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Characterisation of additive manufacturing metal – carbon-fibre composite bond by dual-energy computed tomography

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Abstract
Joining of dissimilar materials is a topic of high interest for the industry. The ability to seamlessly join materials with significant differences in properties would advance the development of efficient designs and concepts within many fields. In this work, bonds between aluminium and carbon-fibre reinforced plastic have been studied. The aluminium side of the bonds were fabricated using classical methods (milling) and additive manufacturing. Two types of bonds were fabricated using additive manufacturing, one flat, relying on the rough surface for adhesion in the bond, and the other with surface features designed to hook into the carbon-fibre plies. All the bonds were fabricated using wet layup of carbon-fibre, the idea was that the aluminium parts would bond to the plastic composite in one step. The bonds were characterised using dual-energy computed tomography. The method used in this work was non-linear and based around fusing of projections acquired with different energy spectra. The mechanical strength of the bonds was also evaluated, both through tensile tests and four-point bending.
It was found that the bonds including additive manufactured aluminium was stronger than the milled samples in general. In the computed tomography data, it could be seen that the adhesion in those bonds were better, most likely due to the rough surface. The strongest bonds were those with additive manufacturing surface features. However, the computed tomography data revealed that these bonds have difficulties with integration between the surface features and the carbon-fibre plies.

Additive manufacturing, Dual-energy computed tomography, carbon-fibre composite, joining

1. Introduction

Joining of dissimilar materials is of high interest since it enables designers to utilize specific strengths of materials while diminishing their weaknesses. Of especial interest is the ability to join metals to plastic composites as it allows for light, and strong, designs to be integrated into each other. This task is commonly performed using rivets and adhesives that can cause several issues [1]. A possible joining method of metal and plastic composites is enabled by additive manufacturing (AM) where the surface of the metal can be fabricated to form a mechanical bond with the plastic composite [2]. These types of integrated bonds could be a joining solution that allows for a homogenous load distribution in the interface between the materials that utilizes both mechanical, and adhesive, load transfer.
Several bond designs for joining of composites and metals have been studied previously. One of the bonds that have been developed is called HYPER. The bond is created with metal pins that are fabricated on the metal surface and lodged into the fibre plies before curing [3]. The method shows promising results [4], [5] but is limited by the shape of the pins that highly limits the orientation freedom in the AM process.
One of the issues with metal/composite bonds is the characterisation as it is difficult to inspect the bond since the AM metal part is concealed within the composite. Destructive testing methods allows for some information gathering, but to be able to gain more information, computed tomography can be utilized [6], [7].
In this work, joints of aluminium to carbon-fibre composite was fabricated. The aluminium was fabricated using selective laser melting to create features on the aluminium parts, *figure 1*. Reference parts were also milled as comparisons. The joints

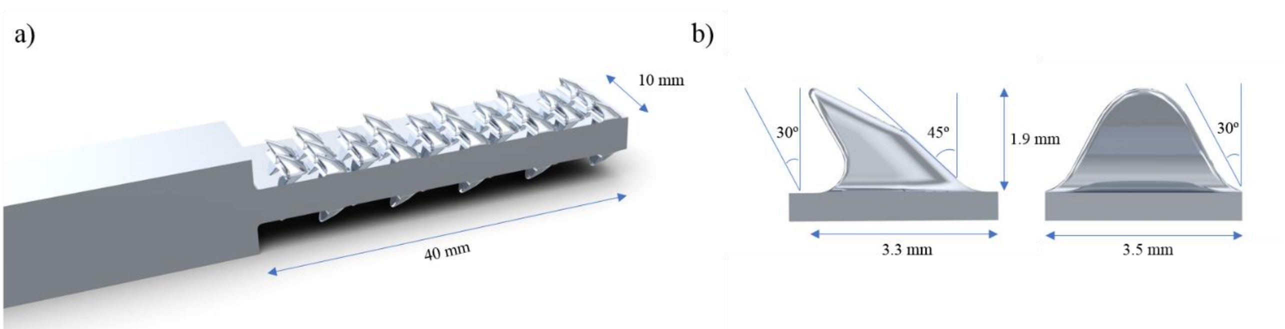

Figure 1. *a) the design of the metal side of joint, displaying scales designed to grab into the carbon-fibre composite b) The general dimensions of the scales seen in a)*

were investigated using dual-energy computed tomography (DECT). The mechanical properties of the bonds were evaluated using four-point bending and tensile tests. The aim was to evaluate the viability and characteristics of the bonds.

The paper starts with a method section that briefly explains how the samples were fabricated and how DECT was employed. This section is followed by the results, displaying CT images and presenting mechanical results. As this is an extended abstract all results could not be included.

2. Materials and Methods

Three types of Aluminium test specimens were fabricated, seen in *figure 2*. Two of the specimens were fabricated using selective laser sintering and one was milled, and sandblasted. One of the AM specimens had scales designed on its surface, measuring approximately 2x3x3mm. The Aluminium parts were bonded to the carbon-fibre composite through wet layup. The composite was made up of 50 layers in total, alternating between plies of +90°/0° and +45°/-45° orientation. The carbon-fibres used were TG300 and the resin was NM 650 epoxy. Curing was performed under vacuum for 24 hours at 21°C followed by 24 hours of curing at 50°C. The final dimensions of the test specimens were 120x10x10mm and can be seen in *figure 3*.

The strength of the specimens bonding was evaluated using four-point bending and tensile tests. In the bend tests the loads were applied outside of the bonded area, resulting in a constant bending moment in the bond. Specifically, the supports were placed 100 mm apart and the load was applied with a spacing of 50 mm, 25 mm from the supports. The moment in the bond could thus be calculated using:

$$M = FL, \qquad (1)$$

where *M* is the moment in the bond, *F* the applied load at each of the loading points, and L the distance between the support and the load (25 mm). Three specimens were tested for each type of bond.

2.1. Dual-energy computed tomography

One of each type of specimens were characterised using DECT. The method used in this work is a variation of the method presented in [8]. The DECT was performed by acquiring two sets of projections, high and low energy, for each specimen and fusing of the projection sets. The projections were fused using templates generated by a sigmodal function and the expression:

$$I(x,y)_f = I(x,y)_H I(x,y)_T + (1 - I(x,y)_T) I(x,y)_L, \qquad (2)$$

where I_f is a fused pixel, I_H a high energy pixel, I_T value from the template (ranging from 0 to 1), and I_L a low energy pixel. The fused projections were finally reconstructed and evaluated in VGStudio MAX [9] using FDK.

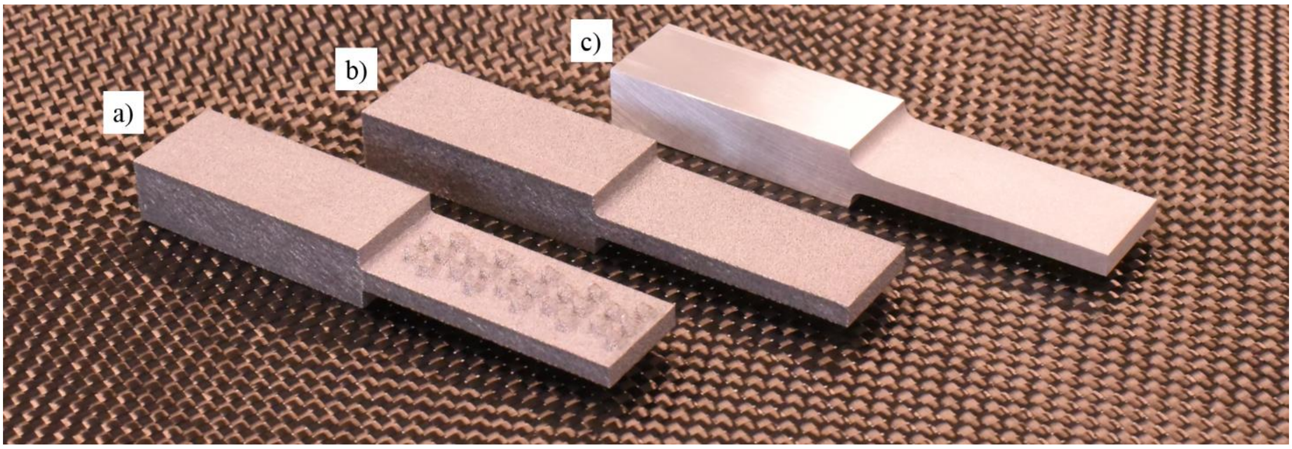

Figure 2. *The Aluminium side of the three types of bonds studied in this work a) Scales fabricated with AM b) Flat surface, fabricated by AM c) Flat surface, fabricated with milling and sandblasting. The samples were fabricated 6 mm too wide so that they could be milled to final dimensions after curing*

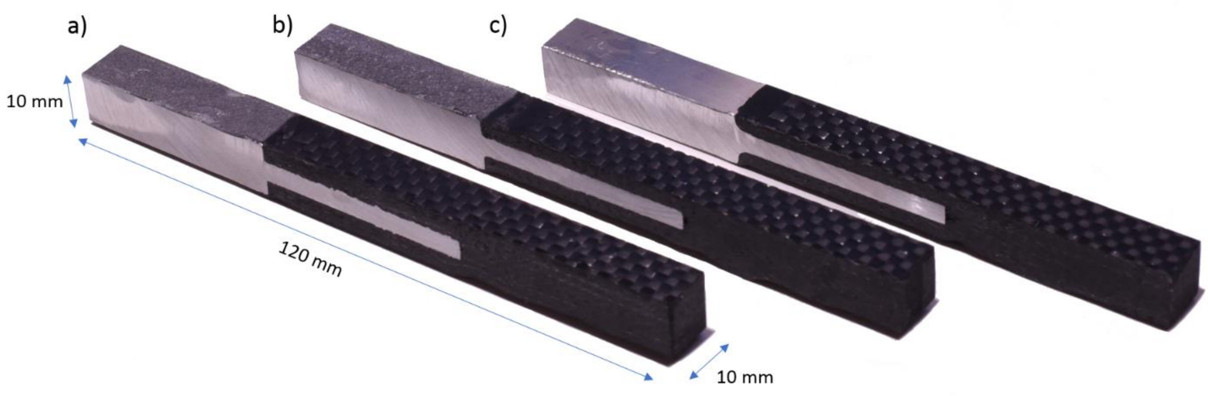

Figure 3. *The finished samples after curing and milling to final dimensions a) AM part with scales b) AM part with no features c) milled part*

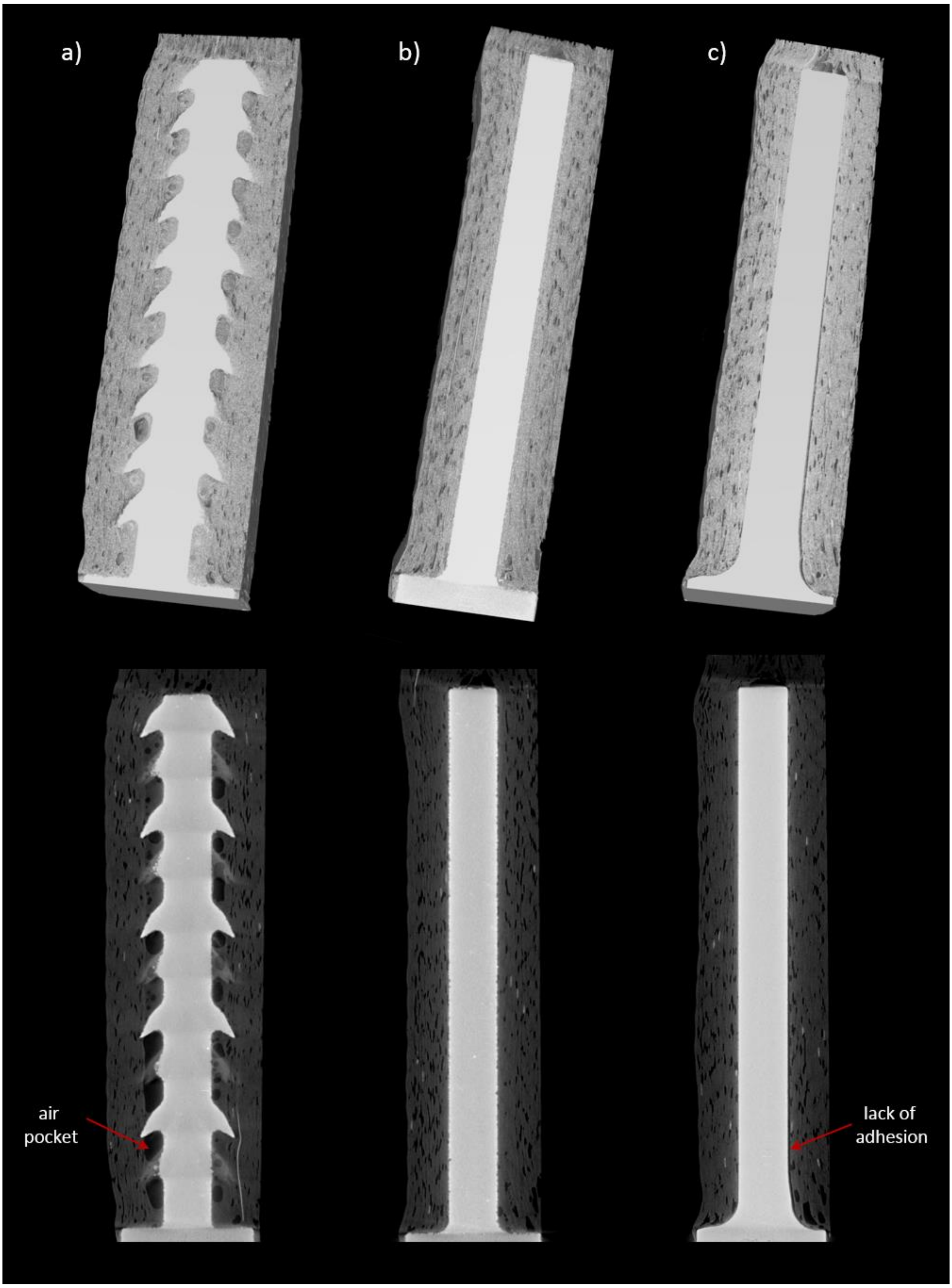

Figure 4. *Results from the CT scans of the samples. The top row contains sliced 3D volumes and the bottom row 2D slices a) Displays the AM bond containing scales. As can be seen, approximately half the height of the scales penetrates the fibre plies and there is significant porosity underneath some of the scales b) The AM bonds without features. The data indicates no problems with the adhesion of the matrix to the metal. The coarse AM surface can be seen interacting with the epoxy matrix c) The milled and sandblasted bond. From the CT images, it can be seen that the plastic composite has partly lost contact with the metal, displaying an air gap*

3. Results and Discussion

Results from the DECT characterisation of the bonds can be seen in *figure 4*. As can be seen from the CT images the scales fabricated on the AM samples does not fully penetrate the fibre plies. A few of the scales show good penetration while other are almost fully outside the carbon-fibre plies. It was also found that there are significant air pockets behind/underneath some of the scale features. For the sample fabricated with AM without surface features it was found that the adhesion between the metal and the epoxy matrix was well developed. The rough surface of the AM part can be seen in the 2D slice and all the small gaps on the surface seems to have been filled with resin, forming a strong bond. For the bond with the milled and sandblasted Aluminium it was found that the adhesion

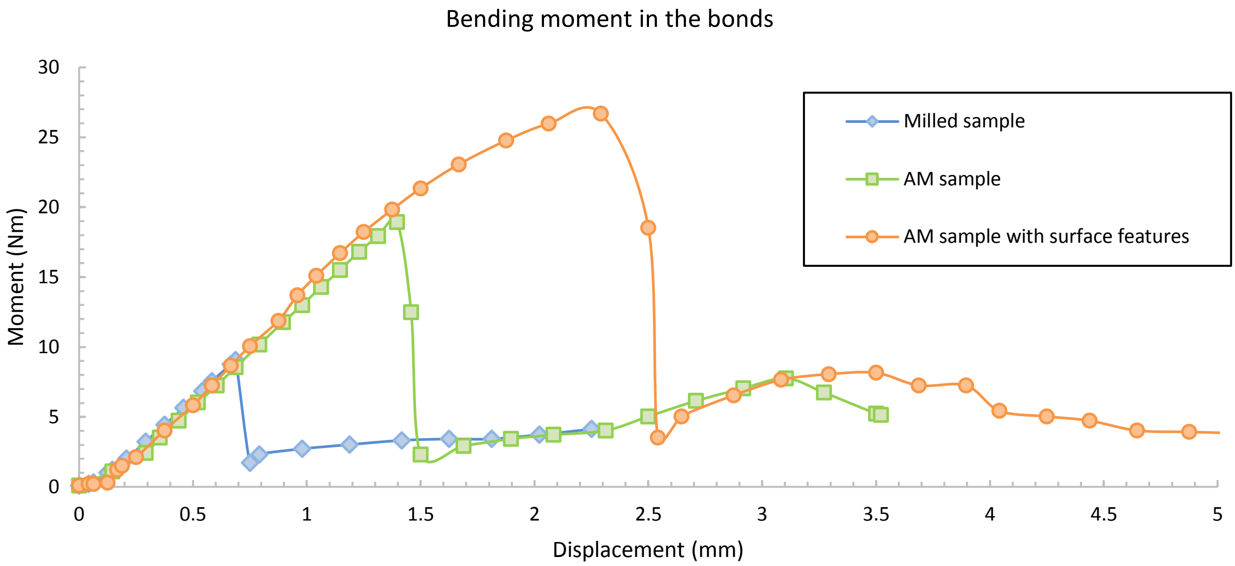

Figure 5. *Characteristic bending moment curves for the three different types of bonds. Flat AM bonds withstood roughly twice the moment of a milled sample and AM bonds with scales withstood almost three times that moment*

between the epoxy matrix and the metal was poor. For the scanned sample, it seemed that almost an entire side of the bond had lost contact.

Results from four-point bending tests of the bonds can be seen in *table 1* and characteristic moment curves in *figure 5*.

Table 1 Test results from four-point bending test for the nine samples that were evaluated.

Sample	Max moment	s. dev.	At displacement	s. dev.
Milled	7.11 Nm	1.73	0.75 mm	0.06
AM	20.17 Nm	1.5	1.38 mm	0.11
AM with scales	29.70 Nm	2.63	2.34 mm	0.15

The mechanical tests showed that the flat AM bonds had roughly twice the strength and flexibility compared to the milled/sandblasted samples. In addition, it was also shown that the strength and flexibility of the AM samples with scales was roughly three times that of the milled samples. The fact that the AM samples with scales displayed significantly better mechanical properties than the other bonds, even though the CT data revealed the overall poor state of the bond, shows the promise of the method. The fabrication of the bond in the lamination stage needs improvement, alternatively the design of the surface features needs to change. The shape of the surface features was, however, designed to allow for freedom of placement during the AM process. Thus, it would be preferable to adjust the lamination process. A vibration treatment, to make plies move down around the features could be a solution.

To numerically determine the strength of the bonds in the AM samples with scales is a difficult task. The interaction between the composite and the metal, and how the defects of the bond affect it, would have to be studied in more detail. However, for the comparison between the other two samples, where the only difference is the surface roughness of the metal parts, the strength of the bond could probably be determined by measuring the interaction area and relating this to the strength. The DECT method could be a valuable tool to achieve these measurements. CT in general is limited by sample size and to achieve results where a surface can be measured, only small samples can be investigated. Thus, limiting the use of CT to development at this point, rather than applications in large components. However, if the fabrication process is perfected at this stage, there should be no need for such inspections.

4. Conclusion

In this work, three types of bonds between aluminium and carbon-fibre composite has been studied. The bonds examined were fabricated using AM and with classical methods. To characterise the bonds a DECT method was employed. The results show that DECT is a valuable tool for characterisation of these types of bonds. It was also shown that bonds fabricated with AM displayed better mechanical properties than milled samples, especially the AM bonds with surface features.

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