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Computed Tomography as a Tool for Examining Surface Integrity in Drilled Holes in CFRP Composites

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Abstract

In light weight structures the joining of composite materials and of composites to metals are key technologies. A manufacturing method associated with joining is the drilling of holes. The hole creation in CRFP through drilling is associated with several defects related to the process, both on the entry and exit sides of the hole and also with dimensional and surface roughness issues of the hole wall. The detection of damage due to the process is not trivial. Especially interesting is non-destructive methods.
In this work X-ray computed tomography is used to determine defects due to drilling of holes in a CFRP composite using twist drills with different geometrical features at different drilling parameters. The results can be used to establish relationship between different geometrical features of drills in combination with cutting parameters and resulting surface integrity of holes.

Keywords: Computed tomography; Drilling; Composite; Inspection; Surface integrity;

1. Introduction

The concern for global warming and cost of fuel has led to an increasing demand on light weight structures in the transportation industry. Introduction and increased use of Carbon Fibre Reinforced Polymer, CRFP materials is one way of tackling this demand. In the aero engine industry the target for such new material are primarily components found in the cold section of the engine, for instance, fan case, vanes and fan blades. Obstacles in the introduction of these components are technologies for assembly and joining, for instance the fastening of vanes in the fan case. These are fastened using bolt joints where the bolt is put through a bushing that is fitted in a through hole in the component ensuring a diversified load distribution around the hole to minimize stress concentrations.

Drilling holes in CRFP, may result in damages of the material as the drill work its way through the material. Several types of defects are related to the drilling operations, both on entry and exit of the hole and also dimensional defects, surface roughness and surface integrity issues of the hole wall. Flaws that may be caused by machining process conditions are e.g. matrix cracking, fibre fracture, de-bonding, delamination and fibre pull-out. To decrease the damages caused by drilling is not only a life issue but also economical. Poor hole quality is the cause of nearly 60 per cent of all components that is discarded [1]. Since drilling is often one of the final machining operations, and a damage occurring at that stage causes huge economic losses when almost finished parts need to be rejected.

Understanding and detecting type, size and location of defects that drilling operations may generate are important for CRFP components. This is important both to be able to set correct safety factors in the design of component to the expected life and in production control for securing system safety for joints in mixed materials. Methods for assessing delamination damage around

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holes have been developed e.g. by Davim et al [2]. Many of these methods however are only handling the damages in two dimensions due to the difficulties in the detection of damage. The ability to detect defects in an efficient manner is thus critical.

To reduce the risk of damage and at the same time have high productivity is not trivial. Teti [3] have presented a review of literature up to 2001 covering several aspects of machining of composite materials, not only restricted to CRFP. In this, the impact of process conditions on hole quality is briefly discussed. Hocheng and Tsao [4] investigated different geometries of drills and based on that discussed forces and the effect on delamination at the exit of the hole. In a recent review, Liu et al. [1], effects of drill geometry and process parameters are discussed. From this, it is evident that there is not a common understanding regarding correlation of process conditions and defects in literature. This may be due to different sensitivity for the different types of damage for different materials. It may also be a result of that different researchers have focused on different effects and not so much on the combination of several geometrical features and process parameters in combination. Beno et al. [5] have studied the combined effects of drill geometry and process parameters on damage and productivity in CRFP. They pointed out the lack of standards for how to evaluate and classify defects in holes in CFRP materials. In their work, a classification system was defined based on optical inspection of damage. The drawback with this method is the method of evaluation of defects. Especially sub surface defects were not detected with that approach. The work in this paper is therefore looking at the possibility of using X-ray computed tomography (CT scan) [6] to evaluate surface integrity in drilled holes in CFRP composite materials.

2. Experimental

2.1. *Materials and process parameters*

The CFRP composite material investigated is a quasi-isotropic C fibre/epoxy-composite laminate. Each layer is about 0.25 mm thick, built according to [45/0/-45/90] fibre directions. In total 16 layers with the fibres (in bundles) in different directions is used. Each bundle contains about 12 000 fibres with a linear density of 800 tex (= 800 g/1000m). Each layer is held together by thin bundles of glass fibres. The C-fibres are TohoTenax HTS40 the glass fibers are E-glass and the epoxy is Hexcel HexFlow RTM6.

A process window for drilling was chosen that include the extreme values from drill vendors recommendations. The cutting parameters applied during the drilling operations varied between; cutting speed [m/min] 60-120, feed [mm/r] 0,03-0,09. Details of drilling experiments are given in Beno et al. [5].

2.2. *Examination of defects*

Two methods of inspection were used in evaluating defects: optical microscopy and X-ray computed tomography. Optical inspection was performed using light stereo microscopy together with the evaluation method as described in detail in Beno et al. [5].

X-ray computed tomography was performed using an industrial metrology CT system with a 225 kV X-ray source, 3μm minimum focal spot size, and flat panel detector with 2000 x 2000 pixels at 16 bit. A number of different set ups were tested to determine the optimal scanning parameters for the drilled CFRP composite material analysed in this work. Consequently, the optimized scanning parameters used in this work are reported in Table 1. The resulting voxel size (i.e. the dimension of the volumetric pixel unit) was about 3.8 μm3 and was sufficient for clear imaging of single fibres and for detecting the defects of interest. To minimise the actual focal spot size on the X-ray target, an electron beam power of only 9 watts (out of possible 225 watts) was used. No physical filtering was applied to the X-rays.

The X-ray projections were used to reconstruct the investigated 3-D volume using filtered back-projection algorithm. For separating different materials and determining their interfaces, thresholding of the reconstructed volume was done with commercial software using adaptive surface determination methods. The CT data were then analysed both for surface and sub-surface defects, taking advantage of the high-resolution 3-D reconstructed model showing different material in different grey-level voxels. In addition, internal slices of the part were visualized by sweeping a sectioning plane around the hole to examine internal defects associated with the drilling process. Finally, dimensions of defects and geometry of the hole could be measured from the 3-D reconstructed model, using dedicated software for coordinate measurements.

Table 1. CT scanning parameters.

Voltage	Tube current	No. of projections	Exposure time	Voxel size
80 kV	116 μA	3142	4 s	$(3.8\ \mu m)^3$

3. Results

3.1. *Optical microscopy*

A common damage in CRFP associated with the layer structure of the material is delamination. The material is strong in the direction of fibres but quite weak perpendicular to this direction making it susceptible to cracking between layers. This is called delamination. This type of damage is of high importance and is difficult to detect in optical microscopy. It may occur primarily at the entrance side or exit side (Figure 1) due to pull or push forces from drilling respectively.

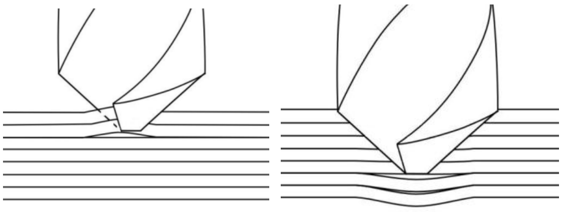

Figure 1. Pull at the drill entrance and push at the drill exit.

When fibres or strands are torn apart from the matrix in the composite material is called de-bonding. This is a big issue in drilling. As a result the fibres are remaining in the hole where the material should have been cut (Figures 2 & 4). This is especially abundant at the exit side of the hole. It may also be found at lower extent in the hole wall. Parts of the fibre material may be torn from the hole edge (Figure 3), this is called fibre pull-out. To some extent pull-out may also be found in the hole wall.

Figure 2. Typical de-bonding damages detected by optical microscopy. The hole has a nominal diameter of 9,5 mm.

Fibre cracking is a damage that occurs inside or on the surfaces of the material as a cause of the torque movement of the drill. The fibres are crossing each other in different layers and sometimes the drilling operation disrupts the order and cracks the fibres inside the material rather than at the surface. This type of damage is difficult to detect in a proper way using optical methods only.

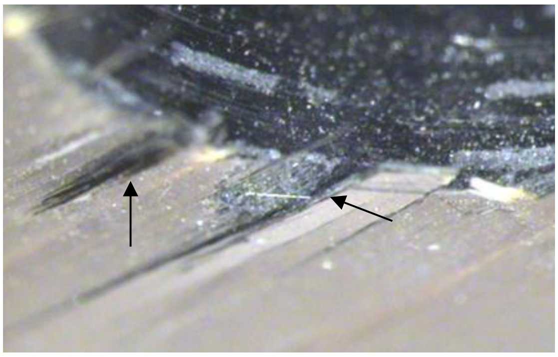

Figure 3. Typical fiber pull-out damages at the hole edge as detected by optical microscopy. The hole has a nominal diameter of 9,5 mm.

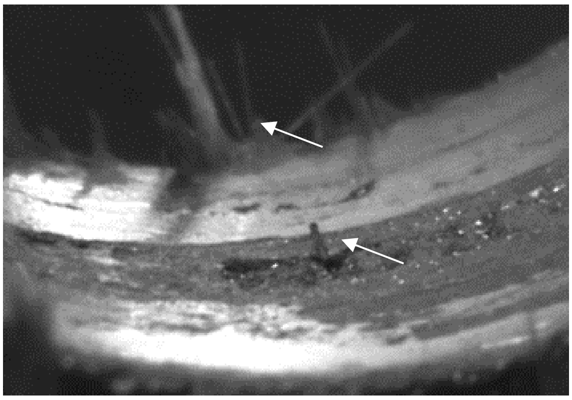

Figure 4. Internal surface of a 9,5 mm diameter drilled hole. Typical cracking and de-bonding damages as detected by optical microscopy.

3.2. *Computed tomography*

The investigated 3-D volume reconstructed from the X-ray projections using a filtered back-projection algorithm could be analysed both for surface and sub-surface defects. Surface defects and surface properties such as fibre de-bonding and surface roughness could quite easily be investigated. Figure 5 shows a typical surface image of a drilled hole based on the reconstruction of the x-ray images.

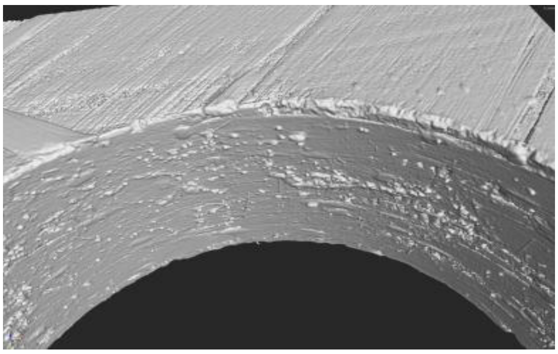

Figure 5. A 3-D model reconstructed from CT scan of the drilled hole, outer surface. The hole has a nominal diameter of 9,5 mm.

Computed tomography gives a lot more information than the optical microscopy. Due to density differences between the carbon fibres, the epoxy resin and especially the glass fibres, the different materials can be easily distinguished in the CT scan information.

Based on this, glass residue from cracked glass fibres, was detected on the surface of the hole, as shown in Figure 6. This was something that was not easily detected in the optical inspection. Furthermore, using a thresholding procedure for separating the grey-levels corresponding to different materials, internal and external surfaces can clearly be identified and specific materials can be selected in the 3-D volume reconstruction. Figure 7 illustrates one way of highlighting the glass fibres material. In this case a red colour is used in order to clearly discriminate it from the surrounding material.

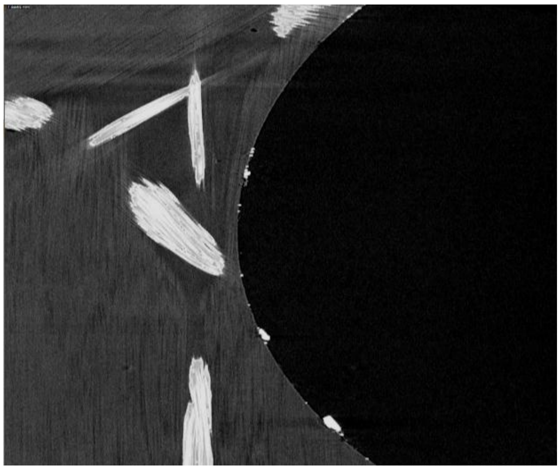

Figure 6. CT slice with glass particles residue in the hole wall shown in white. Hole diameter 9,5 mm.

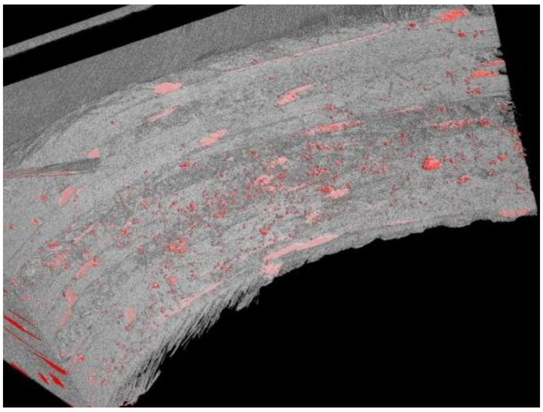

Figure 7. CT image of the inner wall of a 9,5 mm diameter hole, with glass fibre material highlighted in red.

A way to even further enhance the possibility to separate different materials is by virtually isolating a particular material from the rest of the part. This was done for the glass material to make sure that the glass at the surface of the hole was crushed particles attached to the hole and not just parts of fibres still part of the fibre weave. The result from this is shown in Figure 8. This glass residue is a result from the machining process and it differs in amount due to the drilling process used. The glass may potentially be dangerous to the integrity of the hole in a joining situation. The glass particles are rather hard and when a bolt or a bushing is pressed into the hole these particles may be pressed into the hole wall and may there act as crack initiation sites both as stress concentration sites and as “hardness indenters”.

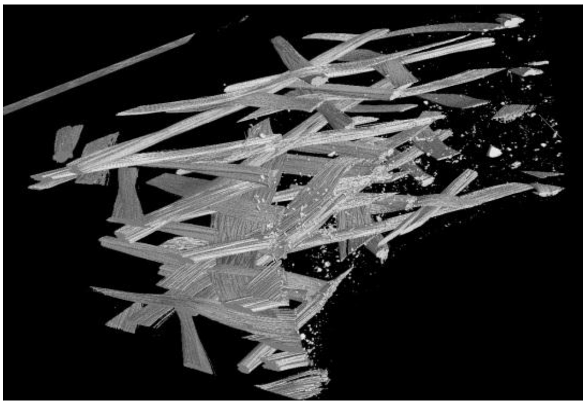

Figure 8. 3-D model reconstructed from CT scan of the drilled hole (same sample as in figure 7) filtered to show only glass material. This shows that the glass particle residue is concentrated to the hole surface.

Dimensions and volumes of glass particles detected on the surface of the hole were measured directly on the 3-D volume reconstruction using a commercial software, showing that the largest of these glass particles had a volume of 104•103 voxels, corresponding to 0.0058 mm^3.

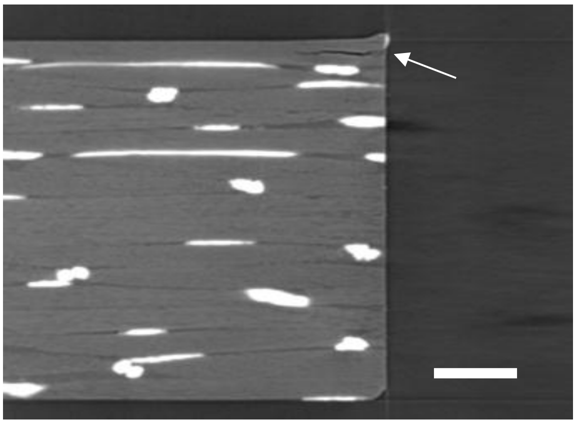

Figure 9. A virtual slice from a CT scan of a drilled hole in a CFRP composite with a delamination crack at the exit side (top) of the hole. White in the picture is glass fibre material. White bar 1 mm.

Setting a virtual plane perpendicular to the hole wall and sweeping this around the hole made it easy to inspect the surface and near surface region of the hole wall. Here both delamination cracks and near surface and sub-surface cracks could be detected (Figure 9 and 10). Delamination cracks with length up to 1 mm were detected.

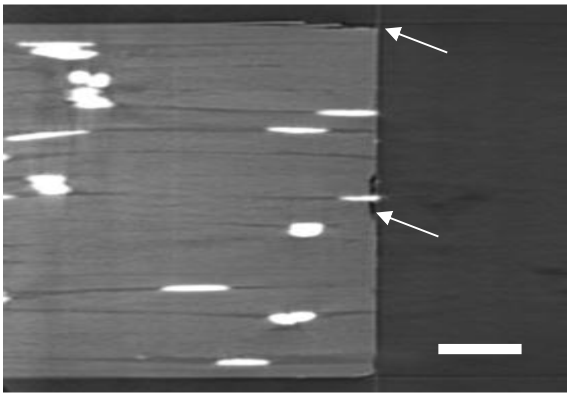

Figure 10. A virtual slice from a CT scan of a drilled hole in a CFRP composite, fibre fracture at the exit (top) side and in the hole wall. White bar 1 mm.

The real advantage of this method is the ability to inspect the complete surface and near surface region of the hole. The 2-D images that can be reproduced in a publication is only giving a limited picture of the power of the method. Working in a "video"-mode, when inspecting the complete surrounding of the hole was the method used in this work.

After applying the adaptive surface determination method (thresholding process), the hole surface was extracted and its diameter was measured, fitting a cylinder (Gaussian fitting method) to the extracted surface. The measured diameter was 9.53 mm. The measurement of diameters using metrological CT systems is generally possible with sub-voxel accuracy, as demonstrated in [7]. However in the specific case of this work, the uncertainty of the diameter measurement is dominated by the form error (cylindricity error) of the drilled hole. In this case this is larger than 0.1 mm, resulting in a relatively poor accuracy.

4. Discussion

Optical inspection has several drawbacks when determining surface integrity of drilled holes in CFRP composites. The obvious problem is the determination of sub surface defects. Damages that affect the surface integrity of the drilled holes are mostly local phenomena. This leads to problems not only when using non-destructive surface inspection techniques, but also when using traditional metallographic methods with cut ups and polishing. The chance of finding the defects with these methods are rather small due to the ratio between inspected volume in a cut up and the total volume of the near surface region around the hole.

When using optical methods the quantification is as evident from the above discussion not easy and to a large extent not meaningful. These methods are more qualitative methods for classifying defect density and categorising them into; no defects detected, small, medium or large defects, as in Beno et al [5].

Table 2. Detectability of defects with different types of inspection methods.

Defect type	Optical inspection	Computed tomography inspection
Delamination	No	Yes Potential for quantification
De-bonding	Yes	Yes
Fibre cracking (at surface)	Yes (not to all extent)	Yes Potential for quantification
Fibre cracking (sub surface)	No	Yes Potential for quantification
Fibre pull-out	Yes (at edges, not easy in the hole wall)	Yes
Glass residue	No (to some extent if expected/known)	Yes Potential for quantification
Dimensional error	No	Yes

The use of CT scanning and sweeping a plane around the reconstructed hole makes it much easier to cover larger volumes in the inspection examining both surface and sub-surface defects simultaneously and thereby making sure that the complete volume of interest is covered.

The fact that glass residue from cracked glass fibres, was detected on the surface of the hole, Figures 6, 7 & 8, was a new finding using CT scan information and this was not easily detected in the optical inspection. This may be potentially dangerous as the glass particles are rather hard and if a bolt or a bushing is pressed into the hole these particles may be pressed into the hole wall and act as crack initiation sites both as stress concentration sites and as "hardness indenters". The fact that CT makes it much easier to detect these types of defects is therefore rather important for the integrity of the surface of holes in CFRP composites.

The voxel resolution of 3-4 μm that was the result of the parameters used in this work seems to be good enough to detect the major types of defects that are associated with the drilling process used here. To obtain these resolutions though, the sample has to be placed near to the X-ray source and also allowed to rotate at that position. The samples therefore have to be rather small. In our case, the 4 mm thick plates had a width of 15-20 mm. This is a drawback for the possibility of inspecting large components. The method however seems very promising for use in the development stages of new products and processes.

5. Conclusions

X-ray Computed tomography (CT scan) is a promising method to evaluate surface integrity in drilled holes in CFRP composite materials. In C fibre/epoxy-composite laminate materials, holes were drilled with spiral drills as recommended by cutting tool manufacturers and examined for surface and sub-surface defects using both optical methods and CT scan.

The CT scans show clearly both cracks and delamination at the surface and in the sub-surface region of the holes produced. Glass residue in the hole wall from the glass fibres that is also present in the material was also easily distinguished by CT. The difference in efficiency for detecting different defects by the different methods is shown in Table 2.

The CT method can cover much larger volumes in the inspection for surface and sub-surface defects than optical methods. The method also holds the potential of quantification of defects in a way that optical methods does not.

Due to sample size and resolution relations, the method is mostly interesting for use in the development stages of new products and processes and may have its limitations for use on large components.

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