INVESTIGATION OF INFLUENCE OF DIFFERENT PIERCING METHODS OF ABRASIVE WATERJET ON DELAMINATION OF FIBER REINFORCED COMPOSITE LAMINATE

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ABSTRACT

Due to the highly abrasive nature of composite materials, cutting composites with traditional rotary cutting tools such as a band saw or Dremel™ tool is a challenge. Cutting composite materials often results in tool wear, high heat, and dust generated during the cutting process. Thermoplastic reinforced composites can be especially challenging to machine because of their tendency to melt due to the high heat generated during cutting. If the melted material gums up the cutting blade, the cutting equipment is no longer able to cut the material effectively. Abrasive waterjet cutting (AWJ) does not have direct contact between the machine and material, so many of the machining challenges are avoided. However, the impact of a waterjet stream may cause delamination of composite laminates. This research addresses the influence of different piercing methods of the waterjet cutting process on delamination of the composite laminate. The investigated geometry is a 25.4 mm x 101.6 mm carbon fiber laminate which is manufactured using 3 plies, 6 plies, and 30 plies of plain weave carbon fiber prepreg. The axial centerline of the sample will be pierced and cut using four different kinds of piercing methods; stationary piercing, dynamic piercing, low-pressure piercing, and very brittle material piercing. After cutting the sample with water jet, the delamination zone of the composite laminate will be observed using a Computed tomography (CT) scanning technology. The analysis shows that the distribution of delamination and the size of delamination depends on the different piercing methods.

INTRODUCTION

Composite materials have many advantages, such as high strength to weight ratio, corrosion resistance, high fatigue strength, and design flexibility [1-6]. Due to these advantages, the use of composite materials in various industries has increased rapidly [1-3]. Composite materials are often applied to aerospace, automobile, marine, and sporting goods [1,4-6]. The composite part manufacturing process often requires post machining steps after curing [4]. However, due to the highly abrasive nature of composite materials, cutting composites with traditional rotary cutting tools such as a band saw or Dremel™ tool is a challenge [1,2,5]. Composite materials are heterogeneous which applies variable force to the machining tool leading to high tool wear and poor machining quality [3-6]. Also, dust and noise which are harmful for the machine operator are generated during the cutting process. Thermoplastic reinforced composites can be especially challenging to machine because of their tendency to melt due to the high heat generated during

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cutting. If the melted material gums up the cutting blade, the cutting equipment is no longer able to cut the material effectively. Considering the problems described above, an alternative technique to machine composite materials is necessary.

The Abrasive Waterjet (AWJ) is a non-traditional cutting technique which uses a high-velocity water jet with abrasive particles to cut a variety of materials [3,7]. Since waterjet uses abrasives to cut without any direct contact between the cutting tool and material, it removes the need to worry about tool wear during cutting [5-8]. AWJ is a cold machining process which does not create a heat affected zone during the machining process [1,3,4,6-8]. The waterjet machining process can be performed underwater, so that less heat, noise, and dust are generated during the cutting process. Therefore, AWJ technology has less sensitivity to material type, high machining versatility, and flexibility [2,3,5]. Due to these advantages of the AWJ machining process, AWJ is widely used for various applications including machining composite material [1,5]. However, cutting composite materials using AWJ also has some challenges [4]. Composite materials are often used to build composite laminates which are built layer by layer. This layering makes interlaminate bonding strength a concern during localized impact like that of an AWJ stream. Therefore, AWJ machining of composite laminates may result in delamination of the laminate [1,4-6,8,9]. Since delamination of composite laminates degrades mechanical properties of the structure, it needs to be considered during machining process in order to be minimized [1,8]. Delamination of composite laminates during AWJ machining process occurs in two steps. First, the crack is initiated by shock wave impact of waterjet [1,4,5,8,9]. Then the crack propagates due to hydrodynamic pressurization during cutting process [5,8,9]. There are many studies showing that delamination on composite laminate during AWJ machining process is influenced by AWJ machining parameters; Pressure, standoff distance, delay & event timing, mixing tube diameter, abrasive nozzle diameter, transverse speed, abrasive flow rate [2,3,5,7,8].

Phapale et al. [1] investigated delamination on composite laminate during AWJ drilling process using different drilling parameters. Phapale et al. [1] showed that the standoff distance and water pressure affects delamination of composite materials more than the abrasive flow rate during AWJ machining process. The authors also introduced a couple of techniques which helps minimizing delamination such as using a backup plate, pre-drilled hole, and underwater cutting [1]. Using a backup plate during AWJ machining not only helps to reduce the delamination, but also reduces hole size variation and hole surface roughness [1]. Dhanawade and Kumar [5] studied mechanism of delamination and kerf geometry on composite material during AWJ machining process. Dhanawade and Kumar [5] controlled 4 different machining parameters; hydraulic pressure, traverse rate, standoff distance, and abrasive mass flow rate to investigate how these machining parameters affected delamination and kerf geometry. Dhanawade and Kumar [5] reported that delamination could be decreased by increasing abrasive mass flow rate. Also, decreasing standoff distance or transverse rate could decrease delamination [5]. Shanmugam et al. [4] indicated that the water wedge effect of hydrostatic infiltration is the main causation of delamination of composite laminate during AWJ machining process. Shanmugam et al. [4] predicted maximum delamination length using an energy conservative model and it showed that the transverse speed of AWJ affected the size of delamination the most. Also, They mentioned that delamination can be reduced by reducing the size of the jet diameter or water pressure [4]. Schwartzentruber et al. [9] focused on the liquid jet impaction during AWJ piercing process. Schwartzentruber et al. [9] studied how jet pressure and nozzle size affected hydraulic shock during waterjet impact on the composite laminate. The authors showed that if the jet pressure and nozzle size were increased, it increased the hydraulic shock loading, which increased delamination [9]. It meant that delamination could be reduced by decreasing the jet pressure and jet size. Also Schwartzentruber et al. [9] described applying a fine sacrificial mesh on the top of the material to cut in order to break up the waterjet, and to reduce hydraulic shock. Ho-Cheng [10] reported that delamination on the composite laminate during AWJ machining process occurred at the bottom section of the laminate which is farthest away from the AWJ nozzle. Ho-Cheng [10] described that when the AWJ pierced the laminate, the thickness of the uncut section of the laminate is getting thinner and thinner, the strength is getting weaker and weaker, and then the laminate bent before the laminate was fully penetrated. It resulted in delamination of the laminate. Mayuet et al. [6] observed delamination on carbon fiber reinforced plastic during AWJ machining process using scanning optical microscope and scanning electron microscope. Mayuet et al. [6] reported that abrasive was the biggest factor which determined delamination. Abrasive flow, size and delay should be carefully considered to minimize delamination [6]. Schwartzentruber et al. [8] utilized a fluid-structure interaction model to simulate AWJ cutting process for composite laminate. Schwartzentruber et al. [8] found that the transverse speed of AWJ, abrasive flow rate and mixing tube size were among the machining parameters that affected delamination of composite laminate the most. Schwartzentruber et al. [8] mentioned that the larger mixing tube diameter created more delamination.

OMAX Corporation, which is an abrasive waterjet machine manufacturing company, demonstrated four different types of piercing methods including stationary piercing, dynamic piercing, wiggle piercing, and low-pressure piercing, on their online blog [11]. Stationary piercing is the simplest form of piercing method. The waterjet nozzle stays in one location while it pierces the part. During dynamic piercing, the nozzle moves toward a cutline slowly while it pierces the material. The wiggle piercing method uses a slight back and forth movement of the nozzle along the cutline while it pierces the substrate and moves toward the cutline after it fully pierces the substrate. During the low pressure piercing method, the AWJ pierces and cuts the material with lower pressure than normal. There is another piercing option which is provided in OMAX AWJ operation software called “Very brittle material piercing method”. The very brittle material piercing method is similar to the low-pressure piercing method which uses low pressure waterjet for both piercing and cutting. However, the very brittle option starts the waterjet from 0 pressure and gradually increases to low pressure unlike the other three piercing methods which pierce the material with fully charged pressure from the beginning of the piercing process. Also, the very brittle material option lets abrasive flow before waterjet starts.

This research is designed to investigate delamination of the composite laminate during abrasive waterjet cutting. This research especially focused on the piercing process of AWJ machining process. Each piercing method is tested on the composite laminate. The delamination zone of the composite laminate will be observed using a micro-computed tomography (CT) scanning technology. Size, location, and distribution of the delamination will be examined.

EXPERIMENTATION

To investigate the delamination effect on a composite laminate during abrasive waterjet cutting process, a composite laminate sample was manufactured. Carbon fiber reinforced prepreg (AWMS45-005 plain weave with Cycom 985 epoxy resin system) was the material used. Three different sample thicknesses were manufactured; 3 plies ([0/90/0]), 6 plies ([0/90/0]s), and 30 plies ([0/90/0]$_{10}$). The samples were stacked on a flat caul plate, vacuum bagged and cured in an autoclave. The cured laminates were 0.83 mm, 2.01 mm, and 7.04 mm thick relatively. Because of the capacity of the micro CT scanning machine, the width of each sample was limited to 25.4 mm. Therefore, the sample size was chosen to be 25.4 mm x 101.6 mm. All samples with the same thickness were cut from one panel. The samples were cut using a surface grinder with diamond grit–edged blade. Figure 1 shows the composite laminate sample (30 plies). The samples were fixed on the waterjet and machined along the central long axis of the sample with various piercing methods; Stationary, dynamic, low pressure, low pressure / brittle option. A Maxiem 1515 abrasive waterjet machine, built by OMAX, was used as shown in Figure 2.

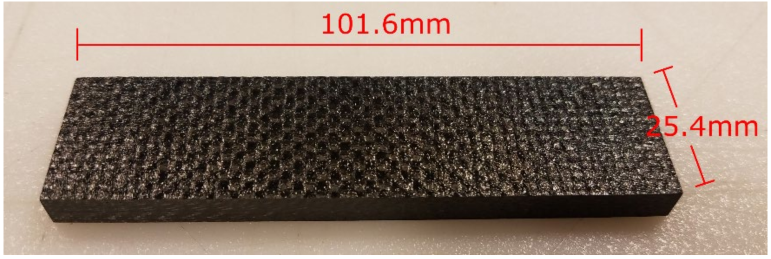

Figure 1. The composite laminate sample (30 plies)

Figure 2. Maxiem 1515 waterjet machine

The waterjet uses 336.46 MPa of water for the high pressure waterjet and 148.24 MPa for low pressure waterjet. The diameter of the mixing tube was 0.76 mm and abrasive nozzle diameter was 3.94 mm, which determined the abrasive flow rate of 194.32 g/min. 80 grit garnet abrasive media was used. The AWJ machining software used was the Intelli-Max Make Standard for Maxiem. The default setting of the software creates a 0.2 seconds delay for the abrasive to start flowing after the water pump starts. The standoff distance was set to 3.18 mm for all samples and they were cut underwater. Shanmugam et al. [4] indicated that the delay time between waterjet and abrasive flow prevented the abrasive to be clogged into the mixing tube of the waterjet.

Intelli-Max Make Standard software is automatically set to use a dynamic piercing method that slowly moves the nozzle to the cutting line while it pierces the material. Therefore, a stationary piercing method cannot be selected as a cutting method. However, it was possible to design the cutline to allow the AWJ machine to make an approximate stationary piercing by limiting the cutline to a very short distance (0.03 mm). Therefore, the stationary piercing method was tested only for its piercing performance, not cutting performance. The abrasive flow had a 0.2 second delay after the waterjet started. Since the software was automatically set to use a dynamic piercing method for cutting, the cutting proceeded with this default setting. The cutline was 25.4 mm and was located in the middle of the sample. The thickness of the material was set in the software to calculate the traverse speed of the machine while cutting. The traverse speed of the AWJ was automatedly calculated to 1.61 m/min. The abrasive flow had a 0.2 second delay after the waterjet started. The AWJ nozzle moved to cut the cutline 0.5 second after the waterjet started. After cutting the cutline, the abrasive stopped first and the waterjet flowed 0.5 second longer to flush the abrasive from the inside of the mixing tube and nozzle. The low pressure piercing method used low pressure waterjet for piercing. As with the dynamic piercing method, the abrasive started to flow 0.2 second after the low pressure water started to flow. The cutting started 0.5 second after the piercing started. The transverse speed was 1.61 m/min. When the machine finished cutting the part, the abrasive stopped first, and then the water stopped after 0.5 second. The low pressure with very brittle material option was also tested. The low pressure with very brittle material option did not have a 0.2 second delay of the abrasive flow. Instead, the abrasive flowed before the water started. Also, the very brittle material option allowed the waterjet to start from 0 pressure to low pressure gradually, instead of shooting the full pressure waterjet onto the substrate. Similar to the low pressure piercing method, the low pressure waterjet was used for cutting. The AWJ started to cut the cutline 0.5 second after the water started. The transverse speed was 1.61 m/min. After the cutting operation, the abrasive stopped first, and then the water stopped 0.5 seconds later. The wiggle piercing method was not supported by Intelli-Max Make Standard software. Therefore, the wiggle piercing method was not tested.

Computed tomography (CT) scans were performed on multiple AWJ-cut specimens using an Xradia Versa 510 X-Ray Microscope (XRM) in Figure 3. A pixel size of 35.4um was achieved with a vertical stitch scan of the specimens as shown. The source was set to 40kV and 3W with an LE2 filter and a 12 second exposure time per frame. Settings were determined to allow sufficient contrast between the composite material and any damage regions (air or media) induced by AWJ. After using Xradia's reconstruction software, the scanned volumes were manipulated and measured in Volume Graphics VGStudioMAX 3.2 software.

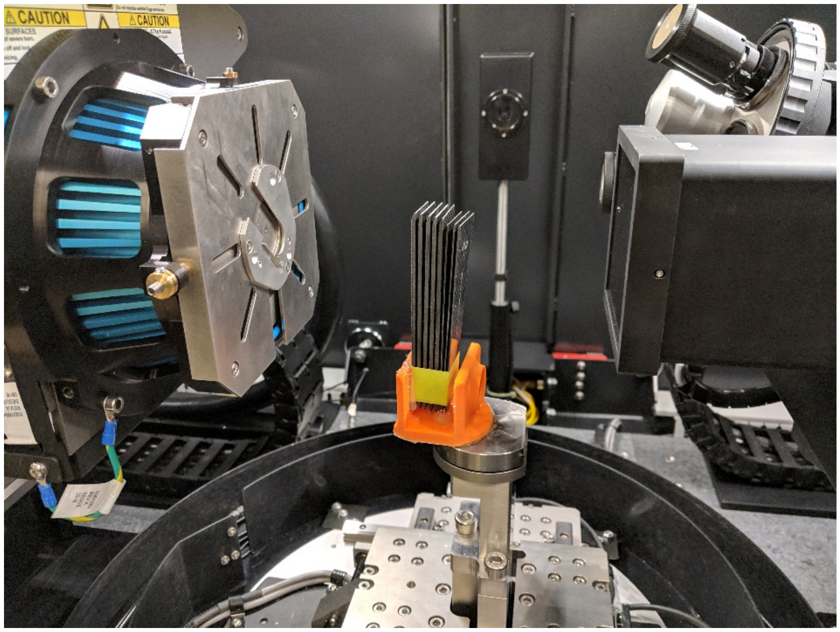

Figure 3. CT scanning process with Xradia Versa 510 X-Ray Microscope (XRM)

RESULTS

Even though the sample size measured 25.4 mm x 101.6 mm, the area scanned was only 63.5 mm ~ 76.2 mm in length because 25.4 mm of the sample length was held in a fixture during scanning, and the area that was in the fixture was not scanned. The processed CT scan image showed the sample image in different shades depending on the relative density of the part. Figure 4 showed the CT scan image of the sample (30 plies). The CT scan image showed the sample with different colors depending on the density of the area. For Figure 4(a), the light color area of the sample was where the density was lower than the darker area. However, in Figure 4(b) which was a 2D slice of the CT scan image, the color of lower density area was darker. It could be an air bubble or resin rich area that does not contain any fiber. This depended on how the operator set the image coloration histogram. Therefore, the CT scanned sample image can look slightly different, but there was no problem detecting the delamination in the sample. The sample can be observed from different angles and its cross-sectional area could be examined as well.

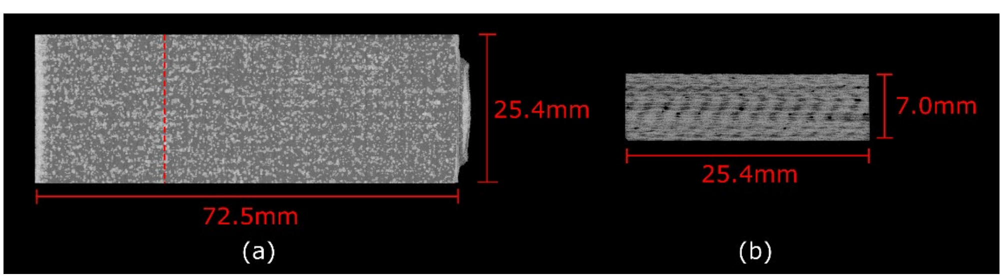

Figure 4. (a) top view and (b) cross-sectional area of CT scan image for control sample (30 plies)

The first step was to investigate the location of the delamination. Delamination may occur in the piercing area, cutting area, or the area where the machine stops, or spread consistently across the overall machining area. Figure 6 shows the 30 plies sample machined with waterjet machining using the dynamic piercing method. The waterjet pierced at (b) and moved to right. It was possible to see significant delamination in the piercing area, and no delamination was observed in other machining areas. In the cutting area, some small white spots were detected and suspected to be delaminations. However, upon observing the cross sectional area it showed that these were air bubbles inside of the laminate that were exposed to the outside due to the machining process. Other than the sample with 30 plies cut using the dynamic piercing method, the delamination on samples were only observed in the immediate piercing area. Figure 7 shows the waterjet cut sample (30 plies) where the waterjet did not pierce from inside of the sample. The waterjet pierced outside of the sample and entered the sample with the waterjet and abrasive already coming out to cut the middle of the sample. It was not possible to detect any delamination in the machined sample with the CT data.

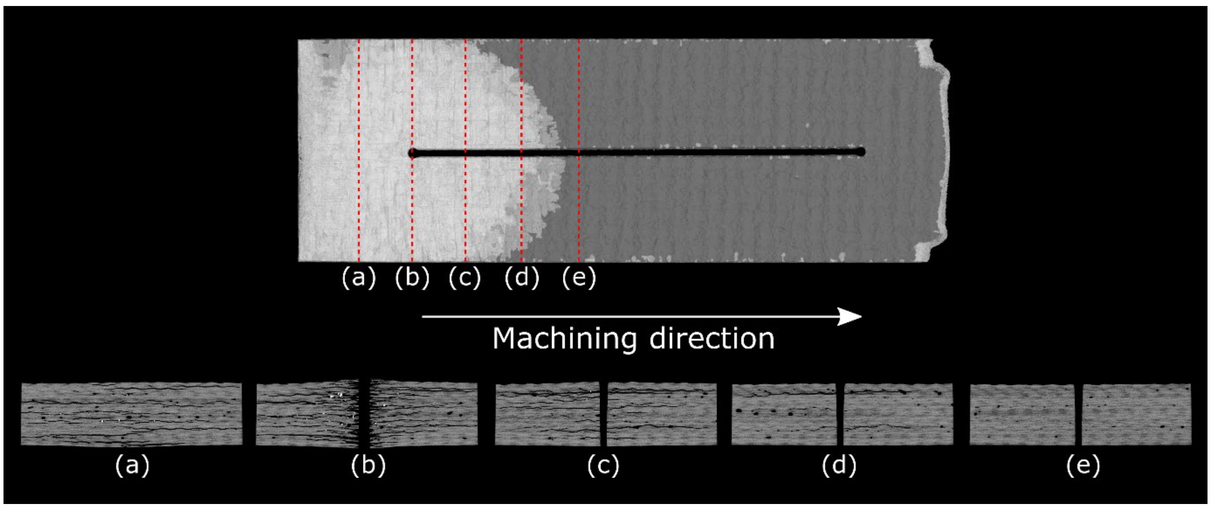

Figure 6. Top view and cross-sectional area of 30 ply dynamic piercing sample in various locations. The waterjet pierced the sample at (b) and moved to right.

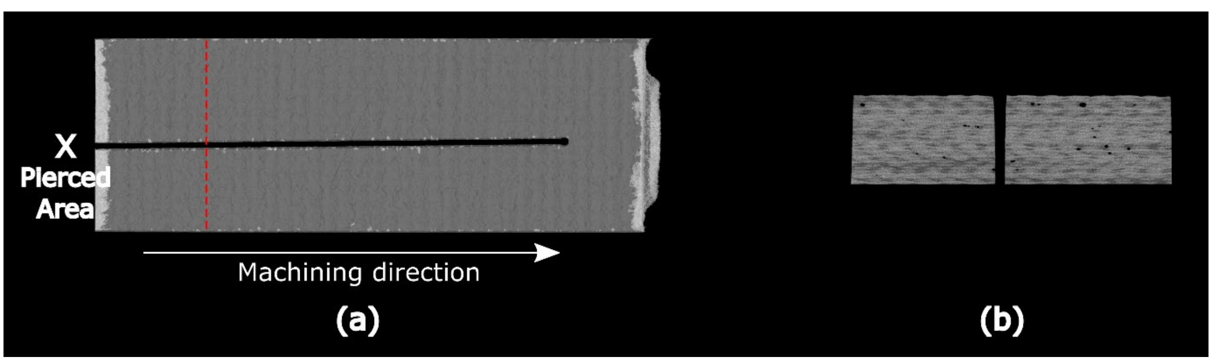

Figure 7. (a) Top view and (b) cross-sectional area of 30 plies sample that was pierced from outside of the sample

The CT scan images of 6-ply samples that were cut with four different piercing methods were examined and compared as shown in Figure 8. It was possible to find delamination in the samples that were machined with stationary, dynamic and low pressure piercing methods. However, there was no delamination detected in the sample that was cut with the low pressure/very brittle material piercing method. On the 6 plies stationary piercing sample, the sample was pierced in two different spots. Both delaminations in the stationary piercing area reached all the way to the edge of the sample. Therefore, it was not possible to measure the full size of the delamination accurately because once the delamination reaches all the way to the edge of the sample, the edge was opened, and the hydrodynamic pressure was released through the open edge. The pressure release affected the size of the delamination, and usually it decreased the size of the delamination. In this case, the size of the delamination was measured and marked with '+' which meant that the size of the delamination may be affected by hydrodynamic pressure release through open edge. The size of the delamination was measured using image processing software ImageJ as shown in Figure 9. The size of the first delamination in the 6 plies stationary piercing sample was 335.24 mm^2+, and the size of the second delamination of the sample was 354.64 mm^2+. The delamination of the 6 plies dynamic sample did not reach to the edge and the size of the delamination was 186.94 mm^2. The delamination in the 6 plies low pressure sample reaches to the edge of the sample and the size of the delamination was 199.96 mm^2+. As it was described above, there was no delamination in the 6 plies low pressure/very brittle material sample. However, some cuts in the sample were not cut all the way. A lot of abrasive was found within the delamination zone of stationary and low pressure piercing samples. The delamination in all samples was distributed across the thickness relatively evenly.

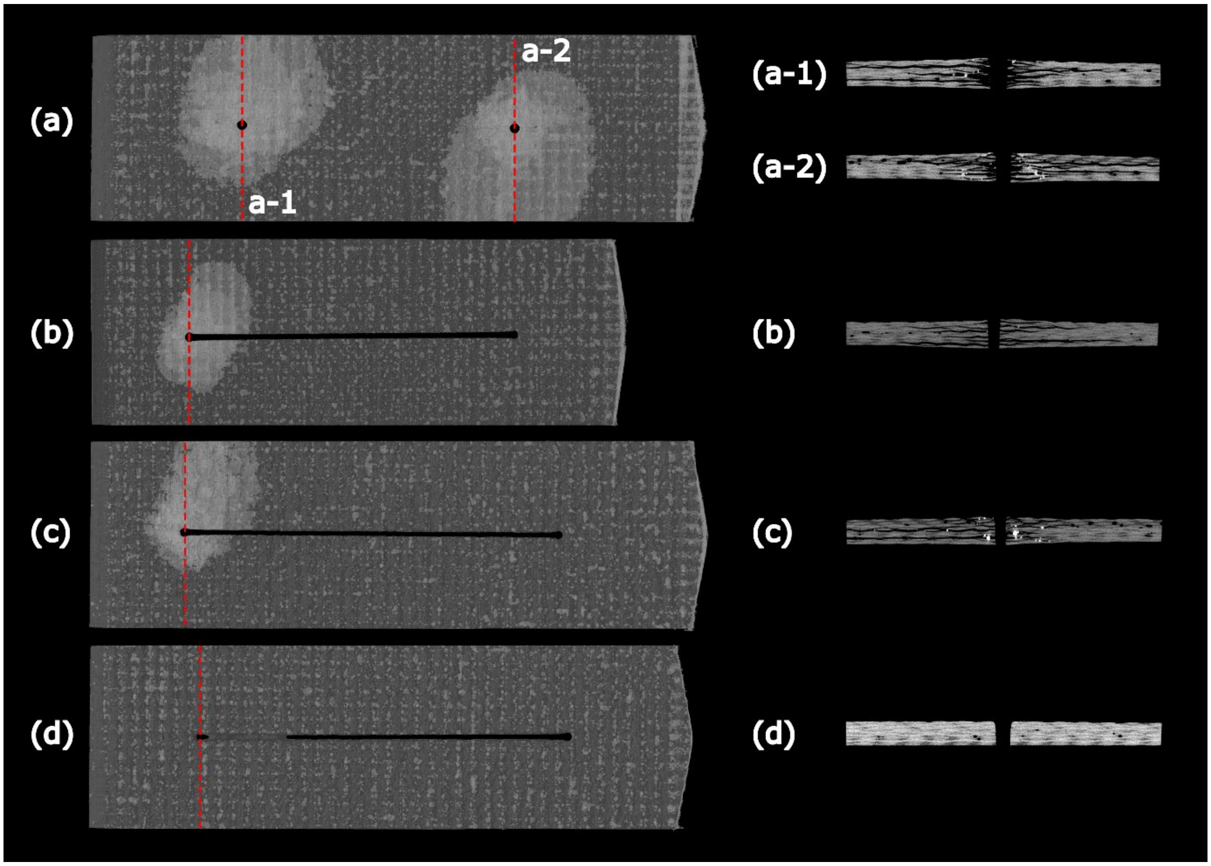

Figure 8. Top view and cross-sectional area of 8 plies sample that were cut with four different piercing methods (a) stationary, (b) dynamic, (c) low pressure, and (d) low pressure/very brittle material

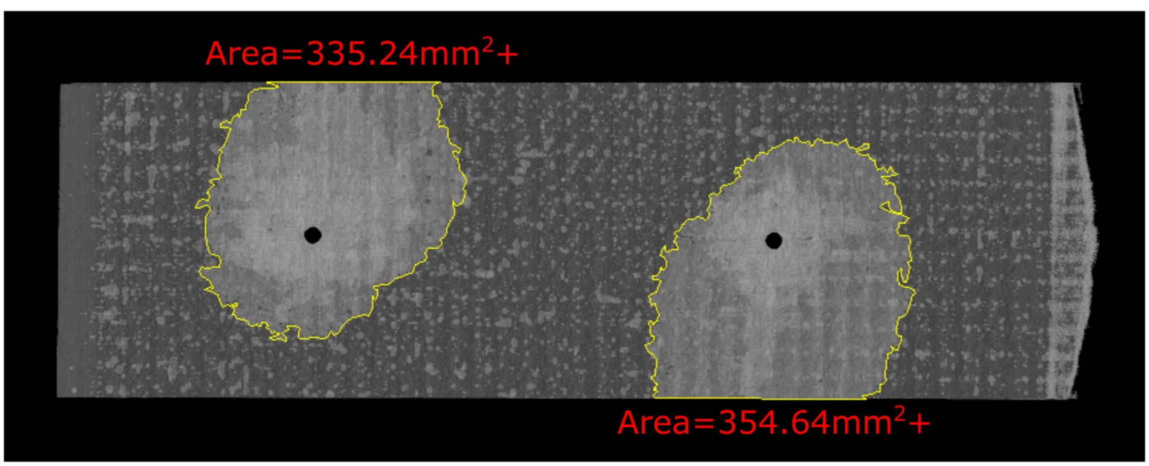

Figure 9. Delamination measuring using ImageJ (30 plies stationary piercing sample)

The CT scan image of three different thicknesses of samples that were machined with a low pressure/very brittle material piercing method were analyzed as shown in Figure 10. The 30 plies and 3 plies low pressure/very brittle material piercing samples did not have any delamination in the AWJ cutting area, just like the 6 plies low pressure/very brittle material piercing samples. However, even when the thickness was set to the correct thickness for the cutting parameter, the low pressure/very brittle material piercing method caused incomplete penetration during the cutting operation. The 30 plies samples that were cut with a low pressure/very brittle material piercing methods were not fully penetrated during the piercing process, and the machine moved along the cutline without fully penetrating the sample. The AWJ only penetrated the sample in the last part of cut where the waterjet stopped. The 6 plies and 3 plies sample were fully penetrated in the piercing process, but when the machine moved towards the cutline, it created a no cut region, but eventually, the AWJ penetrated the material and finished cutting. Figure 11 shows the cross-sectional area of the uncut area of the cut line for a 30 plies low pressure/very brittle material piercing method sample. Overall, the cut depth was increased along the cutline, but the thickness of the uncut area was not decreased consistently.

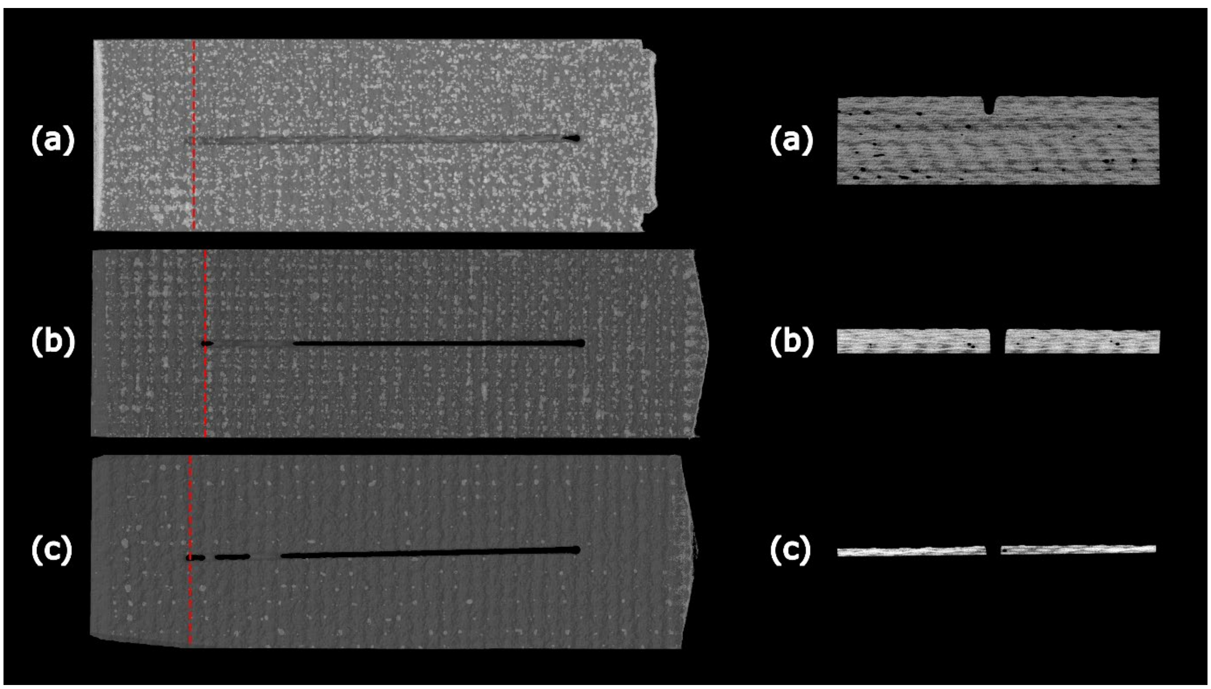

Figure 10. Top view and cross-sectional area of three different thickness samples which were machined using a low pressure/very brittle material piercing method (a) 30 plies (b) 6 plies, and (c) 3 plies

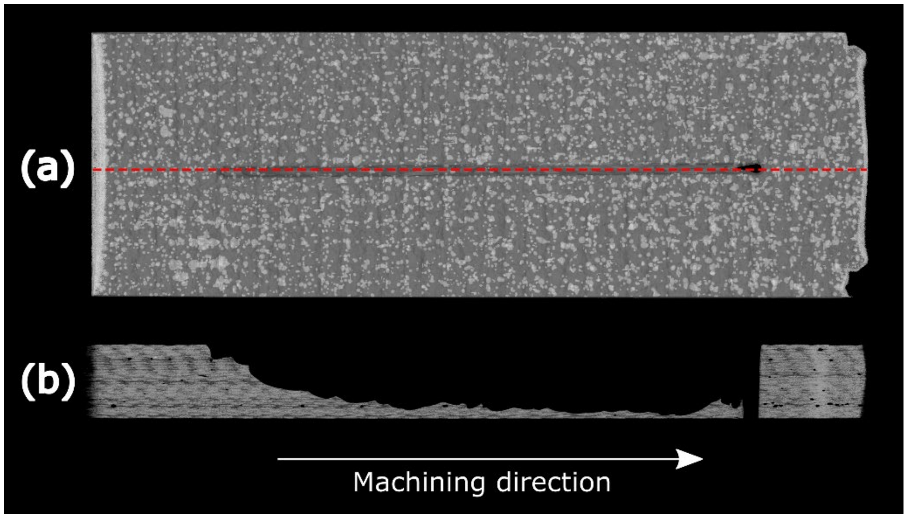

Figure 11. (a) Top view and (b) cross-sectional area which shows uncut region of a 30 plies low pressure/very brittle material pierced sample

The next step was to study the relationship between the size of the delamination and the sample thickness. Three different thicknesses of a stationary pierced sample were compared as shown in Figure 12. The delamination of the 30 plies stationary pierced sample reached to the edge and the size of the delamination was 548.79 mm^2+. On the 6 plies sample, two stationary piercing tests were performed. Both stationary piercings caused delamination and both delaminations reached all the way to the edge of the sample. The size of the first stationary piercing test was 335.24 mm^2+ and the size of the second stationary piercing test was 354.64 mm^2+. On the 3 plies stationary piercing sample, there were also two different tests performed. Both tests caused delamination, but they did not reach the edge of the sample. The area of the first delamination was 33.21 mm^2 and the area of the second delamination was 69.18 mm^2. The delamination in the 30 plies sample was concentrated on the top section of the laminate, and there was a lot of abrasive in the delamination. The delamination of the rest of the samples were relatively evenly distributed across the thickness.

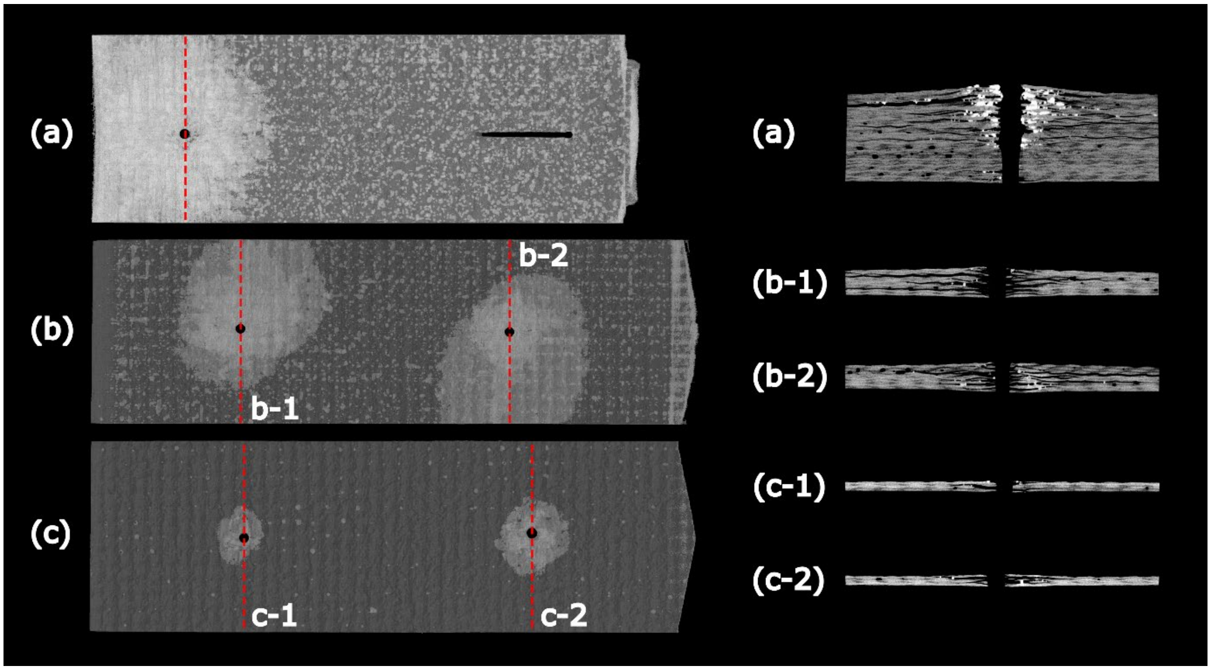

Figure 12. Top view and cross-sectional area of three different thickness samples which were cut using a stationary piercing method (a) 30 plies (b) 6 plies, and (c) 3 plies.

The dynamic piercing method was tested for all three sample thicknesses and it caused delamination in all three samples. The delamination in the three different sample thicknesses that were cut using the dynamic piercing method were also analyzed and compared in same way as the stationary piercing samples as shown in Figure 13. The delamination of the 30 plies dynamic pierced sample reached to the edge and the size of the delamination was 691.55 mm^2+. The delamination in the 6 plies sample and 3 plies sample did not reach all the way to the edge, and the size of the delamination was 136.94 mm^2 and 27.97 mm^2 respectively. The delamination in all three samples was relatively evenly distributed across the thickness.

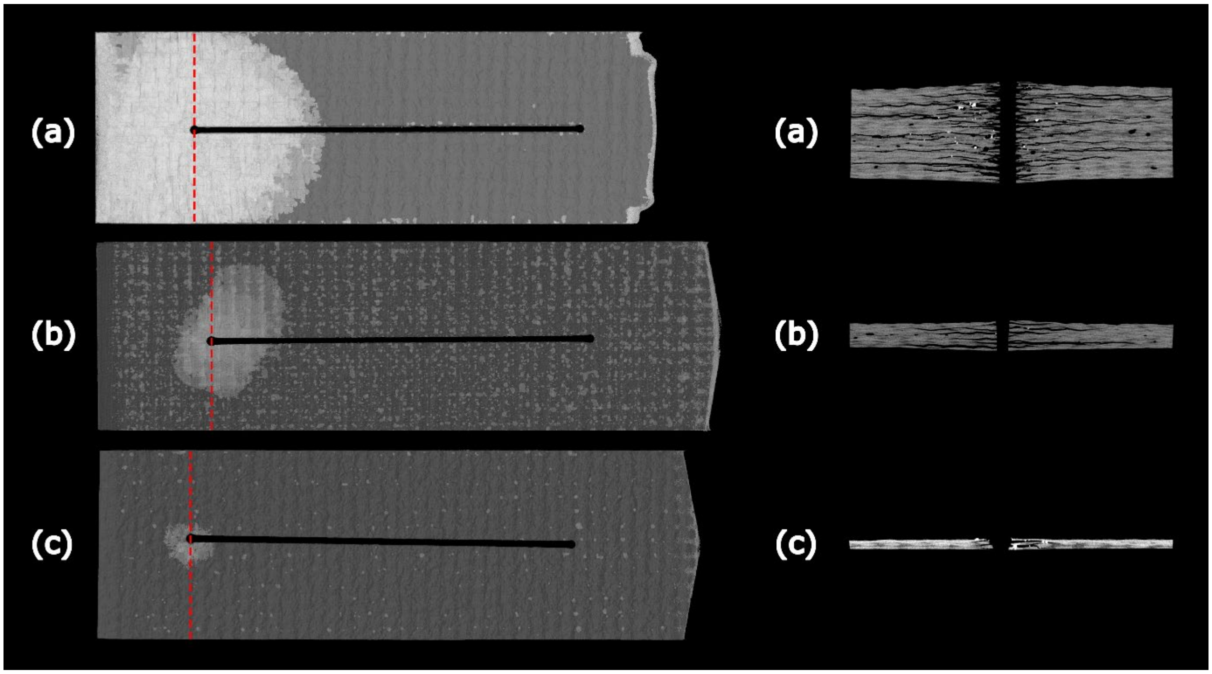

Figure 13. Top view and cross-sectional area of three different sample thicknesses that were cut using a dynamic piercing method (a) 30 plies (b) 6 plies, and (c) 3 plies

CONCLUSIONS

The authors described how different piercing methods of waterjet machining affects the delamination of composite laminates. Four different methods of piercing, including stationary piercing, dynamic piercing, low pressure piercing, low pressure/very brittle material piercing were used to make samples and the delamination of the samples was examined using micro CT scan. The samples that were tested with a stationary, dynamic, and low-pressure piercing methods showed significant delamination inside of the sample. The low pressure/brittle material method did not show any evidence of delamination. Considering the machining parameter difference between other piercing methods and low pressure/brittle material piercing method, the gradual increased piercing pressure and/or the timing of abrasive flow start likely played an important role in the delamination. However, the low pressure/very brittle material piercing method caused incomplete penetration and cutting. Since the water pressure was gradually increased during the very brittle material option, the piercing area and the beginning of the cutting area do not get high enough pressure to cut the material all the way. Therefore, further research is necessary to find an optimal machining parameter for low pressure/very brittle material to ensure it cuts the material all the way through.

The delamination caused by stationary piercing and dynamic piercing in the three different thickness samples was investigated. Thicker samples showed bigger delamination. Usually, delamination was distributed evenly through the thickness of the sample. However, the 30 plies stationary piercing sample showed that delamination is concentrated on the top portion of the laminate. Also, if the delamination reached all the way to the edge of the sample and it opened the delamination, more abrasive was found in the delamination.

The authors focused only on delamination influenced by different piercing methods without changing any default setting of the piercing and machining parameter. This research will be extended to control the other parameters, such as pressure, traverse speed, abrasive flow rate, diameter of mixing tube and abrasive nozzle, standoff distance, event & delay timing, abrasive type to find the optimal piercing setting for composite material using AWJ.

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