Influence of Waterjet Cut Quality for Fabrication of Test Specimen on Mechanical Testing Results

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Abstract

An abrasive waterjet is an effective method of cutting fiber-reinforced composites as it allows for high accuracy cuts without introducing thermal effects or physical contact with a machining tool. In the machining of fiber reinforced composites for research purposes, the fabrication of accurate and undamaged test specimens is crucial for testing mechanical and physical properties. The cutting edge of the test specimen can be varied based on primarily the cutting speed of the abrasive waterjet. The quality of the cutting edges can have a significant impact on the test results since stress concentrations can form in those defects. In addition, the abrasive waterjet leaves what is known as a kerf angle. A kerf angle is formed because of the inherent physics of the cutting process. Throughout this study, the kerf angle was primarily evaluated with carbon fiber reinforced composite samples with varying cutting speeds and different thicknesses. Fiber reinforced composite test specimens were then fabricated with an abrasive waterjet to test the effect of the edge surface finish and its effect on the mechanical properties. A tensile test was conducted with the composite test samples that were cut at various speeds. A Digital Image Correlation (DIC) camera was used to track the local strain change throughout the duration of the test to investigate any stress concentrations which were formed. The kerf angle data along with the cutting speeds effect of the selected composite's mechanical properties was analyzed and presented to address importance of using proper abrasive waterjet cutting parameters for fabricating composite test specimens.

Introduction

The composition of fiber reinforced composites includes a combination of fiber strands surrounded by a polymer matrix. The reinforcement fibers' purpose is to provide the structural stability of the composite and is responsible for withstanding the required load for each specific application. The polymer matrix is critical for bonding the reinforcement fibers and distributing the load throughout the entire part [1]. Fiber reinforced composites are becoming more and more common because of their high strength aspect ratio while also being lighter than other common aerospace materials like steel and aluminum [2]. Based on previous research, depending on the type of fiber reinforced composite, general composites weigh as much as 51% less than an equivalent thickness steel part [3]. With a higher strength to weight ratio, fiber-reinforced composites are an optimal material for applications that require a lighter material yet still require the ability to carry high mechanical loads.

The emergence of fiber reinforced composite parts and structures have increased over the past decades in various industries. Specifically, the aviation and aerospace industries have shown tremendous growth in composite structures [4]. One example of the growth of the composite industry within aviation includes the Boeing 787 Dreamliner. In 2009, the 787 took its first maiden flight, which was the first time a plane that was manufactured with more than 80%

composites took to the skies for commercial use [5]. In the 1970s, the Concorde utilized fiber reinforced composites, but it was only made up of about 7% of the total aircraft [6]. In addition to the aviation industry, aerospace companies have also started to heavily rely on fiber reinforced composites. In 2020, the overall aerospace composite market reached $10 billion in value [7]. As a result, in the ever-growing expansion of the composite industry, the emergence of composite parts and structures has pushed for further research into their mechanical and physical properties.

The fabrication and manufacturing process of fiber reinforced composites can sometimes be quite challenging. Conventional manufacturing methods of composites are obstacles for manufacturers because of the heterogeneous complex of fiber reinforced composites [8]. Often, when a composite part is machined using a CNC machine, it is very common for the fibers to be pulled out of the part with the rotation of the tool. With the pulling of the fibers, the composite inevitably loses a substantial amount of strength. This phenomenon is what is known as fiber pullout. The fibers are separated from the rest of the part, thereby effecting the overall mechanical properties. Another major problem that is induced by conventional cutting methods in composites is delamination. Delamination occurs when the laminate plies are separated from each other during the high-speed cutting process [10]. The torque of the machining tool causes delamination within the composite part therefore weakening the parts mechanical properties. For further evidence of how common delamination occurs in conventional composite cutting methods, a study has concluded that there is a 50% chance of delamination when the cutting feed rate is above 600 mm/rev [11]. Since the conventional fabrication methods for composites have shown inherent problems, there is a need for further research into unconventional fabrication methods and their effect on the composite’s mechanical properties.

One unconventional method of machining composite materials is by using a laser. Laser cutting is a considerably new, innovative way for composites to be accurately cut. By using an intense directional monochromatic light beam, lasers can penetrate the composite at varying thicknesses by adjusting the frequency of the light [18]. As previously mentioned, tool contact with the composite results in a high likelihood of defects intrinsic in the part. Like most all unconventional methods of cutting composites, laser cutting does not use a tool on the part itself which avoids common defects formed in conventional methods. On the other hand, there are many disadvantages that are associated with laser cutting because of its inherent thermal nature [19]. Due to the physical properties of composites, there have been studies showing the laser beam melting or destroying the fibers and matrix in an unwanted way. Delamination and epoxy recession are two of the side effects that are attributed with laser cutting of composite materials. The industries who utilize unconventional methods of composite cutting have reportedly struggled with finding a way around the defects formed during the manufacturing process [20].

Waterjet cutting is another unconventional method of fabricating and manufacturing composite parts, materials, and samples. A waterjet encompasses many advantages compared to other methods of cutting composites. Abrasive waterjets utilize a combination of high-pressure water streams and garnet abrasives [11]. The high-pressure water is streamlined through the jewel orifice and is then mixed with the garnet abrasives inside of the mixing chamber as shown in Figure 1. Once the abrasives have been mixed with the abrasives, the mixture undergoes a narrowing in the focusing tube which utilizes the Bernoulli principle [12]. By narrowing the tube, the pressure is increased even further to provide a more focused, penetrative force into the composite material.

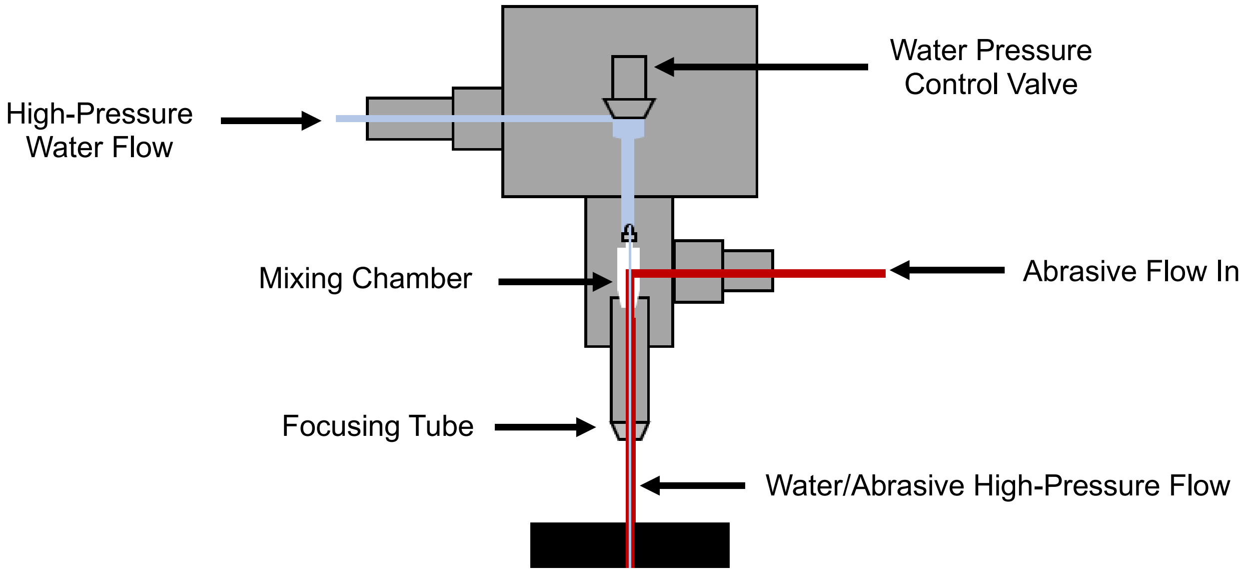

Figure 1. Schematic drawing of the abrasive waterjet.

That penetrative force that is created during the waterjet process has many advantages in the cutting of the composite material. No direct tool contact is one of the most important advantages that a waterjet has over conventional composite machining methods [13]. Without direct tool contact, the waterjet avoids heating the composite material to a temperature that could alter its mechanical properties. If the fiber reinforced composite is heated up during the machining process, the thermal conductivity of the part will result in an unwanted amount of resin degradation [14]. Based on a previous study, once the part has been heated to its glass-transition temperature, the mechanical properties of the composite part have been drastically changed. As a result, both tensile and shear strength are reduced by at least 30% in each of the test specimen groups which were separated by ply orientation. Since the abrasive waterjet does not use a machining tool or bit, another major advantage of the waterjet emerges. During the cutting process of an abrasive waterjet, there is no tool wear which keeps the operating costs extremely low making it very popular for industry. Furthermore, when a computerized numerical control (CNC) machine is used to cut composite materials, there is a high wear factor on the machining tool [16]. This is not only economically inefficient, but if there are multiple composite parts that need to be manufactured, there is a chance that each part would have a different edge cut finish due to the tool wearing down [17]. An abrasive waterjet does not experience tool wear when cutting which allows for a more repeatable cut on each part. The cut may be repeatable without the tool wear, but the waterjet cutting quality is significantly lower than when using a CNC.

Even though waterjets possess many advantages, there are also some disadvantages. One of the most common disadvantages of using a waterjet to cut composites is the edge cut quality that is produced because of the cutting process. Edge cut quality refers to the roughness that is produced from the high-pressure water and garnet stream as shown in Figure 2. The differences in edge cut qualities is a result of the cutting speed, the thickness of the material, and the hardness value associated with each material. If the waterjet cutting process is slowed down to achieve a smoother finish, then the amount of time to manufacture the part will rise significantly [21]. For those in composite industries, even though an abrasive waterjet is an effective way of fabricating parts, the manufacturing time has been one setback compared to conventional methods of cutting composites. Not only is the machining time increased, but the amount of abrasive also becomes quite costly as the waterjet uses a constant flow rate of abrasive throughout the entire cutting process.

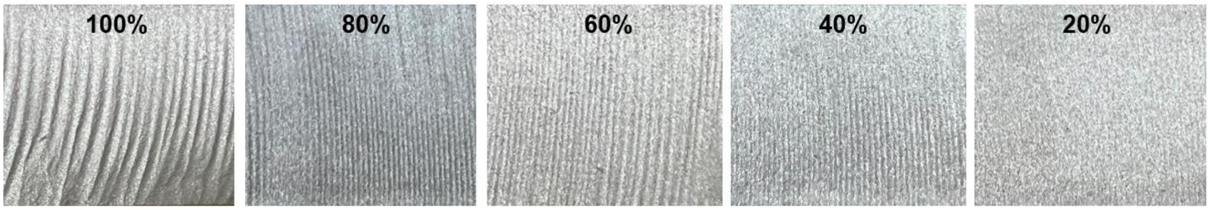

Figure 2. 100% - 20% cutting speeds and the resulting edge surface finish.

Another disadvantage of waterjet cutting is the possibility of blowback. Steel slats are used inside of the waterjet to provide support for the composite structures for the machining processes. Blowback occurs when the cutting stream crosses over those steel slats and rebounds the abrasive back onto the reverse side of the part. This defect impacts the overall finish of the composite part, but if the part is a key structural component, the mechanical properties may also be altered. In addition to blowback, delamination is another defect that is produced during the machining process [22]. Due to the multi-layer fabrication of fiber reinforced composites, delamination is quite prevalent when cutting composites with an abrasive waterjet. Delamination is a common problem with an abrasive waterjet because when the waterjet begins its cutting operation, the pierce point causes an initial crack on the top layer due to the immediate ultra-focused high pressure exerted on the part. Not only is the top layer damaged, but the mixture of the high-water pressure and the abrasives are destructive enough to spread out in between the laminates and propagates that initial crack between the layers of the crack. As a result, the crack will spread out between the layers of the fiber reinforced composites. If the crack begins to propagate outside of the intended cutting area, then the destruction of the fibers and polymer matrix are bound to affect the mechanical properties of the specimen [22].

Lastly, arguably the most challenging disadvantage to control for precise abrasive waterjet cutting into any material is what is known as the “kerf angle” [23]. After the mixing chamber has appropriately combined the garnet abrasives with the high-pressure water stream, the number of abrasives in the centralized area on the part become scattered. When the stream cuts the part, the top of the material will experience the most localized number of abrasives compared to the bottom because the abrasives follow the channel formed during the cut. As a result, the width of the cut on the top layer are inevitably larger than the resulting width on the bottom layer as shown in Figure 3. A taper is therefore formed on the cutting edge of the part. The reduction in cross-sectional area that is resulted from the tapered cut significantly affects the parts mechanical properties. For the edge cut quality, blowback, and delamination there have been a significant amount of research and discoveries in limiting those defects. The edge cut quality can be greatly improved by simply slowing the cutting speed of the abrasive waterjet. Next, blowback can be slightly avoided by ensuring that the part that is being cut is away from the steel slats within the waterjet as much as possible. If the part is too large, blowback may still occur, but if the pierce point of each cut is not directly on the composite part, then the blowback will be kept to a minimal, case depending. Kim states that by using a low-pressure cutting pressure along with an early release of the abrasives can prevent delamination between the layers of the fiber reinforced composite. Kim further states that a ramping up to high-pressure during the cutting process from the low-pressure piercing does not result in interlaminar delamination [26]. As mentioned, edge cut quality, blowback, and delamination of abrasive waterjet cutting has been extensively researched in the past.

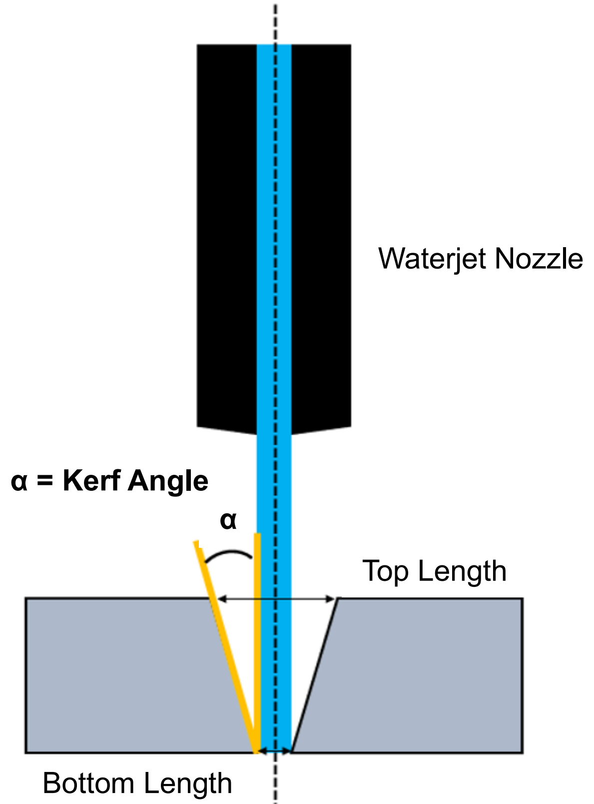

Figure 3. Schematic drawing of the kerf angle.

The kerf angle on the other hand has been an issue that has yet to be completely analyzed and resolved. The kerf angle occurs regardless, to different severities, of the thickness and type of material. It is one of the most challenging abrasive waterjet defects for engineers and researchers to understand and compensate for. Some companies have made efforts to reduce the effect of the kerf angle on the manufactured parts. In recent years, the advancement of the 5-axis abrasive waterjet machine along with further research into the kerf angle has resulted in a better understanding of how to compensate for the taper on machined parts. With the adjustment of the waterjet head, up to 5 degrees maximum, it is possible to angle the high-pressure water abrasive mixture into the part at an angle. Even though the compensation for the kerf angle can be effective in some cases, the rate at which the abrasive waterjet cuts the part is still the main factor in producing the resulting taper [25]. The conclusion of Wang's paper indicates that the angle can be compensated for, but it is not effective enough to completely correct the surface profile. Since the surface profile still produces a taper on the part, the cross-sectional area is therefore altered. With current day technology advancements in abrasive waterjet cutting operations, there is still a need to investigate the effects of two major elements: kerf angle and the effect of the cutting speed on the parts' mechanical properties.

Methodology

As mentioned previously, the kerf angle is a quite difficult defect to avoid during the abrasive waterjet cutting process. There are three main factors that affect the kerf angle formed on the edge because of the abrasive waterjet cutting operation: thickness of the material, the cutting speed of the waterjet, and the hardness of the material. As a result, it was important to study these traits and how the kerf angle forms. Table I provides the recommended cutting speeds from the waterjet manufacturer in inches per minute.

Table I: Carbon fiber reinforced composite cutting speeds.

	1/4"	**1/2"**	**3/4"**
100%	80.10	40.10	25.89
75%	60.08	30.08	19.42
50%	40.05	20.05	12.95
25%	20.03	10.03	6.47

Since material thickness and the cutting speed has been addressed for the carbon fiber reinforced composite samples, the remaining variable that effects the resulting kerf angle on a part is the materials' hardness. To relate the abrasive waterjet machining and the hardness of the material, a confidential equation is formulated for each waterjet manufacturing company. Based on the company's internal evaluations of common materials used throughout the industry, a machinability index is attributed to each material. This machinability index is based on the hardness of the material along with other mechanical properties including ductility and brittleness. From those observations, it was evident that the lower the machinability index, the harder the material, which inevitably confirmed the recommended cutting speeds previously mentioned for the carbon fiber reinforced composite samples. Table II provides the information of the index given for the composite laminate used in this research.

Table II: Material machinability index assigned by waterjet manufacturer.

Composite Laminate	552.71

Based on the machinability index and their relation to the proposed cutting speeds of the waterjet, it was possible to continue to the abrasive waterjet cutting procedure. Once all three variables were addressed, all samples were then cut using the abrasive waterjet with the predetermined cutting parameters as previously shown. The samples were placed on a sacrificial board to prevent any movement of the samples during the cutting process. In addition, a laser was installed on the abrasive waterjet to ensure that the x-axis and y-axis lined up perfectly with the sample's edge. From there, the waterjet was positioned outside of the part to prevent any delamination or other defects in the cuts. The saw cut function was then used to cut 0.75" perpendicular into the sample for each cut. After each sample was cut, the samples were then cleaned with the appropriate chemical agent and potted for microscopic images. For the best microscope images, the samples were grinded with 220-, 500-, and 1200-grit. Polishing was the next step in achieving the cleanest microscopic images, so the samples were polished in a specific order. Once complete, each sample were then analyzed with a scanning microscope with 10x magnification. Since another software called ImageJ was going to be used for the measurement of the top and bottom lengths for each cut, it was imperative that a known distance was captured. To do that, a distinguishable feature for each sample was measured inside of the microscope software. Then, that known distance was able to set the scale factor inside of ImageJ. Without this procedure, theoretically each sample would have resulted in various scale factors, therefore effecting the finals measurements. Then, having set up the scale factor, the samples were then imported into ImageJ for the evaluation of the desired measurements. An unexpected preliminary finding occurred during the investigation. Three zones were distinguished, making it important to further breakdown the kerf angle into the three respective sections shown in Figure 4. The first top zone had a curved section, the second zone was divided up based on the taper of the cut, and the final zone was a straight cut ending at the bottom of the sample. A clear representation of these three distinguishable zones found during the evaluation of the microscopic samples is shown in Figure 4.

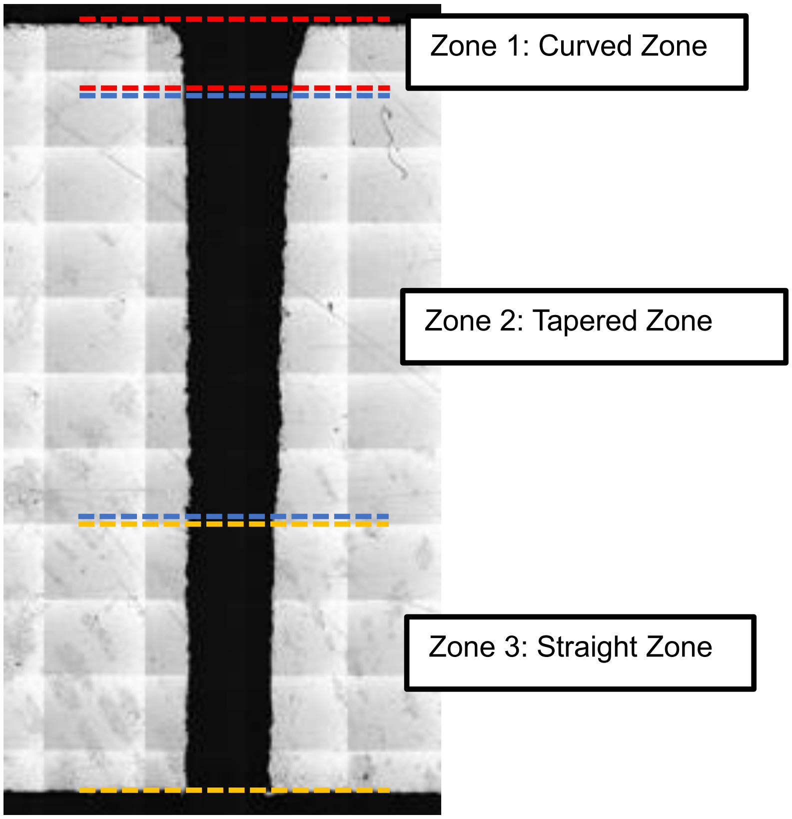

Figure 4: Three distinguishable zones delineated based on microscopic images.

As a result of the three distinguishable zones throughout the initial observations, it was also important to study the effects of the abrasive waterjet cutting process on fiber reinforced composites mechanical properties. When machining fiber reinforced composite parts, the surface finish is crucial in maintaining the intended mechanical properties. For composite parts machined with an abrasive waterjet, the surface finish is extremely important because if there are any defects left on the part, it could possibly result in skewed, unpredictable mechanical properties. As a result, this study also investigated the impact of the edge cut quality formed on fiber reinforced composite test specimens and their mechanical properties. In this case, since an abrasive waterjet was used to machine each test specimen, different edge finishes were achieved by varying the speed of the waterjet. Varying the cutting speeds produced different edge finishes which is likely where stress concentrations could initialize and propagate when under loads. As a result, throughout this study, for each ply orientation group, three different machining speeds were used: 200 in/min, 125 in/min, and 50 in/min. Along with varying the speed of the waterjet cutting operation, different fiber orientations were tested. Per the recommendations of ASTM 3039, two separate sample sizes were fabricated to perform tensile tests. The 0° fiber orientation sample group was manufactured to specific dimensions of 10" long, 0.5" wide, and 0.04" thick. The 90° fiber orientation sample group was manufactured to 7" long, 1" wide, and 0.08" thick. Different fiber orientations were manufactured because it was imperative to investigate the relationship between the fiber orientation, edge surface roughness, and its effect on the ultimate tensile load each sample group could withstand. Table III shows the corresponding cutting parameters for each group.

Table III. Cutting Speeds for carbon fiber reinforced composite tensile testing.

	Cut Quality 1	Cut Quality 2	Cut Quality 3
Sample Group 1 (0°)	200 in/min	125 in/min	50 in/min
Sample Group 2 (90°)	200 in/min	125 in/min	50 in/min

The purpose of testing both 0° and 90° ply orientations were to be able to analyze whether the reinforcement fibers or the polymer matrices were more effected by the edge cut quality. For the 0° test specimens, the reinforcement fibers of the composite were parallel to the load that was applied. It was then conceivable to investigate the effect of the roughness on the edges, fiber orientation, and the strength of the test specimen. On the other hand, the 90° test specimens were used to determine the relationship between the edge finish and the altered state of the polymer matrix. The 90° were able to test primarily the matrix because the load that was applied to the test specimen was now perpendicular to the fiber orientation. By doing this, the polymer matrix was isolated from the reinforcement fibers and an investigation could now be done to evaluate how the stress concentrations formed.

Once the specimens for each group were fabricated with the abrasive waterjet, the ends were sanded using 200 grit sandpaper and an orbital sander. The 0° samples were sanded 2.25” on each end and on both sides. In addition, the 90° samples were sanded 1” similarly. The tabs were necessary because of the high force exerted by the 22-kip load frame shown in Figure 5. Through previous research, without the tabs, the composite samples would become distorted thereby effecting the results. To provide the most precise and secure bond, a bonding jig was designed for the desired adhesion during the 24-hour bonding process. After the specimens were inserted into the bonding jig, a steel plate was compressed onto a lower steel plate to provide equal compression. To ensure the top plate did not move during the 24-hour cure cycle, c-clamps were also placed to secure the top plate and the bottom plate. After 24 hours, the c-clamps and bonding jigs were removed apart, and the samples were pulled out.

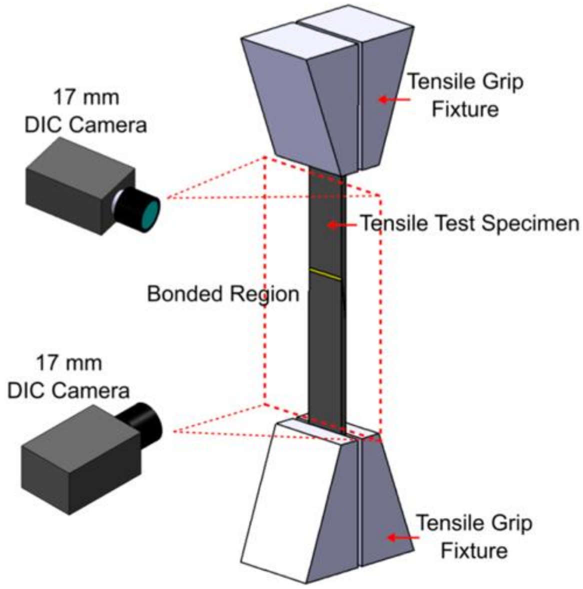

Figure 5. 22-kip load frame with two DIC cameras setup during tensile testing.

After the bonding process, the samples were spray painted so the Digital Image Correlation (DIC) camera could obtain accurate data during the tensile test. First, a white spray paint was applied to one side of all the samples. Then, a black ink roller was used to provide fine speckles to the white paint. Before testing could commence, the DIC was calibrated using a similar speckled patterned calibration tool. The rate at which the 0° samples were pulled by the 22-kip load frame was 2 mm/sec per ASTM 3039. For the 90° samples, after multiple dummy test sampling, it was determined that for the best evaluation, a pulling rate of 0.5 mm/sec was optimal. Throughout the testing of all 30 fiber-reinforced composite samples, the DIC was able to produce images every 0.5 seconds which provided the most accurate analysis possible. During the analysis process, the calibration images that were previously mentioned were used for each sample to calibrate the analysis software as well. For each sample, the software was able to evaluate all the photos from the DIC which amounted to approximately 150-200 images per sample. In addition, with the data outputted by the 22-kip load frame, the software was able to determine specific mechanical properties of each sample and report an excel file for further investigation.

Carbon Fiber Reinforced Composite Kerf Angle Results

The first sample that was investigated was ¼" thick carbon fiber reinforced composite. The 100% (blue) cutting speed shows the greatest angle along the tapered zone. Also, the 100% cutting speed took away the least amount of material but left a much more pronounced kerf angle on the sample. Next, the 75% cutting speed (red) produced a slightly smaller kerf angle than the 100% speed, but it was still relatively tapered. The 50% cutting speed kerf angle more nearly resembled a straight cut, yet still had a slightly tapered kerf angle. Lastly, the 25% cutting speed proved to be the optimal cutting speed for the ¼" thick carbon fiber reinforced composite sample in terms of reducing the kerf angle. Furthermore, since the top and bottom lengths are trickier to delineate from in Figure 6 (a), the top and bottom measurements were expressed in Figure 6 (b). A similar, expected trend occurred throughout the data analysis for the four cutting speeds with respect to their top and bottom lengths. As previously mentioned, the 100% cutting speed had the least amount of material removed by the abrasive waterjet. From there, each cutting speed removed more and more material off the part. The next microscopic image that was analyzed was the ½" thick carbon fiber reinforced composite sample. On average, the kerf angle breakdown in Figure 6 (a) shows a similar pattern. The 100% cutting speed produced a larger kerf angle compared to the remaining three cutting speeds. Meanwhile, similar to the ¼" thick carbon fiber reinforced composite sample, the 100% also removed the least amount of material during its cut as shown in Figure 6 (b). The ¾" thick carbon fiber reinforced composite sample followed the same previously mentioned trend whereas the 100% cutting speed produced the largest taper, while the 25% cutting speed resulted in a cut with a smaller kerf angle.

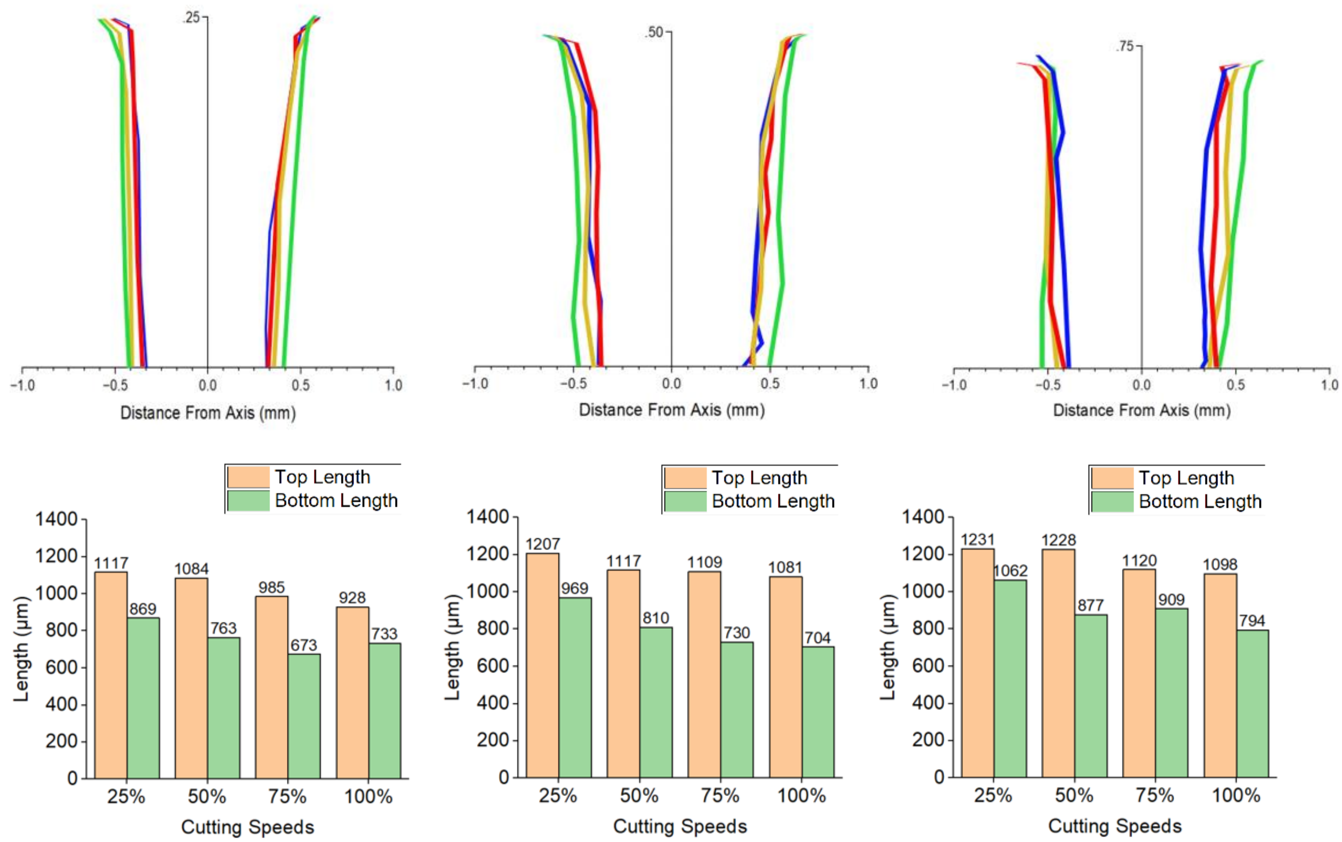

Figure 6. (a) Kerf angle projection graph. (b) Top and bottom length measurements.

Tensile Test Results

The carbon fiber reinforced composite samples results led to a further investigation into the impact of the kerf angle on the specimens' tensile properties. Figure 7 illustrates the maximum stress the 90-degree group could withstand. The data showed an unclear relationship between the cutting speed and the maximum stress each group could withstand.

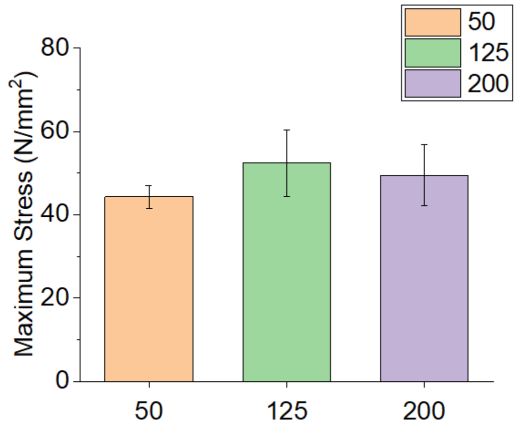

Figure 7. 90° maximum stress with the theoretical cross-sectional area.

Figure 8 shows the results for the tensile testing of the 0-degree test specimens. There is a slight increase in maximum strength as the cutting speed increases. This result is contrary to the initial hypothesis that the slower cutting speed would produce a smoother finish therefore being able to withstand more load.

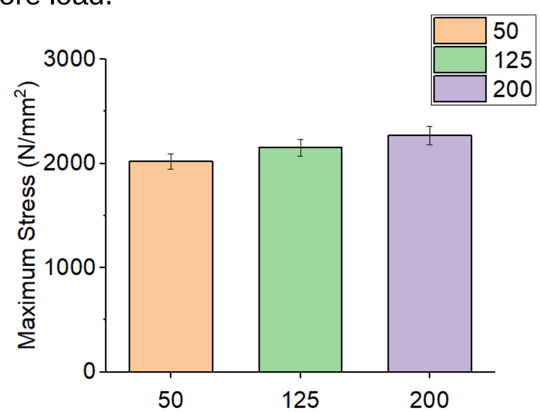

Figure 8. 0° maximum stress with the theoretical cross-sectional area.

Before the testing, each sample was measured using calipers to find the cross-sectional area per ASTM 3039. Based on the results from the kerf angle studies and the maximum stress with the theoretical cross-sectional area, it is concluded that this method is not accurate enough to provide accurate measurements. Since the kerf angle is formed on the part as previously shown, the measurement device used to calculate the width of the test specimen only captures the widest point of the specimen. Figure 9 portrays the traditional and actual ways of measuring the test specimen's cross-sectional area.

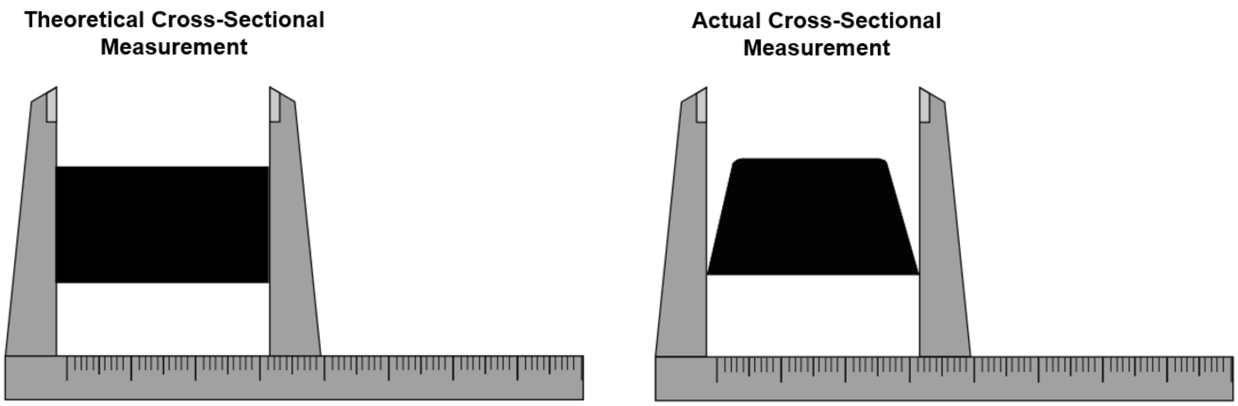

Figure 9. Theoretical vs. Actual measurement methods of samples for stress calculations using vernier calipers.

To determine the correct cross-sectional area, the samples were potted, and microscopic images were obtained. Once the cross-sectional area was determined, it was then possible to input those values in for the calculation of the maximum stress for each sample group. Figure 10 shows the corrected maximum stress values. It was determined that all the 90-degree sample groups withstood relatively the same amount of maximum stress.

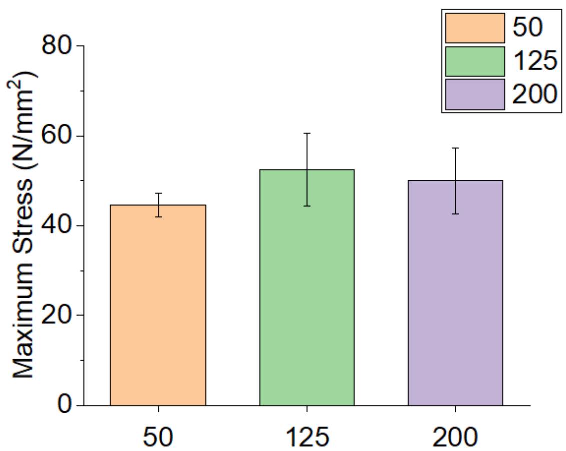

Figure 10. 90° maximum stress with the theoretical cross-sectional area.

Similarly, the 0° sample groups were approximately the same amount of stress each sample could withstand once the cross-sectional area was accounted for. Figure 11 shows the recalculated maximum stress which places importance the kerf angle factor in obtaining the correct and accurate cross-sectional area.

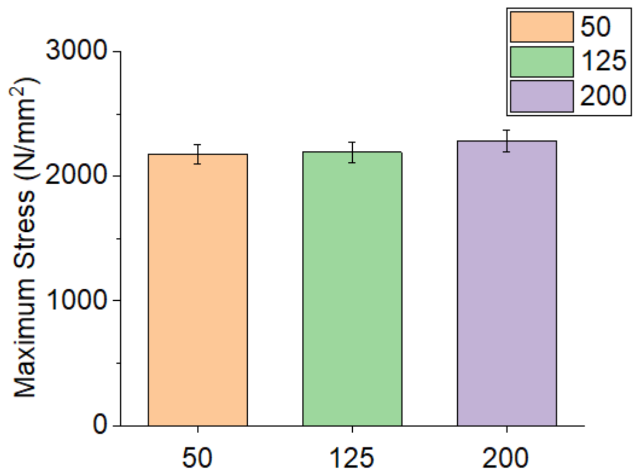

Figure 8. 0° maximum stress with the theoretical cross-sectional area.

Conclusion

Throughout the investigation of the effect of the abrasive waterjet on carbon fiber reinforced composites, many observations were made. First, when a 100% cutting speed was used, the kerf angle was the largest. From the 100% cutting speed, the kerf angle became less and less as the cutting speeds were slowed down. Additionally, the cutting speed of the abrasive waterjet produced varying kerf angle which also altered the amount of material that remained on the part. To test the mechanical properties of the composite test specimens with various edge surface finishes, sample groups were formed to perform tensile tests. Both the 90° and 0° groups' maximum stress values were determined with the cross-sectional area acquired by manual measurements. As a result, the cross-sectional areas were not accurate enough because of the previously mentioned resulting kerf angle left on the specimen. To verify the hypothesis, the specimens underwent high-precision measurements, and the cross-sectional area was corrected. There was relatively no difference in the edge surface finish and the amount of stress the specimens could withstand. This could be the result of the small thickness values of the composite specimens. Since the specimens were so thin, there was not enough material to alter the edge surface finish to the point where stress concentrations could form. Further research must be conducted to fully analyze and verify the previously mentioned hypothesis. In conclusion, when using fiber reinforced composite test specimens for tensile testing, it is recommended to use another means of cutting the samples. The kerf angle itself alters the test specimens enough to the point where the cross-sectional measurements are too inaccurate when following the ASTM 3039 guidelines.

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