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Using NDT Techniques to Detect and Characterise the Damage of End-Of-Life Components in Remanufacturing

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Abstract Remanufacturing is attractive as an environmentally friendly and cost effective solution for end-of-life components. If a remanufactured product is to be substituted for a new product, the manufacturer should ensure that the recovered products meet the required performance specification, using Non-destructive testing (NDT) technologies to detect potential damage of end-of-life product then selecting appropriate remanufacturing methodology is important for enduring that. In this study, two widely used NDT techniques, thermographic inspection and ultrasonic testing were investigated to detect and characterise the damage of selected end-of-life component specimen. Armed with enough information on damage associated with end-of-life products, and based on the NDT result on the end-of-life component, a decision can be made if an end-of-life component can be remanufactured and safely reused at the required performance level.

Keywords: *Thermographic inspection, ultrasonic testing, mechanical failure, damage characterisation, remanufacturing.*

1 Introduction

Remanufacturing is attractive as an environmentally friendly and economically advantageous solution for end-of-life components. Some of the used components may be remanufactured and reused to avoid making or buying new components. If a remanufactured product is to be substituted for a new product, the manufacturer should ensure that the recovered products meet the required performance specification. NDT is a valuable method in assessing the condition of used components without permanent damage to it.

NDT is the examination of the structural characteristics of a material without harming its future functionality and mechanical performance. This concept has been employed for centuries by using methods as simple as visual examination to look for visible cracks, peeling paint or knocking on a piece of wood to test its density. NDT techniques are useful for detecting and characterising defects caused by mechanical failure like fatigue of components. Industries can use the information gathered through NDT to determine the condition of used component and assess if it has enough remaining useful life for reuse. This information can help deciding if any recovery process would bring the component back to operating specifications in a cost effective manner.

This paper presents the research work on using NDT techniques to detect and characterise the damage of end-of-life component in remanufacturing. The next section of the paper contains the literature review on areas related to the scope of the research. Section 3 describes an overview of test specimens and failure modes. Section 4 describes experiments using thermographic and ultrasonic NDT on test specimens. Section 5 presents the results acquired from all experiment on both specimens. Section 6 is a discussion regarding the results of the testing, limitations the NDT experiments, and recommendations for improvements to the test setups. Section 7 is the conclusion where key findings are summarized.

2 Related Research

Some failure modes can often result in crack defects within a material that cannot be seen through visual inspection (Cherfaoui, 2012). These defects weaken the material and can be unsuitable for reuse if it no longer meets its specifications (Garnier et al., 2011). If a component has sustained impact damage or is susceptible to fatigue, its continued use without testing is risky and could result in a complete failure in the future. To verify that a component still meets its specifications and be returned to service, NDT can test for the presence of defects without causing damage and impacting its performance. An example application of NDT to detect defects due to impact or fatigue can be found in carbon fibre. Carbon fibre is a widely used type of composite material formed from carbon fibres bound by an adhesive material like epoxy. The main defects investigated by industry are delaminations, a separation of constituent layers, and result in a loss of mechanical toughness. These delamination defects can be detected using NDT techniques like thermographic and ultrasonic testing (Cantwell and Morton, 1991).

Thermography testing is an inspection technique of monitoring the heat flow distribution of an object so that temperature variations over a material can be recorded and analysed. Pulsed phased thermography (PPT) provides quantitative evaluation of defects with an application of external heating, and the surface

temperature changes sharply due to the thermal disturbance in the material. These abnormal surface temperatures are recorded by infrared (IR) camera and then, captured images are recorded for analysis (Lascoup et al. 2013). Test setups including with inductive coil, heat lamp and laser can be prone to non-uniform heating or saturation of the material, especially when analysing large or thin test specimens. To mitigate these potential issues, parameters and transform algorithms should be chosen carefully to improve the qualitative and quantitative results of any testing (Ibarra-Castanedo and Maldague, 2004). Laser excited thermography was studied for the sizing of surface breaking cracks in determination of crack depth and angle (Schlichting et al., 2012). A type of lock-in thermography, optical excited thermography is efficient for detection of boundaries like delaminations whereas ultrasound excited thermography is sensitive to inner friction and therefore defect-sensitive (Busse et al., 2008). Ultrasound excited thermography generates periodic heat at damaged areas and defects like cracks, delaminations because the defects tend to absorb more ultrasonic energy than the undamaged material. Although lock-in thermography is relatively slow, the signal-to-noise (SNR) of the result is higher than that obtained from a single frequency thermal wave. A higher SNR ratio results in IR images that can better discern the presence of a defect. Recent research indicates that it may be superior to traditional lock-in thermography at detecting surface breaking cracks in a material (Sohn et.al, 2013). The heat flow in the material that is being heated by the laser is in the shape of a symmetrical hemisphere. If there is a surface crack that is perpendicular to the material surface, heat flow around crack would be disturbed and is captured by thermal camera for crack-detection (Li et al., 2011).

Ultrasonic testing is widely used NDT technique that introduces ultrasound waves into material and measures the time delay for the signal to return. From this information, a great deal of information can be inferred like the presence and characteristics of defects or material properties. The method of this technique is to measure the time of travel of stress waves propagating through a material. Information derived from the time of travel allow inspectors to understand the integrity of test specimen for material characterisation and inspection of discontinuities such as flaws and cracks on the surface or within the material (Scott and Scala, 1982). A study of laser ultrasonic system was carried out for the detection of surface-breaking crack with its depth information. The system is a non-contact device with use of multiple laser beams. The depth information was extracted from the difference between peak frequencies of reference and data signal. Moreover, another ultrasonic testing was studied for the sizing of short surface cracks depths based on time domain and frequency domain of Rayleigh waves (Bernard and Edoardo, 2007). From other NDT techniques, dye penetrant and magnetic particle inspection methods are inappropriate for detection of crack depth; whereas ultrasonic and eddy current testing provide deeper insight into the

size and orientation of the material defect. Additionally, eddy current testing has limitations of electrical conductivity of materials versus to the efficiency of ultrasonic inspection (Schlichting et al., 2012).

Investigation of material features of components helps to understand the component's condition and potential for remanufacturing. There is some research regarding thermographic and ultrasonic NDT methods to detect the condition of components for remanufacturing but defect characterisation has not been deeply addressed by NDT. The major objective of this research is to assess the feasibility of two widely used NDT techniques, thermographic inspection and ultrasonic testing for detecting and characterising of damage. The characterisation of defect in terms of length, width and depth can provide valuable information during the remanufacturing process to validate the material's compliance with engineering specifications and guides any corrective rework of the material.

3 Test Specimen and Failure Modes

In this study, end-of-life components made of carbon fibre materials is targeted to investigate because of the emerging vast application of composite materials in different applications. In order to do that, two test specimens were selected for the experiments: The first test specimen (Figure 1) is made of a quasi-isotropic carbon fibre and epoxy composite, its dimensions are 165 mm of length, 110 mm of width and 4.12 mm of thickness, it has delamination damage initiated by impact; the second specimen (Figure 2) is a double cantilever beam (DCB) made of unidirectional carbon fibre and epoxy composite, Its dimensions are 200 mm of length; width is 20 mm and 5.7 mm of height , it has crack damage that propagated from the edge towards to middle of the specimen.

Figure 1: Composite specimen with Damage of Delamination

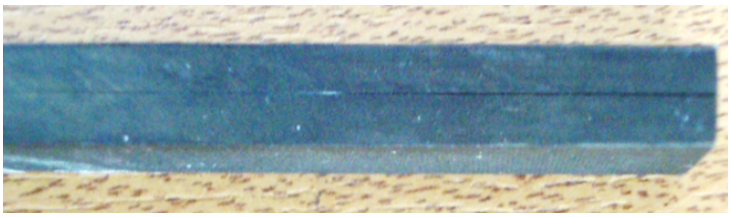


Figure 2: Composite Specimen with sampler damage of crack

4 Experiments

4.1 Thermographic Inspection

The thermographic Inspection was carried out on the ThermoScope II which is a portable system that is capable of flash heating, image acquisition with an infrared camera and an interactive display for use by a single operator. The Mosaiq software was integrated into the setup to display the captured infrared images and allows histogram values to be adjusted. This allows the user to view and filter the image data by levels, which is analogous to the frequency of the IR emissions from the specimens. Utilization of this setting is necessary to remove background noise from the image. The specimen was placed on the testing surface and the thermographic test device was positioned over it. An integrated infrared (IR) heating lamp is briefly activated to heat the surface of the material. The lamp is then turned off and the specimen is imaged by the IR sensor, capturing the top surface thermal distribution. The test results for both test specimens are shown in the results sections.

4.2 Phased Array Ultrasonic Testing

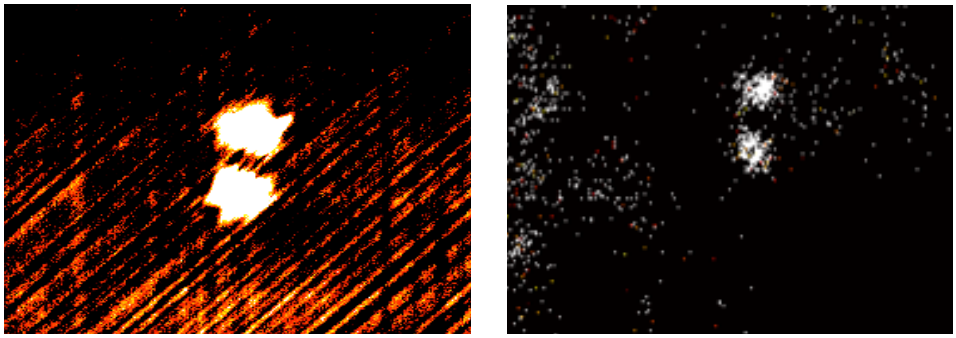
The testing apparatus is an Olympus OmniScan that integrated with the software for immediate configuration of the setup to set the parameters i.e. gain, the speed of sound on test specimen. For the experiment on both specimens, the probe was set to 11 dB and the speed of sound within a composite material was estimated to be 3,000 m/s. The testing was carried out with a conventional long probe which consists of many small ultrasonic transducers. The probe is cut into many small elements, which are individually excited. Before scanning the specimen with the probe, an ultrasonic coupling gel is applied to the surface of the specimen for better transmission of ultrasound energy into specimen. Once the testing was finished, the acquired data was loaded into TomoViewer for data viewing and analysis on the PC. When the acquired data is loaded, A-scan, B-scan, and C-scan views were available for analysis of the scanned area in the material.

5 Experimental Results

5.1 Impact Damage Specimen

Thermographic Inspection Results

Thermographic Inspection captured IR images that revealed two separate subsurface delaminations are found in the impact damage test specimen as shown from the top surface and reverse surface of the specimen in Figure 3.



a) Top Surface b) Reverse Side

Figure 3: IR imaging of the impact damage specimen from the: a) top surface and b) reverse side

The top surface of the specimen resulted in a clearer image of the two delaminations when compared to the image from the reverse side. This indicates that the delaminations are closer to the top surface. The defects were quantified in two dimensions using the captured image. The two delaminations were approximately circular and these results are tabulated in Table 1.

Table 1: Thermography testing results of impact damage specimen

Defect	Length (mm)	Width (mm)
Top Delamination	12.322	11.227
Bottom Delamination	12.884	12.221

Phased Array Testing Results

The specimen was scanned and the collected information was analysed in TomoViewer. Figure 4 is the scan of the entire specimen in C-scan view of high

resolution image that presented the specimen feature. It was found that there is a large defect within the specimen that is seen in white colour in the image. The approximate length and width of the damaged area was measured.

While moving the cursor over detected damage area, B-scan view on the flaw detector displayed a cross-sectional view and it was revealing the existence of other surface and sub-defects. The B-scan view facilitated measurement of the depth of any existing defect. There were five delaminations detected within the composite with different depths as seen in Figure 5. Images of each delamination cross-section were taken and the length, width, and depth were measured. These images were obtained by cross-sectional cursor to reveal each defect.

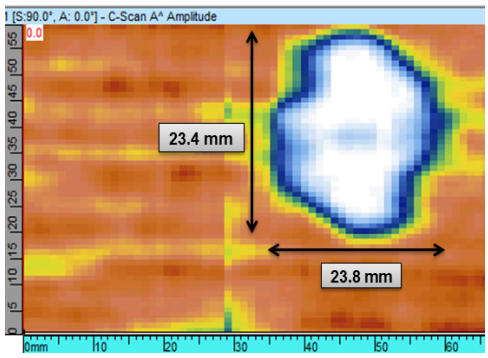


Figure 4: Phased array c-scan of the material surface

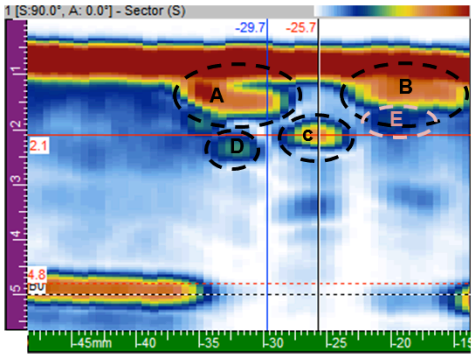


Figure 5: Cross-sectional view showing five delaminations

The approximate measurements for each defect are listed in Table 2. The depth was measured using this cross-sectional view in conjunction with the amplitude versus depth chart at the highest signal amplitude.

Table 2: Approximate measurements of defects, impact damage specimen

Defect	Length (mm)	Width (mm)	Depth (mm)
A	19.4	8.5	0.8
B	18.3	9.5	0.6
C	13	6.6	1.4
D	15.1	10.3	1.4
E	9.8	3.7	1.7

5.2 Double Cantilever Beam Specimen

Thermographic Inspection Results

The DCB specimen has a visible crack on its narrowest sides that appears to be planar and parallel to the largest surfaces. The resulting thermographic image is shown in Figure 6. By visual inspection, there is a crack in the DCB specimen starting from the end of the material going towards to the middle. However, the crack cannot be seen in either IR image. The histogram controls of the image were adjusted in Figure 7 to find a view in which the crack was visible but it was unsuccessful.

Figure 6: IR imaging for DCB composite

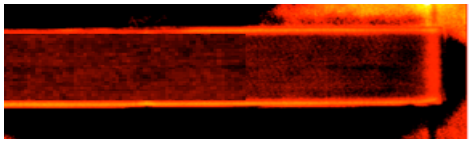


Figure 7: Adjusted histogram values for DCB composite

Phased Array Testing Results

Figure 8 is the phased array C-scan image of the double cantilever beam specimen captured from PA testing. The test specimen's thickness is found by measuring the distance from the top and bottom surface signals. The thickness was calculated to be 5.7 mm, which is the same as the thickness measured with a caliper.

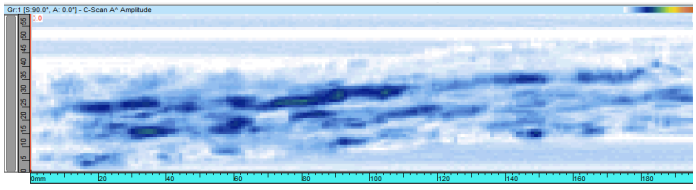


Figure 8: Phased Array C-scan view of the entire specimen

As visually the crack was seen, the depth is 2.9 mm below the composite surface and its width is the same as the specimen width of 20 mm as the crack is seen from both sides of the specimen. The length of the crack is measured by moving cursor on the C-scan image to view different B-scan images. The distance between B-scan images where the defect is seen was 112.3 mm and listed in Table 3.

Table 3: The characteristics of crack in DCB composite

Defect	Length (mm)	Depth (mm)
Crack	112.3	2.9

6 Findings

Thermography testing captured IR images that revealed two separate defects (defects of A and B) in the impact damage test specimen. The defects were measured in two dimensions of length and width, not depth. These defects were at 0.6 mm and 0.8 mm below the surface of specimen as measured by PA testing. However, pulsed thermography testing with this setup did not detect the deeper defects of C, D, and E that is beginning at 1.4 mm below the surface. From these findings, it appears that current pulsed optical thermography test setup was not suitable for detecting delamination defects of at least 1.4 mm depth or lower in carbon fibre composites. Since a sub-surface defect is surrounded by thermally conductive material, thermographic testing has limitations on the measurement of depth and size of defects it can detect. The applied thermal energy will diffuse around the edges of a defect and mask the true size of the defect and this effect becomes more pronounced the deeper the defect is within a material. Though the histogram controls were used to filter out thermal noise, the crack in the DCB specimen could not be seen. The defect was a large crack propagating at 2.9 mm below the surface as measured by PA ultrasonic testing. Since the 1.4 mm defects in the impact specimen were not detected by thermography, it is not surprising that it could not be seen in the DCB specimen. In the current test setup, heat is applied from the top and is imaged as the material cools. This setup was chosen because it is similar to many in-situ applications where the technique is used for detecting surface and subsurface defects and operators do not have access to the backside of the test specimen. A more appropriate thermography technique might have been to apply heat to the side opposite to the imaged surface of this test specimen. By applying heat from the bottom and imaging the material as the top surface temperature rises, deeper delaminations in the carbon fibre would appear in the IR image as cooler areas because the delaminations have lower thermal conductivity than the undamaged material and obstruct the flow of heat. Heating the specimen from the bottom would have been particularly successful in the DCB specimen as opposite side is accessible because the large defect would impede heat flow to a great portion of the surface and heat diffusion around the edges would have only a small impact.

Phased array ultrasonic produced the most complete results and detected five defects at varying depths within the impact damage material. A significant advantage of PA testing over thermography is its ability to discern defects further below the surface. Three defects of C, D, and E, were successfully characterized by PA, whereas analysis of the thermographic data does not indicate any of these defects. This result indicates that phased array is a useful technique for detecting defects in carbon fibre sheets of at least 4.1 mm thickness. The phased array test setup is likely to be able to characterise defects in carbon fibre of even greater thickness because the return signal strength was observed to be high at 4.1 mm. However, some limitations can be inferred from the results. The bottom surface of specimen was not seen because the delaminations that are closer to the probe prevent the signal from effectively probing the region beyond it. Thus, additional defects can be hidden by the presence of another defect that is closer to the probe. While testing the reverse side of a material can mitigate this, however this is not always possible due to the various materials in different shape/dimension and their reverse side is not always accessible.

Because the DCB specimen had a rough finish, scan data was incomplete in some areas where the probe elements did not make good contact with the material, the efficiency of energy transfer to and from the material is reduced and the return signal strength is much lower. Thermography testing is less affected by rough surfaces since it does not require direct contact with the surface and may be a more suitable technique for shallow defects. A consideration that may be taken into account in the future is the loading on the material from the weight of the probe and force applied by the test operator. Significant force was applied to the probe during the DCB experiment to ensure good contact between the probe and the rough surface. The effect of this pressure may be to compress defects like crack and make them difficult to detect. This undesired load may be unimportant in inflexible materials like steel but this pressure can be enough cause issues during a scan in a relatively elastic material like carbon fibre. Testing of the DCB specimen was challenging due to the size, shape and surface finish of the specimen. The specimen was similar in size to the probe and testing had to be conducted on sides of the specimen that were not wide enough to allow all of the probe elements to be in contact with the surface. Phased array probes are not suitable for components smaller than distance between transducers within the probe. Due to the bar's shape, it was not possible to test the specimen from its narrowest sides. The experimental setup could be improved with a mechanical jig to guide the probe in a straight path across the specimen surface.

7 Conclusions

From the experiments conducted, thermographic and ultrasonic NDT has been found to be effective in detecting defects such as delamination and crack within carbon fibre materials. Phased array ultrasonic had the best performance in detecting and characterizing delaminations in both specimens. It was capable of quickly scanning a material to generate a complete set of data to measure the shape, dimensions, and depth of delaminations. However, analysis of the data showed that defects can be masked by discontinuities that are closer to the probe and non-homogenous materials may be difficult to scan. Small test specimens or those with rough, irregular, or curved surfaces can be difficult to scan because the phased array probe may not make good contact with the tested material's surface. Pulsed thermography was able to detect subsurface defects within carbon fibre at a depth of at least 0.8 mm. It was not able to detect delaminations at 1.4 mm or deeper, and is not recommended for detecting defects deep within a material because thermal diffusion in the surrounding material blurs the defect. When compared to the phased array ultrasonic results, this blurring effect caused the apparent size of the defect to be smaller than its actual size. The test apparatus did not provide enough information to calculate the depth of the defects but it could be modified to estimate the depth by analysing the temperature-time profile of the surface above a defect. Because it does not require contact with the surface of a material, it may be better suited than ultrasonic for testing materials with rough surfaces.

In this paper, ultrasonic and thermographic NDT techniques were reviewed and two carbon fibre specimens were tested to assess the efficacy of these techniques in detecting and characterising of discontinuities within the material. The results show that, for remanufacturing applications where components likely have deeper defects, phased array ultrasonic NDT is the most powerful technique of those tested for detecting and characterizing sub-surface defects. However, for rough surfaces, pulsed thermography may be easier to use to detect discontinuities that are close to the surface of a material. Industries can use ultrasonic or thermographic NDT depending on the component they wish to test and the probable defects in the material to decide if remanufacturing is feasible and if any recovery processes would bring the component back to operating specifications in a cost effective manner.

8 References

Bernard, M. and Edoardo, M. (2007), "Ultrasonic sizing of short surface cracks", *Ultrasonics,* Vol. 46, No.3, pp. 195- 204.

Busse, G. et al. (2008), “Aerospace Applications of Lock-in Thermography with Optical, Ultrasonic, and Inductive Excitation”, *International Symposium on NDT in Aerospace*, 3-5 December 2008, Germany

Cantwell, J.W. and Morton, J. (1991),”The impact resistance of composite materials”, *Composites*, Vol. 22, No. 5, pp. 347-362

Cherfaoui, M. (2012), “Innovative Techniques in Non-Destructive Testing and Industrial Applications on Pressure Equipment”, Procedia Engineering, Vol.46, pp. 266-278.

Garnier, C. et al. (2011), “The detection of aeronautical defects in situ on composite structures using Non Destructive Testing”, Composite Structures, Vol. 93, No.5, pp. 1328-1336.

Ibarra-Castanedo, C. and Maldague, X. (2004), “Pulsed phase thermography reviewed, Quantitative Infrared”, *Quantitative Infrared Thermography Journal*, Vol.1, No. 1, pp. 42-70

Lascoup, B. et al. (2013), “On the feasibility of defect detection in composite material based on thermal periodic excitation”, *Composites Part B: Engineering*, Vol. 45, No. 1, pp. 1023-1030.

Li, T., Almond, D.P. and Rees, D.A.S. (2011), "Crack imaging by scanning pulsed laser spot thermography", *NDT & E International*, Vol. 44, No. 2, pp. 216-225

Schlichting, J. et al. (2012), “Characterizing Cracks by Laser Excited Thermography”, *NDT&E International*, Vol.45, No.1, pp. 133-140.

Scott, I. G. and Scala, C. M. (1982), "A review of non-destructive testing of composite materials", NDT International, Vol. 15, No. 2, pp. 75-86

Sohn, H. et al. (2013), “Laser Lock-in Thermography for Fatigue Crack Detection in an Uncoated Metallic Structure”, *Proceedings of SPIE 8692, Sensors and Smart Structures Technologies for Civil, Mechanical, and Aerospace Systems*, 19 April 2013, California, USA