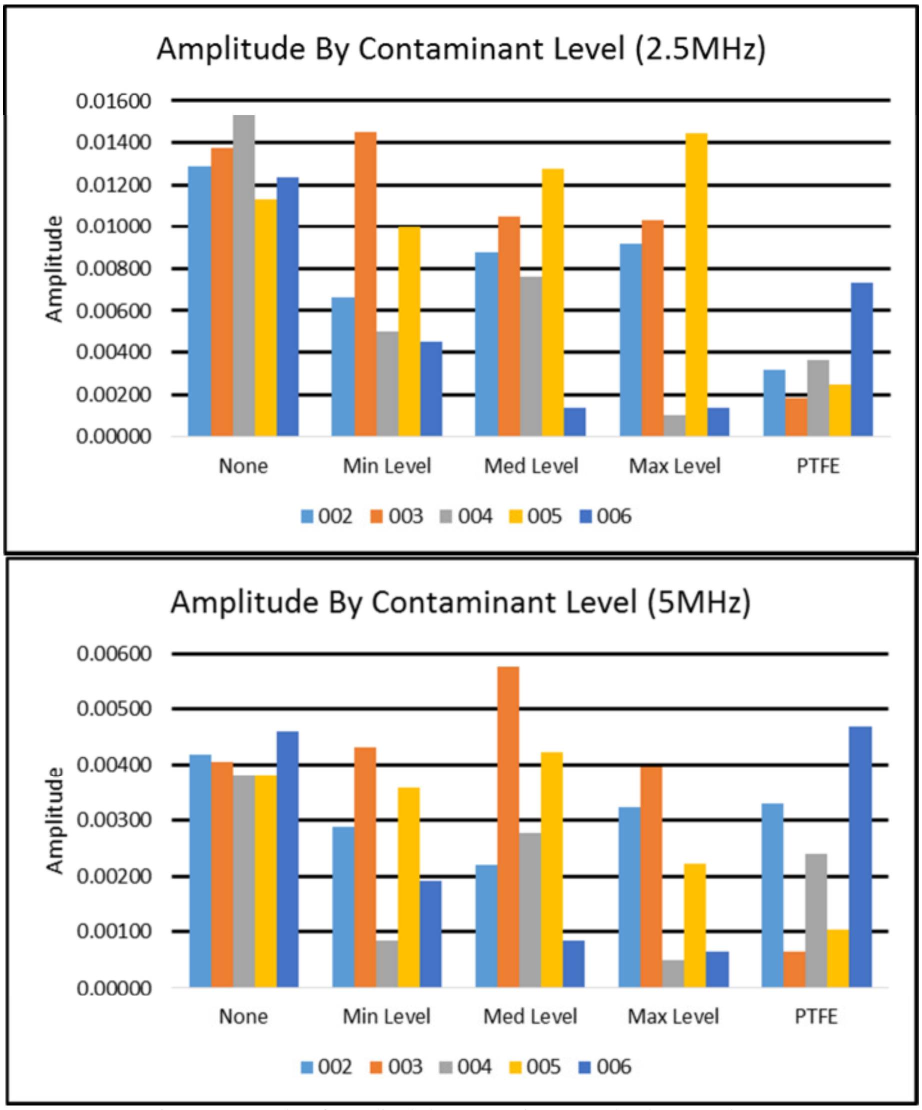

Figure 7 ~ Graphs of Amplitude by Contaminant Level 2.5MHz & 5MHz

The graphs above show the combined results of all tests by contaminant at 2.5MHz and 5MHz respectively. PTFE is the amplitude for the PTFE insert in each panel, and “none” is the defect free (clean) section from each panel. “min level” is the minimum amount of inserted contaminant, “med level” is twice the minimum amount of inserted contaminant, and “max level” is three times the minimum amount of inserted contaminant. As you can see, there is a wide variation in amplitude of the clean section. The levels of amplitude drop do not always correlate to the level of inserted contaminant. This can be due to contaminant moving into other layers, or being pressed completely out of the panels. The patterns also vary from 2.5-5MHz. This may be due to the probe not being in the exact same spot as the previous test. Even a single millimetre of difference can alter the amplitude, due to the material path changing (more fibre than epoxy, or vice versa).

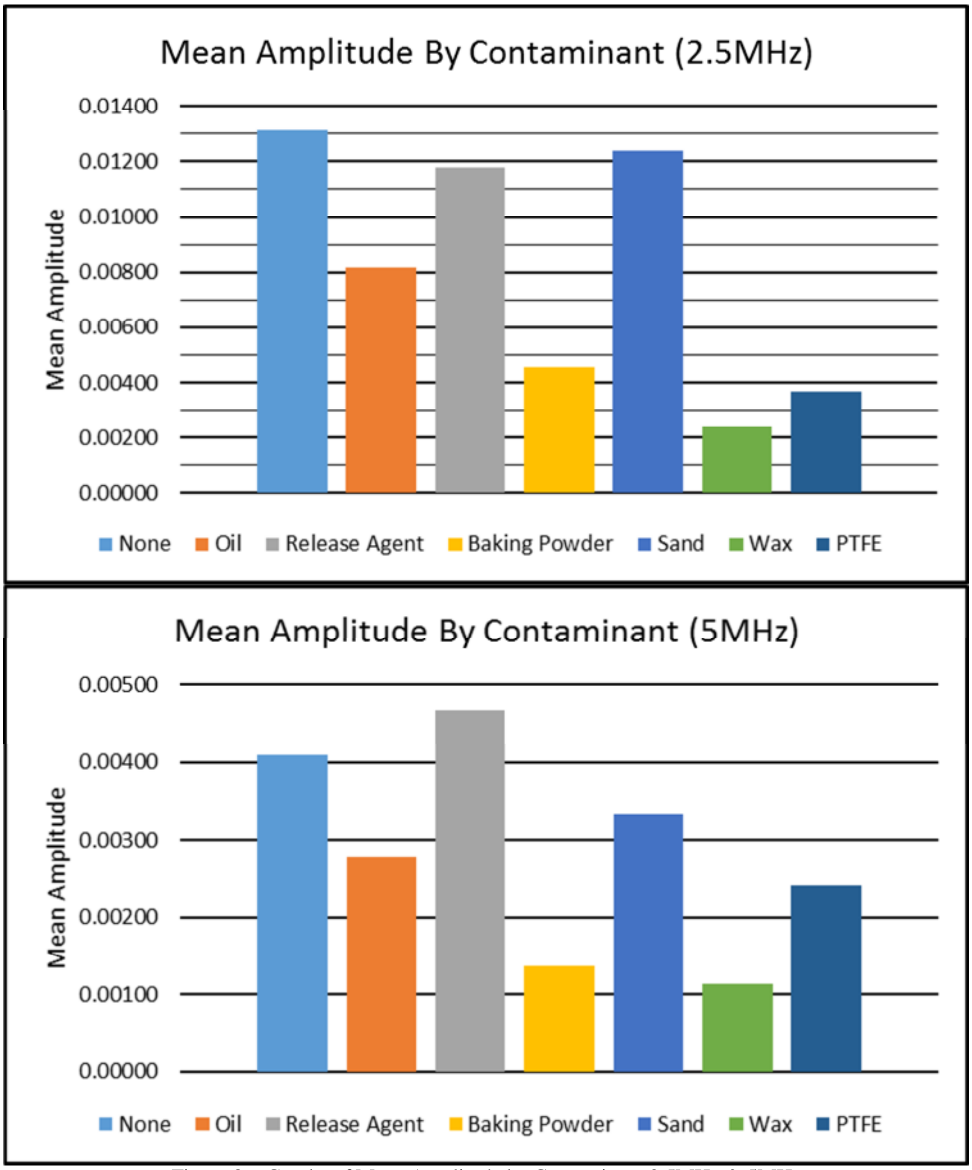

Figure 8 ~ Graphs of Mean Amplitude by Contaminant 2.5MHz & 5MHz

The Above graphs show the mean amplitude by contaminant for 2.5MHz and 5MHz tests. The graphs clearly show that release agent (sample 003) and sand (sample 005) are the two most promising for kissing bond simulation. Sand and release agent are both ultrasonically invisible, and both have amplitude variations well within the expected range from a good composite sample. Whilst oil has the third largest amplitude, the fact that it was pressed out of the panel and visible in the C-Scan means that it is not likely to be a kissing bond. The higher amplitude is due to the small amounts contaminant remaining within the panels. The literature review found that only silicon based contaminants truly weakened bond strength [3], so it is not entirely surprising that the sand and Frekote release agent have shown to be the most promising thus far.

3.5 Sample Sectioning

The destructive testing equipment required for the additional tests to fully categorise these as kissing bonds was not available. The only option left was to section the samples and examine the contaminant between the layers. Samples 002, 003 and 005 were chosen for this task. A Diamond wet wheel tile cutter was chosen to section the samples, as it is designed for cutting tough ceramics up to 12mm in thickness, and is water-cooled to avoid damaging the epoxy with excessive heat during the cutting operation. Samples 002, 003 and 005 were cut, examined visually and then under a light reflection microscope.

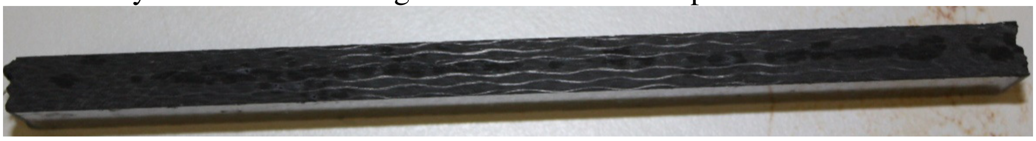

Figure 9 ~ Sample 002 Sectioned

Figure 9 shows the cross section of sample 002. As you can see, the oil has spread out of its implanted region, and migrated through the multiple layers of the composite. Small pockets of liquid still exist (dark spots), and are slowly releasing the remaining liquid, making the oil more visible. It can be difficult to see as photographing dark patches on a black surface allows for little contrast. A close up of the area can be seen in Figure 10.

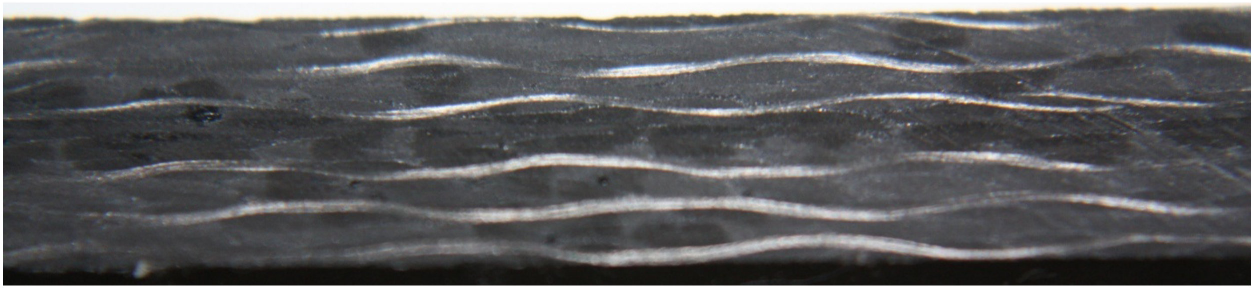

Figure 10 ~ Section 002 D4 Close Up

Sample 003 was then sectioned and visually inspected (Figure 11). No contamination was visible.

Figure 11 ~ Sample 003 Sectioned

Sample 005 was then sectioned (Figure 12). The inserted contamination is more visible at D2 than in D4. This is in line with the levels of inserted contaminant. Figure 13 shows a close up of the sand contaminations, showing areas of constant sand. Although no attempt has been made to quantify the change in bond strength, due to a lack of test equipment, the strength of sand is significantly less than that of epoxy, and so should fail at greatly reduced loads.

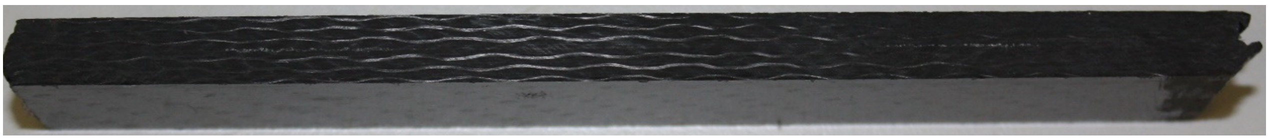

Figure 12 ~ Sample 005 Sectioned

Figure 13 ~ Section 005 D2 Close Up

Following the visual inspection, the samples were then viewed under a light reflection microscope.

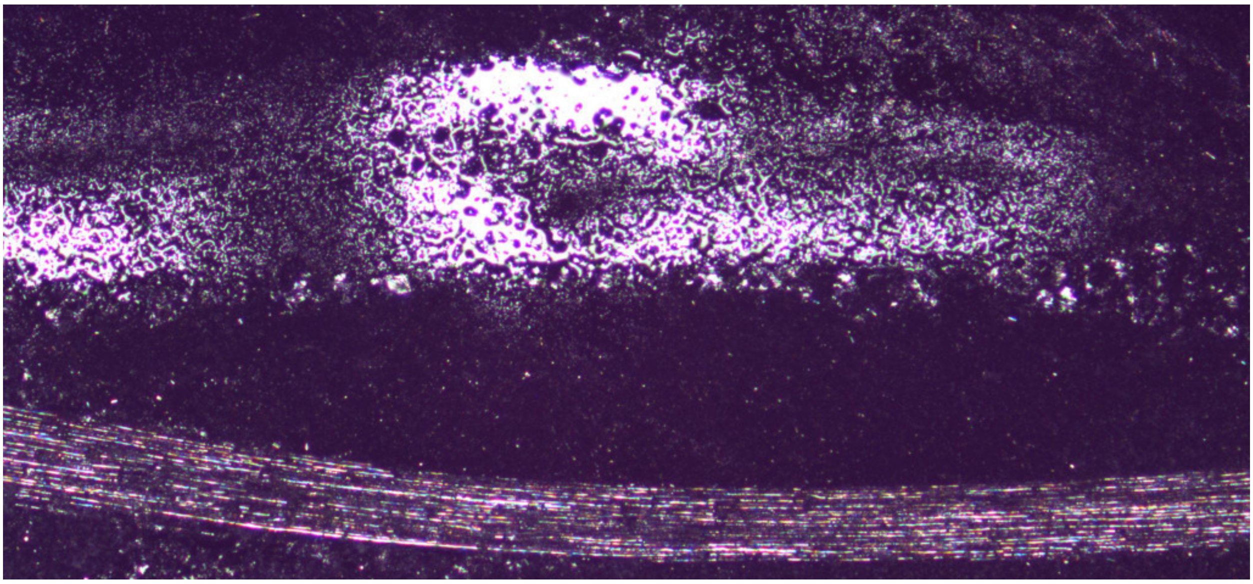

Figure 14 ~ Oil Contaminant 5x Zoom

The oil image, figure 14, show the centre spot of oil contamination and the speckled oil that has been released from the contamination centre.

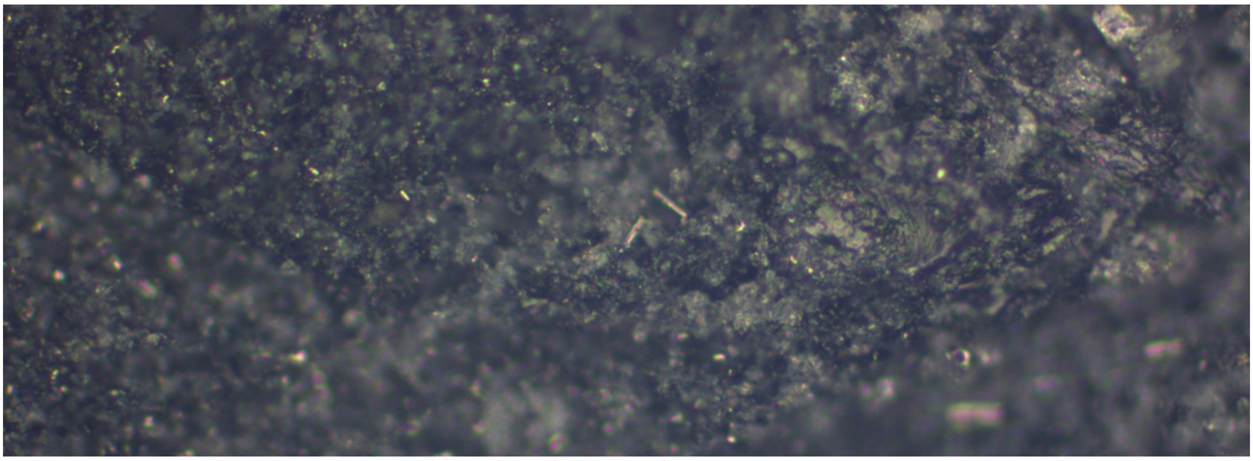

Figure 15 ~ Frekote Contaminant 20x Zoom

In the Frekote image, figure 15 blurred patches can be seen. These may be the presence of the silicon contamination left behind by the Frekote, but it is not clear. Frekote may possibly be a good contaminant for kissing bond simulation, but there may not have been sufficient release agent inserted during creation. This requires further experimentation.

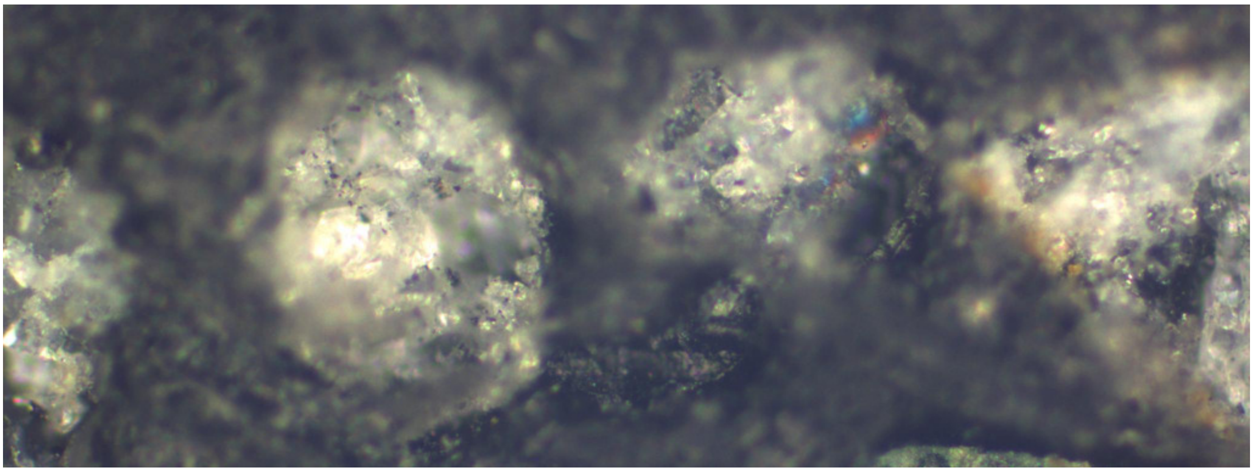

Figure 16 ~ Sand Contaminant 20x Zoom

In figure 16 (sand contaminant) the heated sand appears to look like glass. There are minute gaps between the sand which allow for epoxy bonding, making this a more likely kissing bond like defect, with pockets of bonding and no bonding, but continuing mechanical contact.

4. Conclusions

The visual inspection revealed noticeable defects in sample 002 and 006. These are the oil and wax (liquid) contaminants. This was disappointing as it meant that two of the five contaminants had failed before any ultrasonic inspection had taken place. The ultrasonic immersion testing then revealed the first of the dry contaminants (baking powder) to be visible to conventional ultrasound, leaving only two samples in the running. Whilst it is disappointing to lose the potential kissing bonds (as a considerable amount of work had gone into their creation), it is equally important to know which contaminants do not work for kissing bond synthesis. The visual testing and immersion tank ultrasound testing did not conclusively prove that liquid contaminants could not be used to produce artificial inter-laminar kissing bonds. It simply proved that the liquids used (and their quantities) were not suitable for this type kissing bond production.

The initial amplitude measurements taken with the Ritec system showed good agreement with the C-Scan results. Pulling the data out of the A-Scans and plotting the bar graphs also revealed the sand and release agents to be likely kissing bond candidates. This meets one of the three criteria for a contaminant being classified as a kissing bond. The other two steps involve destructively testing the samples to ensure they fail below 20% of the nominal strength value, and then examining the failure mode to ensure that the failure mode is purely laminar. This is the subject of ongoing research and currently it is only possible to state that, the sand and release agent look like the two most promising contaminants for kissing bond creation. For Future work, additional silica/silicon contaminants should be investigated for inter-laminar kissing bond creation. Additional samples should also be created and destructively tested to see if the contaminants and methods used truly do create artificial kissing bond defects. Three point bending tests could be used to assess the stiffness in the defect regions without destroying the samples.

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