EXPERIMENTAL ANALYSES FOR THE FLAWS CAUSED BY FIBER INSERTION AND STITCHING IN 3D PREFORMED T-JOINT CARBON FIBER REINFORCED POLYMER COMPOSITES USING X-RAY MICRO-COMPUTED TOMOGRAPHY

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ABSTRACT

Stitching can reinforce T-joint structure. However, T-joint and stitching might cause new types of internal flaws due to the characteristic of the structure. The corresponding study was poorly documented, especially using NDT. The purpose of this paper is to indicate internal flaws caused by T-joint and stitching in stitched 3D T-joint carbon fiber reinforced polymer matrix composites.

In this paper, an investigation of internal flaws caused by T-joint and stitching in stitched T-joint carbon fiber reinforced polymer matrix composites was undertaken. A three-dimensional (3D) woven stitched T-joint structure was introduced, which was manufactured using a fiber insertion and three-dimensional woven process. A 100 um overview on the entire component and an 8 um high resolution X-ray micro-computed tomography on the T-joint zone were performed. The corresponding experimental analysis was conducted. As a conclusion, a few types of internal flaws caused by T-joint and stitching are indicated, including fiber preform distortion on the T-joint zone, vertical micro-cracks in the noodle, dry-core (incomplete infusion of noodle core) and resin redundancy. A few types of flaws are excluded from the influence of T-joint and stitching, including matrix cracks, voids and porosities.

1 INTRODUCTION

Composites made from three-dimensional (3D) textile preforms can reduce both the weight and manufacturing cost of advanced composite structures within aircraft, naval vessels and the blades of wind turbines [1]. The in-plane stiffness and strength of 3D woven composites were found to be lower, while the out-of-plane properties were higher compared to conventional 2D laminates [2]. The assembly of 3D complex composite structures indicates the need for efficient joining methods. The most frequently used joint found in structural applications is the T-joint.

Composite T-joints are being used extensively in the marine and aerospace industries. In 1989, the influence of joint geometry on the ability to transfer out-of-plane loads for a hull bulkhead joint in small boats was examined, where the hull bulkhead assemblies were designed on the basis of sandwich beam and laminated plate theories. An analytical solution was developed to predict the failure load, and experimental specimens were produced and tested to failure in order to be compared with the analytical method [3]. In 1992, it was reported that the behavior of joints is very dependent on geometry and material make-up, and the gap between the panels and the edge preparation of the tee piece also influences joint behavior but to a lesser degree. The variations that increase joint stiffness do not always lead to higher joint strengths. An attempt was made towards identifying and evaluating the efficiency of tee joints. The most efficient joint was reported to be using a large radius flexible resin fillet with an overlaminate of minimal thickness, just sufficient to withstand the membrane tensile loads [4]. In 1996, a review was conducted to accelerate research on out-of-plane joints in fiber-reinforced plastic structures including the connections between two orthogonal plate elements and top-hat stiffeners attached to plates, where both single skin and sandwich topologies were included [5]. Another work concerned with T-joints subjected to tension (pull-out) force and the behavior up to ultimate failure was reported in 1996 as well [6].

The purpose of T-joints is to transfer flexural, tension and shear loads to the skin. T-stiffeners are used extensively in aircraft wings in order to prevent skin buckling during wing loading. However, designing composite joints is more difficult than metallic joints due to the mechanical properties of composite materials. Composites are anisotropic and have a limited ability of yielding. The low degree of yielding means that stress concentrations are not relieved by plastic deformation, which is important in multi-fastener single-lap joints. The distribution of load between the fasteners may be more uneven than in metallic joints due to the fact that the stress concentrations around the holes are not relieved [7]. In the design of T-joints, filler is inserted in T-joints and resin is used to reinforce the structure. The fiber insertion technique has the potential of creating a low-cost T-joint with improved damage tolerance and failure strength. In 2001, an experimental and numerical investigation of transverse stitched T-joints in flexure and preliminary experimental results in tension were conducted using PR520 toughened epoxy resin, where it was reported that flexural specimens failed in part due to unsymmetrical loading of the fiber insertions and in part from high stress concentration in the resin-rich fillet region; tensile specimens had symmetric loading of both sets of fiber insertions and failed due to matrix cracking at the web-to-flange interface; both flexure and tension specimens exhibited additional load carrying capability beyond initial failure indicating a significant damage tolerance [8].

Non-destructive testing (NDT) of composite materials is complicated due to the wide range of defects encountered (including delamination, microcracking, fiber fracture, fiber pullout, matrix cracking, inclusions, voids, and impact damage). The ability to quantitatively characterize the type, geometry, and orientation of defects is essential [9]. The ability to accurately characterize such micro-size defects is a challenge. As a radiographic technique, high-resolution X-ray micro-computed tomography is used to inspect internal flaws through the reconstruction of the interior structural details on a scale of interest. However, the corresponding study on T-joint was poorly documented.

Stitching can reinforce T-joint structure. However, T-joint and stitching might cause new types of internal flaws due to the characteristic of the structure. The corresponding study was poorly documented, especially using NDT.

The purpose of this paper is to indicate internal flaws caused by T-joint and stitching in stitched 3D T-joint carbon fiber reinforced polymer matrix composites. In this paper, a 100-um overview and an 8-um high resolution X-ray micro-computed tomography were performed to characterize internal flaws. The corresponding experimental analysis was conducted. As a conclusion, several different types of internal flaws caused by T-joint and stitching are indicated. A few types of flaws are excluded from the influence of T-joint and stitching.

2 MATERIALS

The T-joint component selected for this evaluation was sewn using stacked TC-06-T 3k carbon fiber. The 3D architecture was woven using 3K/12K carbon fiber. A continuous row of stacked 12K tow fiber was used for insertion. A toughened epoxy resin infusion system was selected.

The T-joint component was fabricated using three-dimensional (3D) preform consisting of multiple layers of woven fabric. The noodle for T-joint insertion was pre-shaped through compaction. During processing, the twisted round-shape stacked 12K carbon fiber tows were placed into the molding tool and compacted to a triangular-shape as the tool was bolted together. After the fiber insertion process was completed, the resin infusion process was initiated. The T-joint dimensions is 12.6 mm X 6.3 mm. The radius of the T-joint is 6.3 mm, shown in Fig. 1a. The area of the T-joint is 17 mm^2. The complete 3D preform model is shown in Fig. 1b.

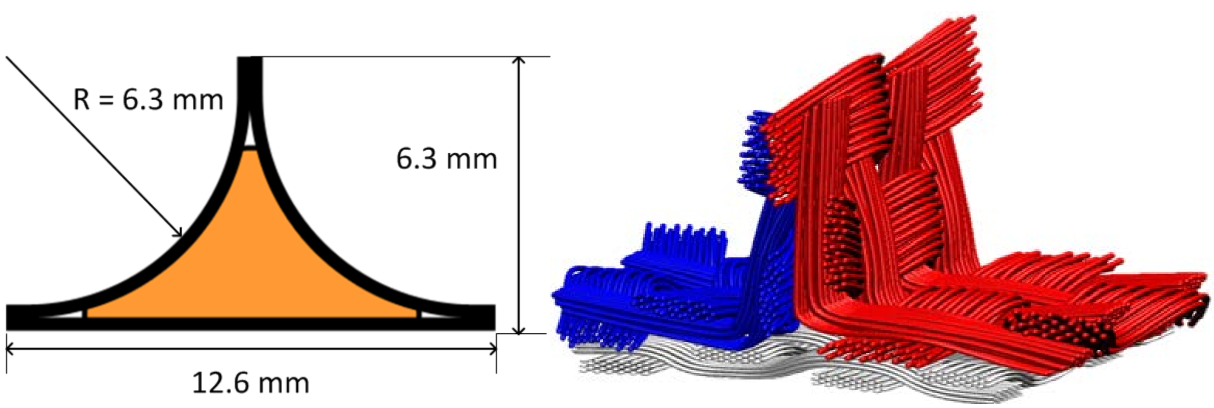

Figure 1: (a) The T-joint dimensions, (b) the complete 3D preform model.

The complete stitched T-joint carbon fiber reinforced polymer matrix composites specimen is shown in Fig. 2. This specimen contains 6 stitching lines. The purpose of these stitching is to consolidate the T-joint structure and to reduce dry-core (incomplete infusion of noodle core). The specimen measures 152 mm in length, 148 mm in width, 63 mm in height, 5 mm in thickness (excluding the T-stringer).

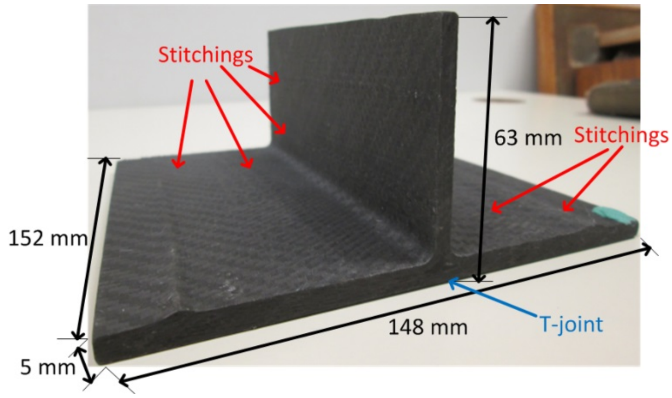

Figure 2: The complete stitched T-joint carbon fiber reinforced polymer matrix composites specimen.

3 X-RAY COMPUTED TOMOGRAPHY

3.1 Micro-CT

The division between what is considered 'conventional' computed tomography and 'micro-tomography' is an arbitrary one, but generally the term micro-tomography is used to refer to results obtained with at least 50-100 um spatial resolution [10].

X-Ray computed tomography (CT) has become a familiar technique, mainly due to its use in medical applications. However, the application of micro-CT is limited within the measurements largely dependent on scientists with expertise in X-ray techniques and instrumentation. Recently it is also increasingly gaining popularity as an accessible laboratory technique for NDT of materials and components, especially due to the recent appearance of several commercial systems. Such instruments offer the potential for the widespread use of micro-CT as a tool for characterization of damage in composite materials [11].

Application of micro-CT to composite materials was concentrated on metal-matrix and ceramic-matrix composites in the past. The spatial scale of features in these materials including fiber location and waviness [12], fiber breakage [13], local porosity and density [14], void volume [15], fatigue crack growth [16], etc. are accessible to micro-CT. However, recently some studies on polymer matrix composites have also been reported. In 2000, impact damage including fiber fracture and delamination in T300/914 carbon fiber/epoxy laminates was characterized [17]. In 2002, impact damage in an epoxy/E-glass composite was also measured [18]. In 2004, micro-CT was used to determine internal structure in a polymer foam reinforced with short fibers [19]. In 2005, a study was undertaken to assess the capabilities and limitations of micro-CT for fiber-reinforced polymer-matrix composites, where different specimens with a variety of damage types, geometries and dimensions were investigated to assess the effect of the system resolution on the ability to determine the internal geometry of flaws including delamination, matrix crack, and especially micro-crack, which is a subject of critical interest in the study of fiber-reinforced polymer-matrix composite laminates [11]. In 2006, an evaluation of micro-CT was performed to determine the geometry of fiber bundles and voids in glass fiber reinforced polymers (GFRP). As a consequence, each fiber bundle and inter bundle voids can be observed separately [20].

3.2 Experimental details

An X-ray micro-CT was performed using 100 um resolution for an overview inspection on the entire component. Then an 8-um high resolution inspection was performed on the T-joint zone. The inspected area is 10 mm X 10 mm. The inspection results are marked in the three-dimensional coordinate system: x-y, y-z, x-z. The inspection data can be reconstructed as a model in the three-dimensional coordinate system, shown in Fig. 3.

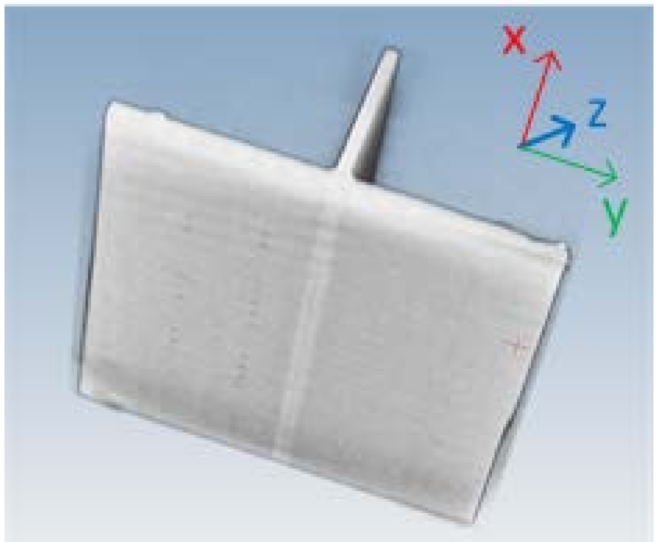

Figure 3: The inspection data reconstruction in the three-dimensional coordinate system, resolution: 100 um.

4 RESULTS AND DISCUSSION

The carbon fiber reinforced polymer matrix composite with a T-joint was inspected and the corresponding analysis was performed. The inspected defects include fiber preform distortion on the T-joint zone, matrix cracks and vertical micro-cracks in the noodle, dry-core (incomplete infusion of noodle core), voids and micro-porosities, resin redundancy. These defects are located in the T-joint zone or caused by the T-joint.

4.1 Fiber preform distortion

Under the 100 um resolution overview inspection on the entire component, the fiber preform distortion was inspected on the T-joint zone. In Fig. 4, the coordinate system is marked y-z. The depth of the inspection in Fig. 4 is 4 mm (the distance to the flat surface, marked x-axis). The fiber preform distortion takes place from a depth of 3.4 mm to 4.6 mm (x-axis).

The potential cause of this type of fiber preform distortion is the interaction of the resin infusion and the T-joint structure. The fiber preform distortion can reduce the mechanical parameters of the entire component by causing fiber preform non-uniformity and resin redundancy in the partial zone. Caution in the procedure of the resin infusion regarding the T-joint structure is essential to the T-joint composite manufacturing.

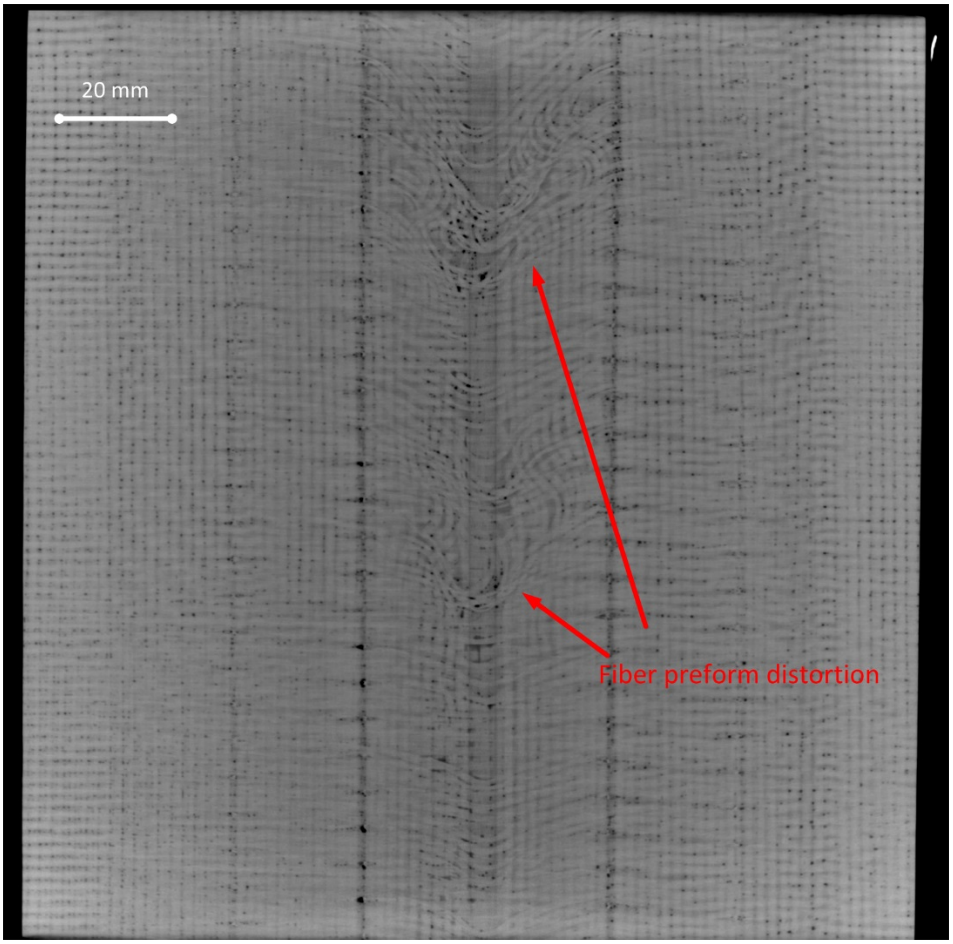

Figure 4: The fiber preform distortion on the T-joint zone, depth: 4 mm (x-axis).

4.2 Matrix cracks and vertical micro-cracks in the noodle

The 8 um high resolution micro-CT inspection was performed on the T-joint zone. In Fig. 5, the inspection was performed almost near the surface (the depth is marked z-axis). The coordinate system is marked x-y. Matrix cracks and vertical micro-cracks in the noodle were inspected.

The first slice of the 8 um micro-CT inspection is the T-joint surface (z-axis). The matrix cracks with yellow mark in Fig. 5 can only be inspected in the first 30 to 40 slices. Therefore, the cracks are evaluated as surface cracks. The depths (z-axis) of these cracks are from 0.24 mm to 0.32 mm.

The disparate type of vertical cracks with purple mark shown in Fig. 5 can be inspected in the entire thickness (z-axis) of the T-joint. The depth of the vertical crack A with purple mark in Fig. 5 is 0.64 mm (z-axis). In Fig. 6, two other vertical micro-cracks B and C are marked in purple. The inspection is from a depth of 0.712 mm (z-axis). The depth of the vertical micro-crack B is 1.04 mm (z-axis). The depth of the vertical micro-crack C is 0.96 mm (z-axis).

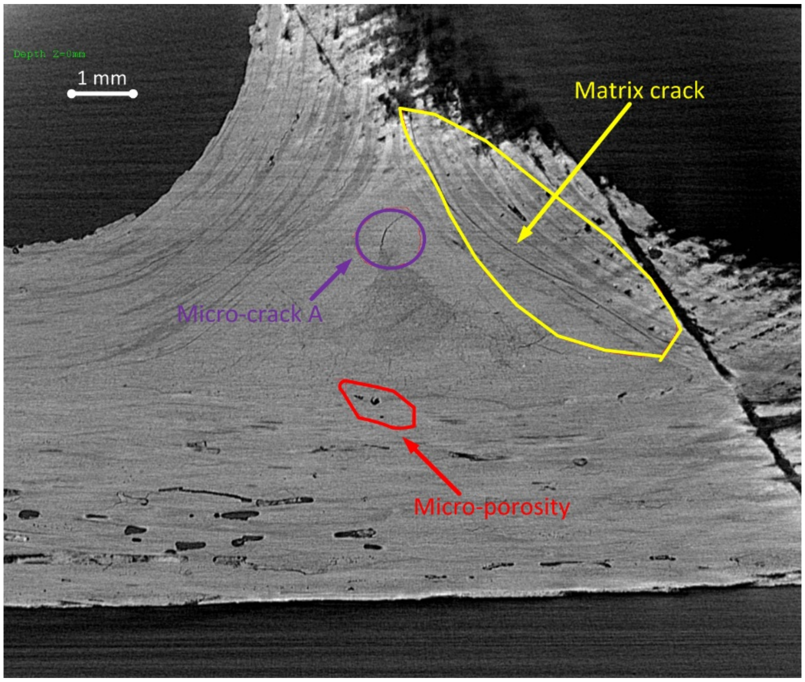

Figure 5: The um high resolution inspection on T-joint zone, depth: almost near surface (z-axis).

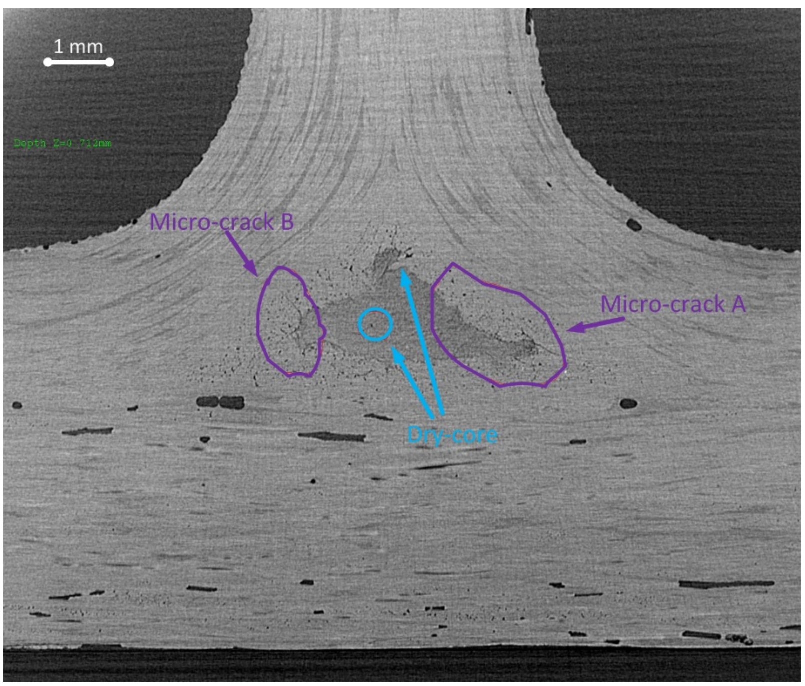

Figure 6: The 8 um high resolution inspection on the T-joint zone, depth: 0.712 mm (z-axis).

The potential cause of the vertical micro-cracks in Fig. 5 and Fig. 6 is the stitching, which increase the tension in the T-joint. Cracking is one of the fatal flaws in composites manufacturing, which can reduce mechanical parameters critically. Caution in the procedure of stitching and the development of new stitching methods are essential to the T-joint composite manufacturing.

4.3 Dry-core (incomplete infusion of the noodle core)

An essential consideration of stitching in this component is to reduce dry-core, which is caused by incomplete resin infusion of the noodle core. However, dry-core consisting of a few sub-micro-sized voids in the noodle is still inspected. These voids in the noodle are of sub-micro size, which is difficult to measure accurately. In Fig. 6 and Fig. 7, two larger voids in the noodle are marked in blue. Fig. 7 is the inspection from the depth of 1.056 mm (z-axis).

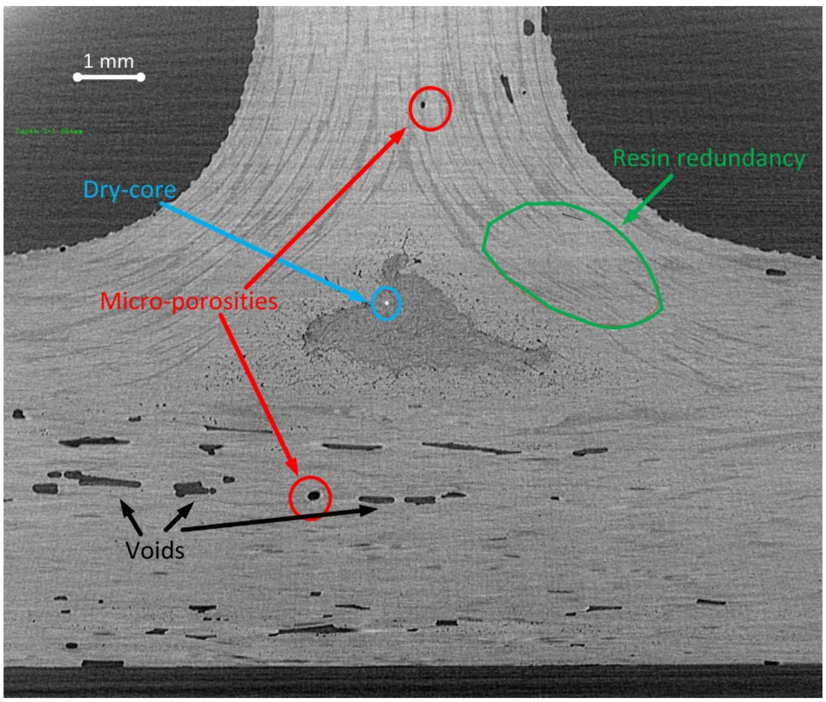

Figure 7: The 8 um high resolution inspection on the T-joint zone, depth: 1.056 mm (z-axis).

4.4 Voids and micro-porosities

Some voids are inspected in this component. A few of these inspected voids are micro size, which are defined as micro-porosities. In Fig. 5 and Fig. 8, typical micro-porosities are marked in red. Fig. 8 is the inspection from the depth of 1.28 mm (z-axis).

Voids and micro-porosities are essential flaws to composites manufacturing. However, it is difficult to conclude that T-joint and stitching cause the presence of voids and micro-porosities.

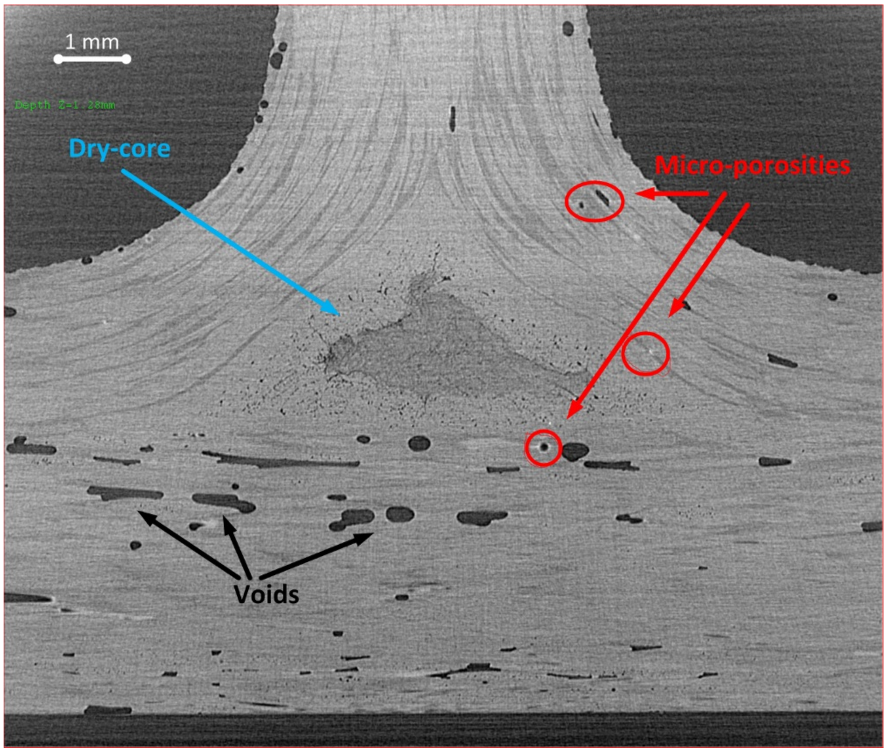

Figure 8: The 8 um high resolution inspection on the T-joint zone, depth: 1.28 mm (z-axis).

4.5 Resin redundancy

Resin redundancy is inspected in the T-joint zone. In Fig. 7, an evident resin redundancy zone is marked in green. Resin redundancy is also one of fatal flaws in composites manufacturing. The resin redundancy takes place more often in T-joint zone than in the flat zone. Therefore, one can conclude that the T-joint has an influence on the increase of resin redundancy.

5 SUMMARY

These results demonstrate that high resolution X-ray micro-CT can perform confident characterization of the internal flaws in the T-joint zone of carbon fiber reinforced polymer matrix composites. The fiber preform is distorted on the T-joint zone. The T-joint can cause the presence of vertical micro-cracks in the noodle and the increase of resin redundancy. No evidence indicates that the T-joint can cause the presence of voids and micro-porosities. The stitching is incapable of entirely eliminating dry-core in the noodle. A comprehensive comparison of high resolution X-ray micro-CT inspection on non-stitched T-joint and stitched T-joint samples is significative to indicate the influence of stitching.

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