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Crack Growth in Directly Bonded Carbon Fibre Reinforced Thermoplastic and Nano-Structured Aluminium Monitored by Time-Lapse Synchrotron X-ray Computed Tomography

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Abstract

The current study examines the 3D damage mechanisms of an aluminium alloy directly bonded to a carbon reinforced thermoplastic using two different types of surface treatments by time-lapse X-ray Computed Tomography (CT). Down-sized double cantilever beam specimens are gradually subjected to increased load by using a simple clamping solution and X-ray CT scans are performed for each load step. The damage mechanisms along with the crack opening relative to the crack length is observed to differ significantly for the two considered bonding cases. The presence of a nanostructure on the aluminium surface is found to divert the crack propagation path and thus strengthening the interface properties of the bond line.

Keywords: time-lapse X-ray CT, dissimilar bonding, carbon reinforced thermoplastic, crack growth

Background and Objective

The use of carbon fibre reinforced thermoplastics (CFRTPs) for industrial application is increasing, however it is rarely feasible to replace an entire structure with CFRTPs and thus bonding to other materials such as aluminium is required. However, it is challenging to join CFRTPs to other materials by adhesives due to their chemically inactive nature, and mechanical joining adds weight to the structure and introduces stress concentrations. Alternative bonding methods such as ultrasonic welding [1,2], friction spot joining [3,4], and induction heating [5] among others [6,7] have been proposed, however limitations to the adherend thickness and limited bonding area still exist. In response to these challenges, the authors proposed an alternative bonding technology [8,9] where CFRTP and aluminium can be strongly bonded directly in a hot-press during the manufacturing process by modifying the aluminium surface. The proposed bonding technology can both be applied for regular joining of parts but can also applied to large areas and therefore is well suited for mass-production of multi-material parts e.g. for the automotive industry. By allowing the technology to be used in industry, it will be possible to use CFRTPs in more applications providing lighter structures with the possibility for recycling of the materials at the end of the structural life. Nevertheless, further understanding of the strengthening and damage mechanisms is necessary.

Thus, the current work studies the damage progression of a crack in a bonded CFRTP and aluminium specimen by monitoring the region around the crack tip in three dimensions (3D) using X-ray Computed Tomography (CT). Visualising the crack progression in 3D makes it possible to obtain an enhanced understanding of the damage and strengthening mechanisms of the proposed bonding technology. Such an understanding is required to establish realistic strength and life-time prediction models, which is necessary for industrial application. Furthermore, it is possible to visualise strong and weak points in the bond by monitoring the crack growth, and thus the current work also provides valuable input on how to improve the bonding technology even further.

Experiments

The experiments of the current study monitored the progression of an interface crack between aluminium and CFRTP by two different bonding methods using time-lapse X-ray CT. The crack progression of the bonded surface was monitored by carrying out repeated X-ray CT scans of the same region and gradually progress the crack using a simple loading clamp device. The crack length was also monitored by a camera with digital image correlation software to monitor the approximate location of the crack. To be able to scan a larger region without compromising the resolution, four overlapping scans were carried out per load step and subsequently stitched into one volume. The time-lapse experiment for each specimen was terminated when the crack-tip had progressed outside field of view of the X-ray CT scan, resulting in a different number of steps for each specimen, since the cracks progressed at different speeds.

Samples: The samples were manufactured as down-sized double cantilever beam (DCB) specimens with the dimensions as shown in Fig. 1(a). For all the specimens, an A5052 aluminium (0.11%Si, 0.3%Fe, 0.03%Cu, 0.06%Mn, 2.57%Mg, 0.22%Cr, 0.03%Zn, 0.02%Ti, 96.66%Al) was bonded to a CFRTP with a polyamide 6 (PA6) matrix using plain woven T300 carbon fibres as reinforcement. First larger specimens were bonded in a hot press at 300C° for 3 minutes, which then subsequently were cut out into the 5x50mm mini DCB specimens used for the X-ray CT experiments. A polyamide insert film was used to create the pre-crack. Experiments were carried out on a total of four specimens, two specimens using as rolled (AR) A5052 aluminium only subjected to a silane coupling treatment, and two specimens using aluminium with a nanostructured (NS) surface combined with a silane coupling treatment. Holes with internal thread were drilled in the pre-cracked region of all the specimens to firmly attach the loading clamp (see Fig 1(b)). The considered specimens were referred to as AR1, AR2, NS1, and NS2. Two load steps were carried out for AR1, three for AR2, six for NS1, and three for NS2.

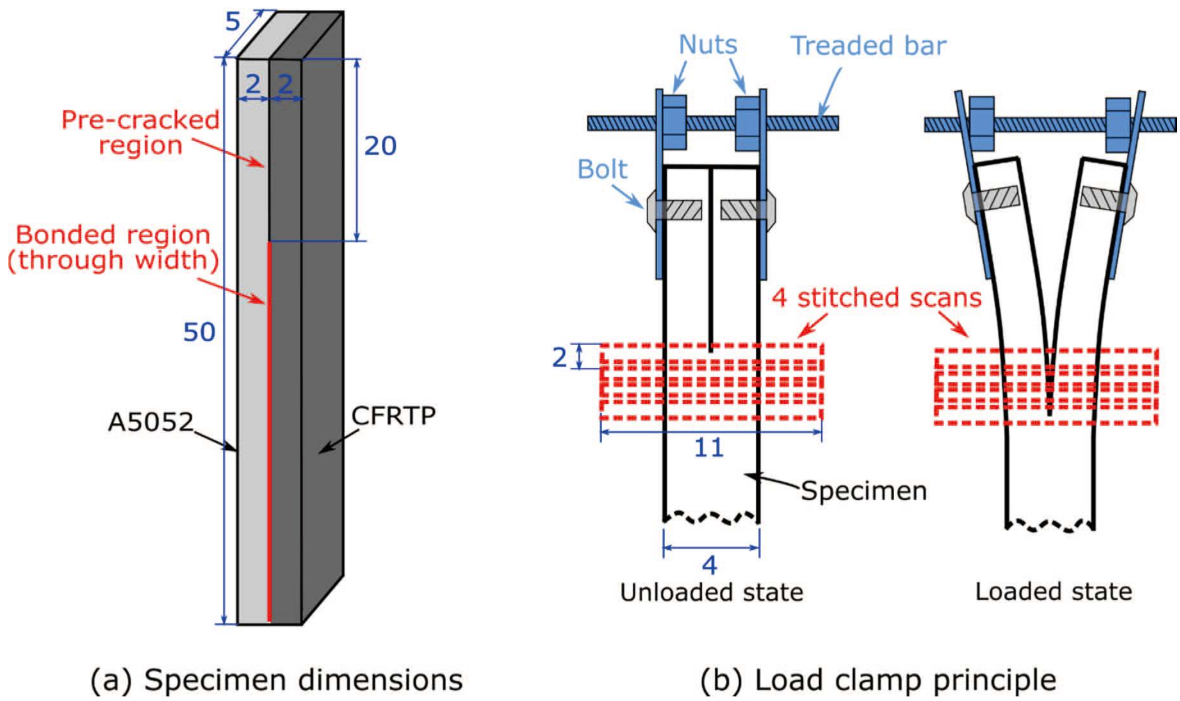

Fig. 1. Illustration of (a) specimen dimensions and (b) load clamp principle for all the samples

Measuring conditions: The X-ray CT experiments were carried out on beamline BL14B2 with an X-ray energy of 30 keV, direct expose interval of 50, rotation step degree of 0.2, camera length of 110mm, and exposure time of 500ms over a 180° rotation. In general, the scan time for the combined four scans was 2.5-3 hours per load step. Due to time limitations, the experiment for the last specimen was carried out with a rotation step degree of 0.5 (lower number of projections). The voxel size for all the X-ray CT scans was 2.86 µm.

Results and Discussion

Fig. 2 illustrates the location of the scanned region of a specimen, along with an example of the monitored crack progression for the NS1 specimen. It is seen that the crack path is diverted away from the bonded interface and into the CFRTP resulting in intralaminar failure. In other words, the high strength of the bond resulted in failure elsewhere, which is generally desired of a joint.

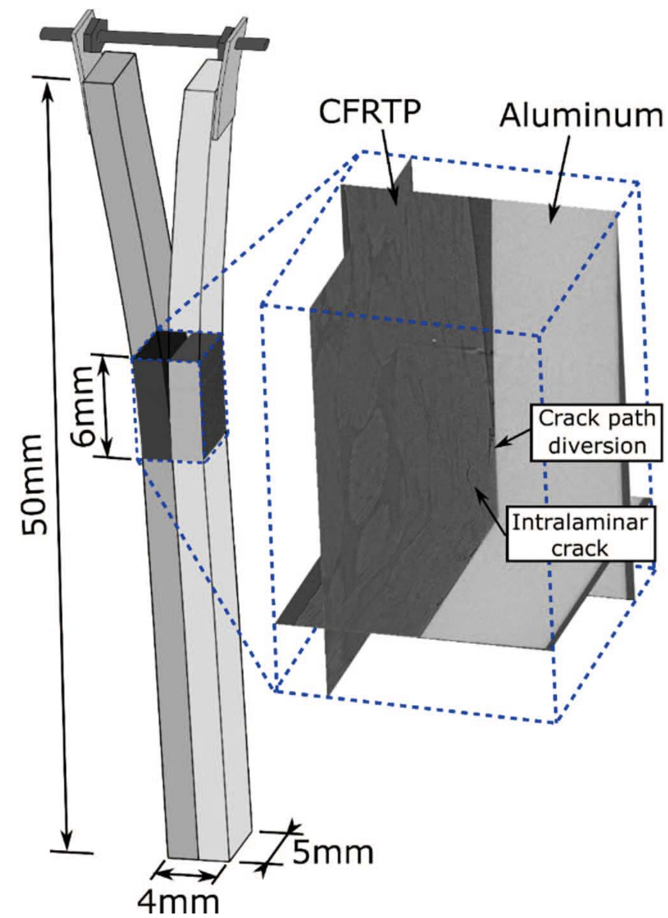

Fig. 2. Example of scanned region on loaded specimen along with crack path for NS1 case

Previous studies using single-lap joint tests to compare the AR and NS cases obtained similar bond strengths [8], since the bond for both cases was sufficiently strong leading failure in the matrix rather than the bond. However, a clear difference is observed in the opening mode of the crack examined in the current study using the mini DCB specimen s. Fig. 3 compares the 2D views of the reconstructed data of the same region for three of the load steps of the AR1 (Fig. 3(a)) and NS1 (Fig. 3(b)) cases. It can be seen that the opening of the specimen relative to the crack length is significantly smaller for the AR case than for NS. Thus, it takes significantly higher force to progress the crack of the NS case than the AR case, showing a significant difference in bonding strength. Furthermore, it is seen that intralaminar failure is induced for the NS case, which was not observed for the AR case. Hence, the presence of the nanostructure was observed to divert the fracture path, which is desired in general, however also should be considered when establishing models to predict the bonding behaviour. In addition, it should also be noted both cases include voids near the bond line. These voids were found to appear in the resin rich regions of the plain weave fabric and only locally close to the bond line and is therefore likely an artefact of the bonding method. Thus, these voids could be avoided by carrying out the bonding procedure under vacuum, which is believed to further improve the bonding properties. If the voids can be avoided, less scatter in the strength data is also expected, which is required for industrial application of the proposed bonding method.

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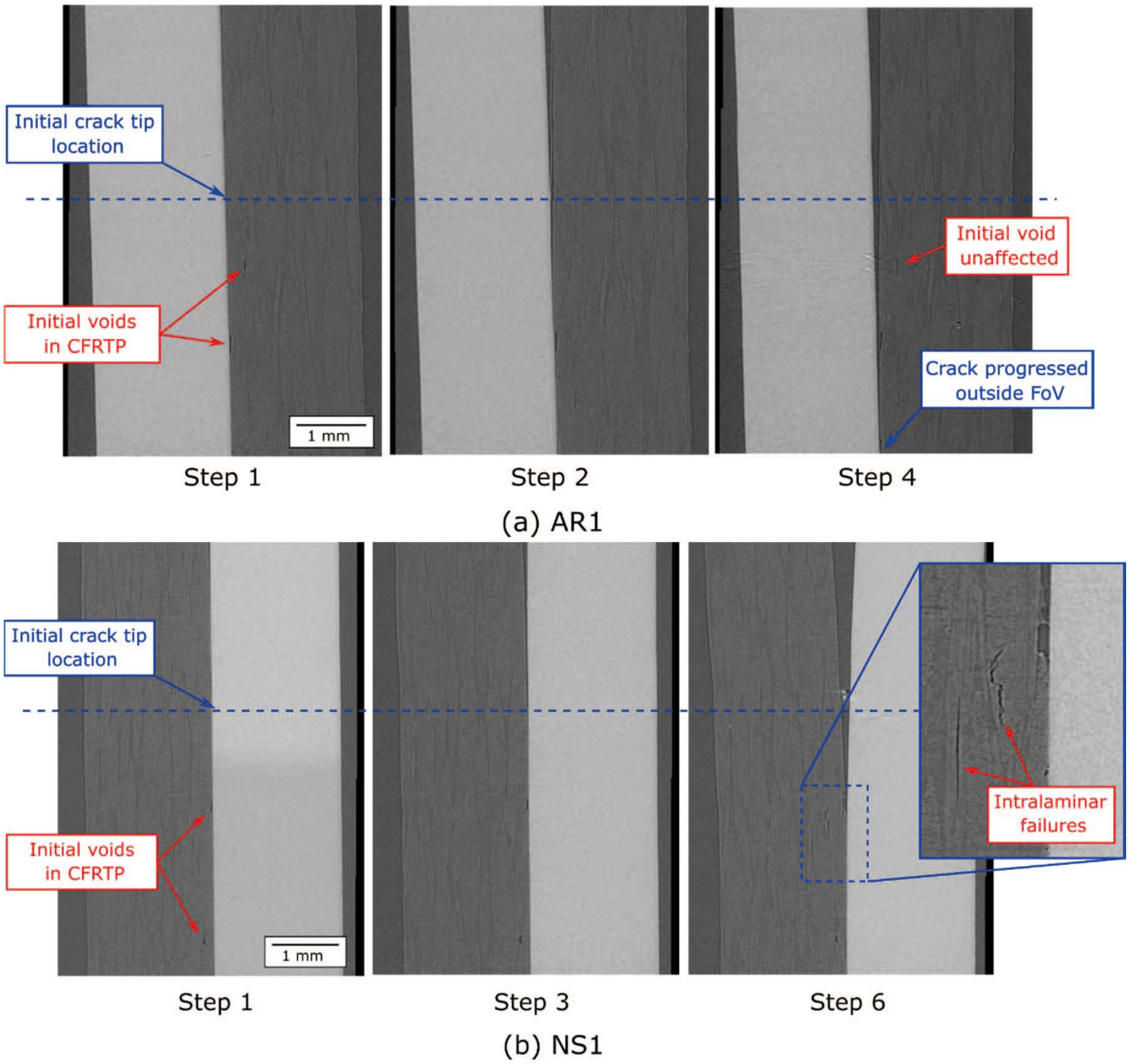

Fig. 3. Reconstructed 2D views of X-ray CT data for the four stitched scans of (a) AR1 and (b) NS1 at different load steps

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