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Paper

QUALITY ISSUES ASSOCIATED WITH ABRASIVE WATERJET CUTTING AND DRILLING OF ADVANCED COMPOSITES

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ABSTRACT

To improve strength to weight ratios, the fiber reinforced polymer composite materials are often used in conjunction with another material, like metals, to form hybrid structure. Due to the inherent inhomogeniety and anisotropy of Fiber-reinforced Plastic (FRPs) and Metal-Fiber laminates, cutting and hole generation techniques are currently rife with damage phenomenon that need to be addressed such as delamination, edge chipping, and crack formation, in order to ascertain the structural integrity of a component. Of these, delamination and in particular, fiber break out at the jet entry, and exit-ply delamination has been identified as most deleterious. This paper reports the quality of machined surfaces produced in polymer and metal-fiber Composites. In this study, damage characteristics in machining are assessed in terms of delamination, and hole defects or damage area.

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1. INTRODUCTION

Since its inception a over two decades ago, the Abrasive Waterjet (AWJ) process has gained immense popularity owing to the numerous advantages offered by this process like absence of heat-affected zone and no residual stresses. These days this process is being applied into the cutting and drilling of hard-to-cut materials such as advanced composites [1-7]. However. in cutting and drilling composite materials with AWJ, defects such as delamination, cracking and fiber pullout will often occur either at jet entry or exit side of a composite. These defects can induce severe degradation in the mechanical properties of machined composites. In addition, delamination is one of the most important defects in the composites and frequently happens due to the high velocity impact of the jet [6-9]. The water penetrated between laminate layers during cutting and drilling is suggested as the main reason for damages [6]. A study on examining the mechanism of the delamination is reported by Hashish [8] who suggested that the hole piercing of composite laminates by high pressure waterjet caused fracture, cracking or delamination. He proposed that the shock loading of water and hydrodynamic pressurization are responsible for the damage. Wang conducted a study on minimizing the defects in composites. Wang [9] recently suggested that pre-drilling a starter hole could minimize the material defects. Decreasing the pressure or the jet size and supporting the bottom surface of the material can reduce the undesired failure at exit [7]. In cutting and drilling process, it is found that delamination always propagates along the radial direction of the drilled hole. Most of the studies mainly focus on the incomplete cut of thick materials in which delamination was observed at the exit of the waterjet. Wang [2] studied the effect of the delay time of abrasive supply on the delamination and suggested a semi-analytical model for predicting crack length.

There is a need for the better understanding of how composite materials are machined and how the defects occur, In this study, we will focus on the delamination damage produced in AWJ cutting and drilling. Previous research work has been conducted mainly on kerfs characteristics and machinability rather than crack initiation and propagation at various conditions. However, not much research has been reported in applying the existing AWJ machining models to composite materials. In this study, we will compare WJ and AWJ in terms of feasibility for machining and drilling of composites. In addition, the effect of the WJ and AWJ process parameters on sub-surface defects and delaminations will also be studied.

2.0 Theoretical models for Drilling and Delamination

It is very important to predict how big delamination will be. Otherwise, machined materials will not be used properly due to their changed material properties. In drilling of composite materials, the diameter of a hole should be consider based on prediction of delamination size so that delamination will only cause acceptable damages in the composite materials. From this point of view, attempts to develop an analytical model for delamination have been conducted. In this section of the chapter, we will look into a semi-analytical model for delamination.

Raju-Ramulu's transient drilling model and Conical Cavity model [10] are based on the idea of momentum and energy conservation between the incoming and outgoing jet streams within the eroded cavity. In these models, some assumptions are made for simplification. Also, there are some parameters, which should be experimentally determined. A main difference between Raju-Ramulu's model and Conical Cavity model is that the former assumes a cylindrical cavity while the latter assumes a conical cavity.

The cylindrical cavity assumption used in developing the fluid flow relations agrees approximately with observed cavity shapes. However, a modified "conical-cavity" version of this model has also been developed that accounts for the taper seen in actual AWJ drilled holes [11].

$$\frac{dh}{dt} = \left[\frac{k_3}{(R^* + h\tan\theta)(R^* + 3h\tan\theta)}\right]\left(\frac{1}{a + k_1 h}\right)^2 \tag{1}$$

$$k_1 = \frac{\pi r C_D \rho_s}{\dot{m}_a + \dot{m}_w}\left(2 + \frac{R^*}{r\cos\theta}\right)^2$$

$$k_3 = \frac{5\xi \dot{m}_a}{6\pi R^{*2}}$$

where θ is the conical cavity half-angle., ξ is is an empirical constant, termed the *inverse specific erosion energy*. Geometric definitions are shown in Figure 1.

Shanmugam et al. [9] suggested a semi-analytical model. The procedure of the model will be illustrated in this section. In general, the maximum crack length in which we are interested can be expressed in the following form of function.

$$C = f(V_t, d_j, P, S, \dot{m}_s, E_1, E_2, \upsilon_1, \upsilon_2, \mu_1, \mu_2, \nu_{p1}, \nu_{p1}) \tag{2}$$

Where, the jet traverse velocity, V_t, the jet diameter, d_j, the water pressure, P, the standoff distance, S, he mass flow rate of slurry jet, $\dot{m}_s$, the Young's modulus, E, the volume fraction, υ, the shear modulus, μ, and the poisson ratio ν_p are parameters which influence on the maximum crack size.

$$f(C, d_j, \frac{d_j}{V_t}, \dot{m}_s, \frac{P}{\rho_w}, E^*) = 0 \tag{3}$$

Where, C is the maximum crack length, V_t is the traverse speed, the ratio of d_j/V_t represents the effect of jet exposure time and P/ρ_w represents the effect of jet kinetic energy rate. In order to define the relation between variables above, a dimensional analysis approach is used. From the Buckingham's π theorem, the following form between dimensionless variables can be established.

$$f(\prod_1, \prod_2, \prod_3) = 0 \tag{4}$$

Where,

$$\prod_1 = \frac{C}{d_j}$$

$$\prod_2 = (\frac{d_j}{V_t})(\frac{E^* d_j}{\dot{m}_s})$$

$$\prod_3 = (\frac{P}{\rho_w})(\frac{\dot{m}_s^2}{E^{*2} d_j^4})$$

$\prod_2$ and $\prod_3$ represent the effects of jet exposure time and jet kinetic energy rate, respectively. As a result, an equation, which shows the relations between the variables above, can be derived with several experimental constant that should be determined as follows.

$$\prod_1 = k \prod_2^a \prod_3^b = kY \qquad (5)$$

Where, Y= $\left((\frac{d_j}{V_t})(\frac{E^* d_j}{\dot{m}_s}) \right)^a \left((\frac{P}{\rho_w})(\frac{\dot{m}_s^2}{E^{*2} d_j^4}) \right)^b$ and constants k, a, and b should be determined based on the experimental data.

3. EXPERIMENTAL CONDITIONS AND PROCEDURE

3.1 Materials and Preparation

Three multi directional/multi-layer metal-fiber (hybrid) composite materials were utilized in this study. The material used in this experimental study is a Carbon Fiber Reinforced Plastic (CFRP). CFRP composite materials of thickness 4.5mm and 5.8mm with a plane weave fabric surface plies. The average fiber diameter and ply thickness are estimated to be 6㎛and 120㎛, respectively as shown in Figure 2. Hybrid composite has a ply thickness of about 145 ㎛.

3.2 Experimental Procedure and Analysis

AWJ system in our manufacturing lab is Flow International model WJP1313. This machine has the ultra high pressure (UHP) cutting system, which consists of a XY control table, a pressurizing pump, and a cutting head. A variety of materials can be cut with UHP waterjet. The AWJ is NC controlled with the CNC control system. The maximum water pressure available is 350 MPa. The abrasive garnet selected had a mesh size of #120. The abrasives were transferred from a hopper to the mixing chamber by the venturi action. The debris of workpiece material during the experiment was collected into a catcher tank, which is filled with water. The parameters used in the experiment are AWJ pressure, standoff distance, material thickness and abrasive flow rate. The AWJ pressure is manually controlled using the pressure gage. The standoff distance is controlled through the controller in the operator control stand.

Design of experiments

Cutting and drilling Experiments were conducted in this study using abrasive waterjet (AWJ) and pure waterjet (WJ). The abrasive flow rate is dependent on the water pressure in this experiment because abrasive is mixed with waterjet in the mixing tube by the venture action. For this reason, the abrasive flow rate increases with the increase of the water pressure. The abrasive flow rates were calibrated by measuring the time spent for a certain weight of abrasives to be completely consumed in the hopper. Abrasives with a mesh size of #120 are used. The supply pressure was manually controlled using a pressure gage and the standoff distance was also manually controlled. The traverse speed and supply of abrasives were automatically controlled by the abrasive waterjet system programmed by NC code.

Tables 1 and 2 show the cutting experimental conditions and the run order. In the same condition as shown in Table 2, two specimens with different thickness were machined. Among various experimental parameters, only three of them are chosen, which are the traverse speed, the water pressure and the material thickness. Specimens were machined under nine different traverse speeds, three different water pressures, two different material thickness and three different abrasive supply conditions. The length of cut for each experimental condition was 28.5mm. Although the abrasive flow rate is changed it is just dependent on the water pressure as mentioned before. In abrasive supply conditions, the first condition is the machining by pure waterjet and the second is the machining by abrasive waterjet and the third is the machining by abrasive waterjet with delay time. We will refer these conditions as WJ, AWJ and AWJD, respectively. Using a stopwatch and averaging six measurements calculated the delay time in AWJD experiments. The abrasives used were 120 mesh garnet.

Tables 3 show the drilling experimental conditions and the run order for drilling process, respectively. During the experiments, video pictures were recorded to precisely measure the drilling time. The software to review the moving pictures was Adobe Premiere Elements, which supports up to 0.01 second of the time measurement. For the each case, total three of attempts were made to reduce experimental errors. A total of 81 tests were conducted because the abrasive flow rate is dependent on the water pressure.

A diamond saw system was used to precisely cut a cross-section of a specimen to be used for analysis. In order to ensure that delamination in a cut specimen does not propagate, the diamond saw system was operated with low speed and force applied to the specimen. Nikon optical microscope was used to see the microstructure and delaminations of the specimens. Nikon camera for taking a picture and NIS software for editing photos are installed in this system.

Surface roughness is one of the most important criteria, which help us determine how rough a workpiece material is machined. During these experiments, numerous surface roughness measurements will be conducted. Surface roughness will be measured at two different areas: 1mm far from the entrance of waterjet, 1mm far from the exit. Mahr surface profilometer analysis system was used to measure machined surface. In this measurement system, the length of measurement was 5.6 mm, cut-off length is 0.8mm and traverse speed of the stylus was 0.5 mm/s. Among various surface roughness parameters, arithmetic average roughness (R_a), maximum height of the profile (R_t) and ten point height (R_z) were evaluated

4. RESULTS AND DISCUSSION

In abrasive waterjet system, there are various parameters affecting machining quality results.. Comparison between the experimental results and analytical drilling and delamination model predictions will be presented..

CFRP Composites

There are three experimental parameters considered during the cutting experiment. Figures 3 and 4 show the photomicrographs of the machined surfaces using both pure WJ and AWJ under varying cutting conditions. The first is the traverse speed, the second is the water pressure and the third is the abrasive supply condition. For the traverse speed, it is observed that the traverse speed has a strong effect on the surface roughness of the cut surface as can be seen visually. In addition, Figures 3 and 4 also shows the three cutting zones as defined by Ramulu-Arola [5] These three damage zones consist of an initial damage region at jet entry (IDR), a smooth cutting region (SCR), and a rough cutting region (RCR) near the jet exit. The initial damage region extends from the jet entrance. This region shows high surface roughness values and rounding of the entrance kerf geometry. This initial damage zone occurs as the result of a high density of abrasive wear tracks formed on the face of the kerf. The smooth cutting region occurs below the initial damage zone and extends to the beginning of the rough cutting region. Relatively good surface finish and lower values of surface roughness appear in this region. The rough cutting region exists below the smooth cutting region. This region shows jet deflection wear striations and high surface roughness values as a result of the large abrasive particle attack angles.

Figure 5 show typical surface profiles recorded at the smooth cutting and rough cutting regions for both WJ and AWJ for similar cutting conditions. The surface roughness generated by AWJ is about 2.5 times less than the WJ. Figure 6 show the summary results of CFRP Cutting by WJ, AWJ and AWJD . Clearly, from the experimental data, the surface roughness increases as the traverse rate increases regardless of the other experimental conditions. This trend happens because the waterjet stream has to cut the increased area of the material with the same given amount of time as the traverse rate increases. This means that the consumed energy to cut the unit area decreases as the traverse speed increases. As a result, the surface finish becomes worse as the traverse rate increases. The water pressure also has a clear effect on the surface roughness. It is shown that the surface roughness increases as the water pressure increases. This result occurs due to the fact that the waterjet stream has the bigger kinetic energy for cutting a material as the water pressure increases. For the abrasive supply condition, it is shown that the WJ (pure waterjet) system has the greater surface roughness than the AWJ (abrasive waterjet). This result takes place because of the difference of cutting mechanism between those two conditions. In the WJ condition, the rate of material removal is much slower and there are high-localized pressures on the workpiece material. The localized pressure often causes material failure rather than micromachining material removal. In other words, pure waterjet system machines the workpiece material by micro cracking and fracturing rather than micro cutting and erosion. Contrary to the WJ condition, a material is machined by shearing, bending and erosion rather than micro cracking in AWJ condition. As can be seen WJ condition the trace of the jet deflection remains near the exit region in the cut surface. This is due to the fact that as the depth of cut increases there is more loss in kinetic energy of the waterjet. As a result, the surface is not machined well near the exit region where the kinetic energy of the jet is not enough and the traces of the jet deflection remain on the cut surface. The surface roughness of exit area appeared to be greater than that of the entrance area regardless of the abrasive. As expected, the surface roughness more rapidly increases with the increase of the traverse speed in the WJ condition. This is probably due to that the pure waterjet can quickly lose the kinetic energy, penetrating the material. The effects of abrasive waterjet with a delay time (AWJD) appear to be very similar to that of the AWJ condition. Among the area used for measuring the surface roughness, only a small limited area is affected by the AWJD condition and hence was presented here..

During the cutting experiments, unexpected delamination took place several times. Most of the delamination occurred at a low pressure and high traverse speed under the WJ condition. As stated before, this is because the WJ condition often causes cracks rather than erosion on the surface. Figure 7 shows the typical delamination and cracking CFRP cutting. Under the condition of low pressure and high traverse speed, the kinetic energy of the waterjet for cutting is insufficient and conditions are given in the table of Figure 6.. The delamination appears to be observed mostly near the exit region and can be seen in Figure 3. This is due to the fact that there is the lack of support of exterior fibers at the exit region and there is the loss in cutting energy of the jet as the waterjet penetrates the material. In the WJ conditions, although the velocity of the jet is higher than that of the AWJ condition, momentum of the jet decreases more rapidly with propagation due to the relatively low mass of the waterjet. In other words, the kinetic energy of the jet in the WJ condition is consumed quickly compared to the AWJ condition. In addition, relatively low material removal rate of the WJ condition allow a sufficient time for a crack to initiate by the shock wave impact of the waterjet. For the reasons above, the delamination is more likely to occur under the WJ condition.

In order to assess the cracking and delaminations, the effects of experimental parameters on the induced crack lengths were measured and analyzed. It is shown that the crack length increases with the increase of the traverse speed from the experimental result. In the cutting experiments, delamination occurred. In order to predict delamination process, Wang's analytical model was used. Wang's model requires some constants to be determined through the experiments. We use the experimental data under the conditions in which delamination occurred. From the delaminations results shown in Figures 3 and model prediction shown in Figure 7, the error percentage between the model estimation and the real data was found to be 10.2% . Therefore the semi- analytical approach provided by Shanmugam and Wang is good estimation model for the crack length. Even though there are no experimental data results for the crack length at high water pressures, it is predicted that the crack length increases as the water pressure increases. This happens because the waterjet leads to the increase of the kinetic energy enough for cutting without delamination as the water pressure increases.

Figure 8 shows the AWJ piercing of holes jet entry and exit surfaces in CFRP composites for varying process conditions.. Delamination damage is clearly visible on the surface of the woven fabrics. There were three experimental parameters considered during the drilling experiment to see relationship between the piercing time and the depth of cut. It is found that the entrance diameter R*, is almost constant to variation of the water pressure and slightly increases with increase of the standoff distance. Similarly, the exit diameter is almost constant to the change of the water pressure. The first is the standoff distance, the second is the water pressure and the third is the material thickness. As can be expected from the results for the entrance and exit diameters, the taper ratio, decreased with increase of the water pressure and slightly increases with increase of the standoff distance. Those results physically make sense because with decrease of the water pressure and increase of the standoff distance the kinetic energy of the waterjet for drilling decreases. Due to the difficulties in measuring the depth of cut at a certain point of time, a method that measured the piercing time for a given thickness of material was used. The measured piercing time appeared not to be change much at the short standoff distance and the high water pressure. Therefore, more precise equipment system for measuring time is necessary for accurate results. For the reason, we used the conical model given in Equation 1, to estimate the time for piercing using the pre-determined constants from previously published experimental CFRP data [6]. Predicted piercing times were within 12% of the experimental times. In general, the results were consistent with that of Reference 6.

During the drilling experiments, delamination occurred under various conditions. All the drilling experiments were conducted under AWJ conditions. It is important to look into experimental conditions and results to prevent defects and delaminations in composites. In order to analyze the characteristics of delamination in a pierced hole, damages on the specimens were evaluated based on the result parameters which were the entrance diameter, exit diameter, taper ratio, delamination length and damaged area. Figure 9 shows the approach used to quantify the delaminated damage area, delaminations and the effect of process conditions on the damage. In order to calculate the damaged area, we assumed the damaged area to be an ellipse. Therefore, the equation for an ellipse was used. From the experimental results, it is clearly observed that the damaged area decreases with increase of the water pressure and decrease of the standoff distance. As stated above, this is because the water jet of low kinetic energy at low water pressure and long standoff distance causes more delamination. If the energy of the waterjet is not sufficient enough for machining a workpiece material but enough for the crack to initiate with a sufficient time, delamination may occur. Currently, the work is in progress, on finding solutions and conditions that will reduce delamination and damage reduction in cutting and drilling.

Hybrid Composites

Figure 10 shows the typical AWJ cut and trepanned holes surfaces along with the observation made on jet induced delamination at the outer titanium foil or ply. Distinct material removal mechanism was observed for titanium and composite ply when we compare with diamond cut surface.. Titanium ply was cut by means of ductile shearing, abrasive plowing, and scratching action similar to the result in AWJ machining of Ti-6Al-4V performed by Seo et al.[7].

Figure 10 also shows the SEM micrograph of the machined surface on Graphite and titanium ply. Unlike titanium which is ductile, PIXA-M composite ply was cut by micro-chipping, fracture fibers, and erosion which is similar to AWJ material removal mechanism of FRP composite materials and continuous-fiber ceramic composite materials (CFCC). Roughness values were not quantified as profile traverse length is grater than the hybrid composite sheet thickness. However, recorded profile height distribution analysis of AWJ surface showed average roughness of 62.5-120.9 % higher than a diamond cut surface. Difference in average roughness between the best and worst condition was less than 0.27 μm. This could result from abrasive wear tracks that aligned in thickness direction..

High pressure waterjet technology is a versatile tool, and should be used carefully when machining advanced composites. The results from this preliminary study confirm that abrasive water jet machining was not only feasible for machining of TiGr composite materials, but also, possesses great potential for industrial applications.

5. CONCLUSIONS

A systematic study of the parametric effects contributing to the surface quality and damage induced in cutting, drilling of CFRP and Hybrid composites using with a waterjet (WJ) and AWJ was conducted. Based on this experimental study, the following conclusions were made:

- **Cutting**
- From the surface roughness results we can conclude that Ra increases proportionally with increasing traverse rate, regardless of the material.
- Pure waterjet(WJ) often causes delamination rather than erosion especially under the conditions of the low pressure and the high traverse speed.
- Wang's semi-analytical model was a good estimator for the crack length in composites
- Abrasive waterjet condition(AWJ) shows the best surface finish compared to pure waterjet condition(WJ) and Abrasive waterjet with a delay time(AWJD).
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- **Drilling**
- Modified Raju-Ramulu's analytical model or conical cavity model suggests a good estimation for depth of cut once experimental empirical constants were determined.
- The damages on a material appear to decrease with increase of the water pressure and decrease of the standoff distance.
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Table 1. Design of experimental parameters for cutting process

Parameter	**Level**
Traverse Speed Vt (mm/s)	2, 5, 10, 15, 20, 25, 30, 35, 40
Abrasive Waterjet Pressure (MPa)	200, 275, 300
Abrasive Flow rate (gm/s)	11.9, 12.2, 14.3
Material Thickness (mm)	4, 5.8
Standoff Distance (mm)	3
Delay time (s)	0.93

Table.2. Experimental run order for cutting experiment

Run#	Abrasive conditions	Supply Pressure (MPa)	Abrasive Flow Rate (g/s)	Traverse speed (mm/s)								
1	Without abrasive (WJ)	200	11.9	2	5	10	15	20	25	30	35	40
2		275	12.2	2	5	10	15	20	25	30	35	40
3		350	14.3	2	5	10	15	20	25	30	35	40
4	With abrasive (AWJ)	200	11.9	2	5	10	15	20	25	30	35	40
5		275	12.2	2	5	10	15	20	25	30	35	40
6		350	14.3	2	5	10	15	20	25	30	35	40
7	Abrasive with delay time (AWJD)	200	11.9	2	5	10	15	20	25	30	35	40
8		275	12.2	2	5	10	15	20	25	30	35	40
9		350	14.3	2	5	10	15	20	25	30	35	40

Table.3. Design of experimental parameters for drilling process

Parameter	**Level 1**	**Level 2**	**Level 3**
Material Thickness (mm)	4.5	7.0	9.5
Standoff Distance (mm)	2.0	3.0	4.0
Abrasive Flow rate (gm/s)	11.9	12.2	14.3
Abrasive Waterjet Pressure (MPa)	200	275	350

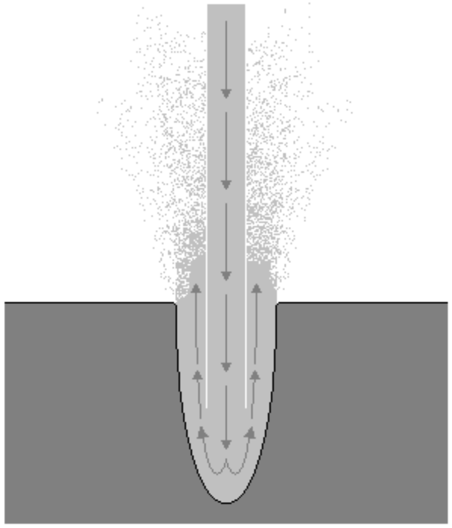


Figure. 1 Typical drilled hole profile (R* is upper radius of the hole, h is the depth or thickness of the sheet)

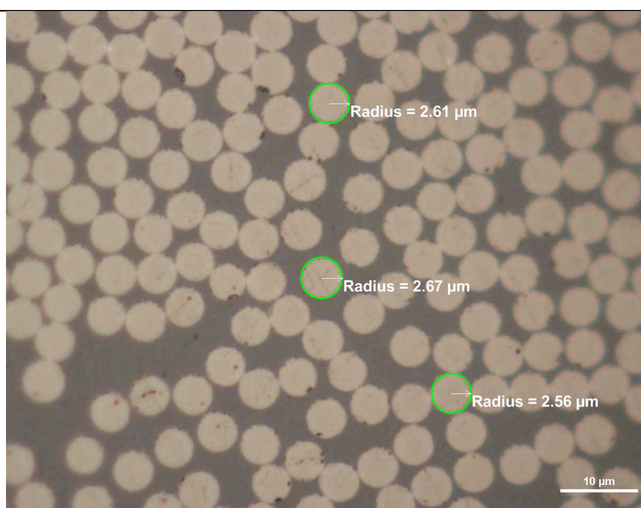
	
Cross-section of 4mm thick specimen at ninety degree direction at 1500X	Cross-section of 4mm thick specimen at zero degree direction at 70X

Figure 2 CFRP Material Microstructure

Cross-section of cut specimens

Experimental Conditions		Machined by Pure waterjet (WJ) Material thickness: 4 mm, standoff distance: 3 mm AFR indicates abrasive flow rate	
AFR	11.9 gm/s	12.2 gm/s	14.3 gm/s
Supply Pressure	200 MPa	275 MPa	350 MPa
Traverse speed (mm/s): 2			
10			
25			
40			

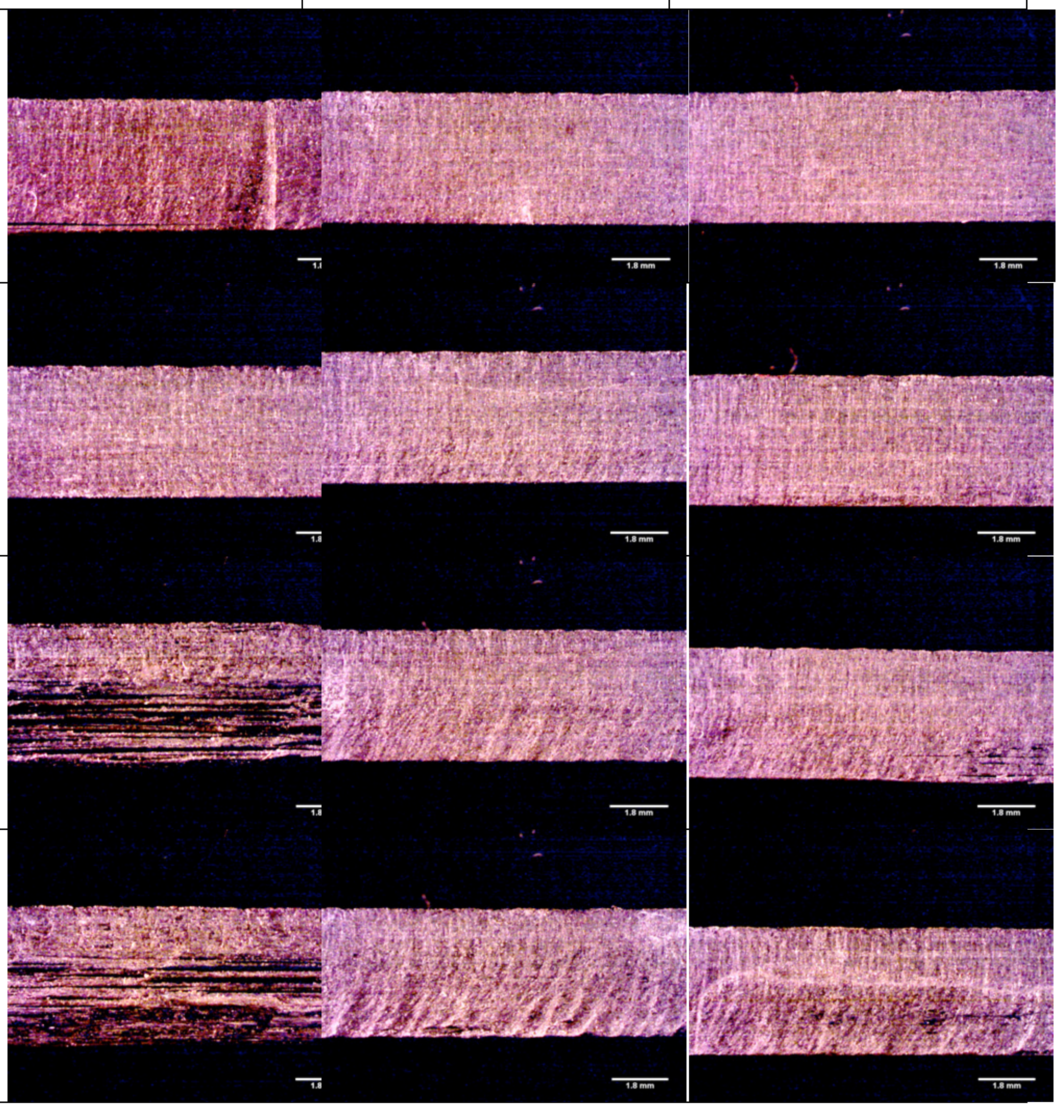


Figure 3 Optical Micrographs of Waterjet Cut Surfaces at Varied Cutting Conditions

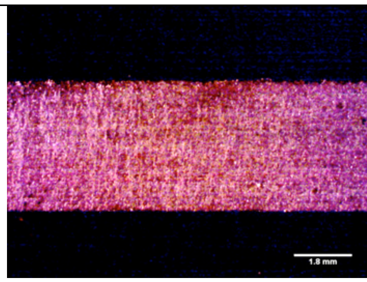
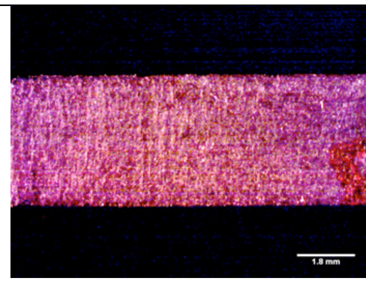
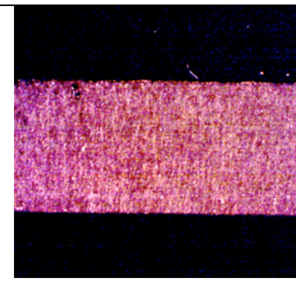
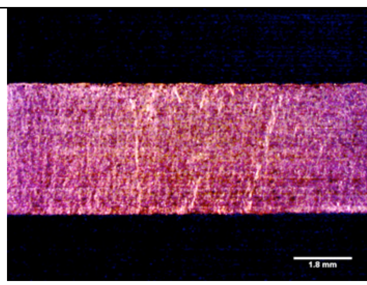
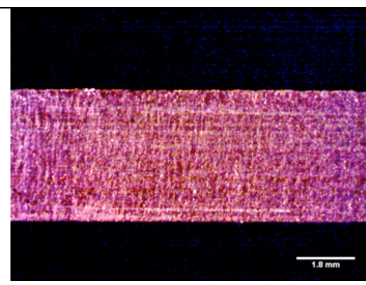
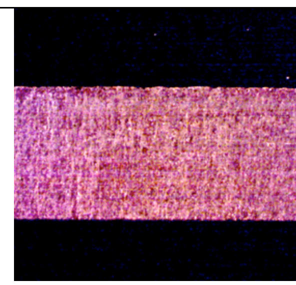
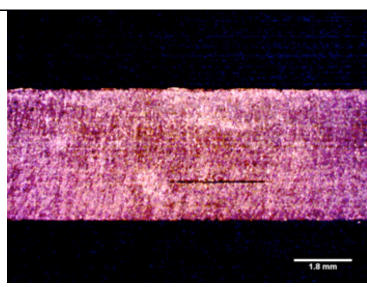
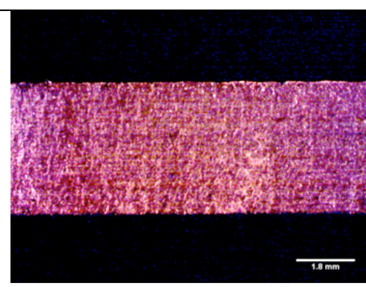
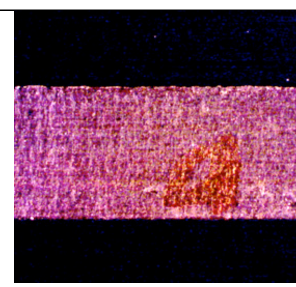
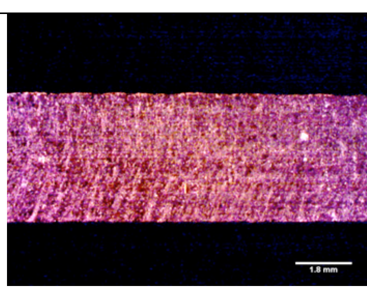
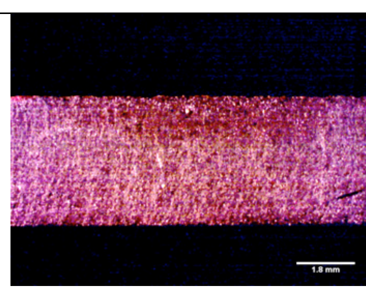
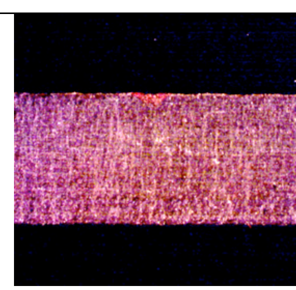
Experimental Conditions		Machined by abrasive waterjet with delay time (AWJD) Material thickness: 4 mm, standoff distance: 3 mm Delay time: 0.93 second, AFR indicates abrasive flow rate		
AFR		11.9 gm/s	12.2 gm/s	14.3 gm/s
Supply Pressure		200 MPa	275 MPa	350 MPa
Traverse speed (mm/s)	2			
	10			
	25			
	40			

Figure 4 Optical Micrographs of Abrasive Waterjet Cut Surfaces at Varied Cutting Condition

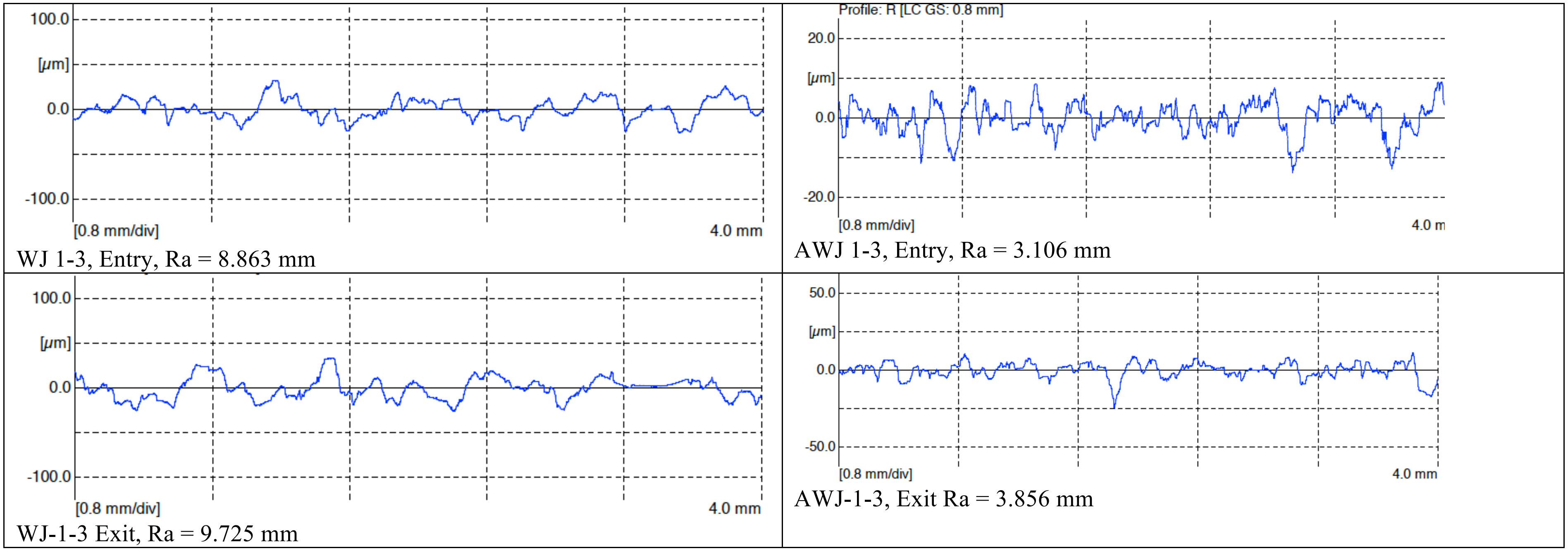
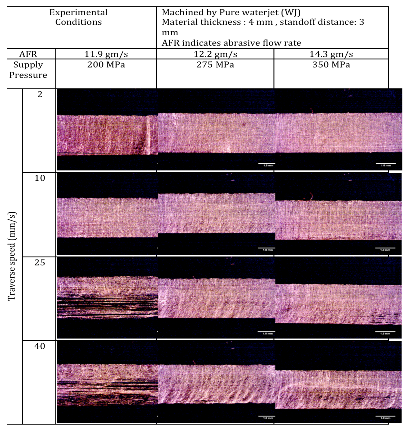


Figure 5 Typical surface profile height variations in WJ and AWJ Cut surfaces for Same Cutting Condition

O : Delamination observed ×: No delamination observed

Run #	Jet condtions	Pressure (MPa)	Traverse speed (mm/s)								
			2	5	10	15	20	25	30	35	40
1	Without abrasive(WJ)	200	×	O	O	O	O	O	O	O	O
2		275	×	×	×	×	×	×	×	×	×
3		350	×	×	×	×	×	×	×	×	×
4	With abrasive(AWJ)	200	×	×	×	×	×	×	×	×	×
5		275	×	×	×	×	×	×	×	×	×
6		350	×	×	×	×	×	×	×	×	×
7	Abrasive with delaytime	200	×	×	×	×	×	×	×	×	×
8		275	×	×	×	×	×	×	×	×	×
9		350	×	×	×	×	×	×	×	×	×



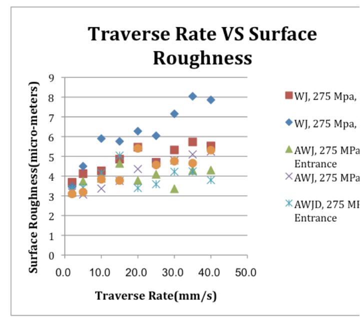
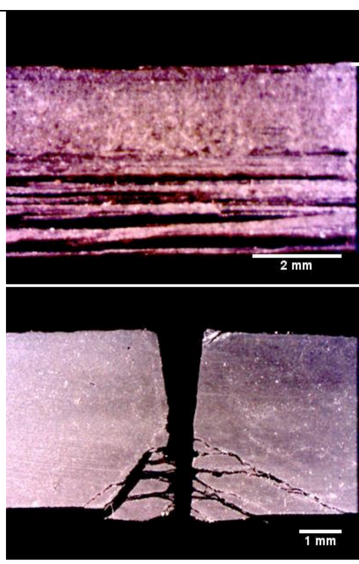


Figure 6. Summary of Cutting results



Wang's Model Prediction

From the delamination conditions,

We can get the experimental constants using Matlab as follows.

k=1.0473, a=-0.5847, b=-0.7474

Then, the governing equations is as follows

$$\frac{C}{d_j} = 1.0473Y$$

$$Y = \left((\frac{d_j}{V_t})(\frac{E^* d_j}{\dot{m}_s}) \right)^{-0.5847} \left((\frac{P}{\rho_w})(\frac{\dot{m}_s^2}{E^{*2} d_j^4}) \right)^{-0.7474}$$

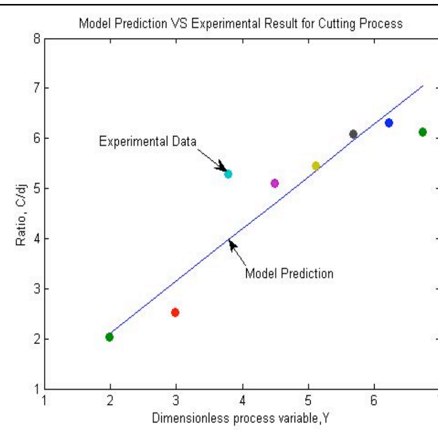


Figure 7. Typical delamination in Cutting and Model Prediction

Drilled specimens

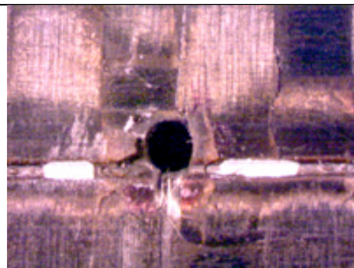
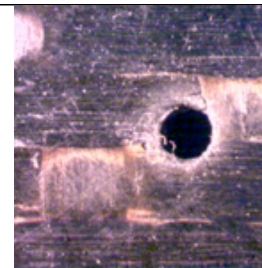
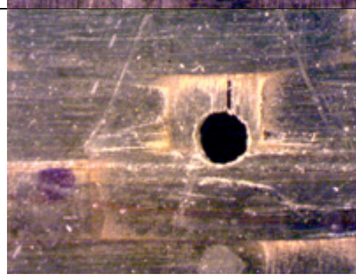
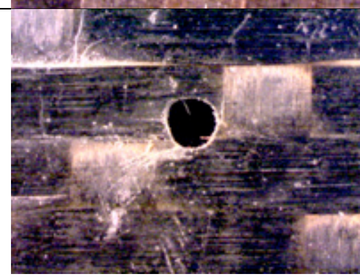
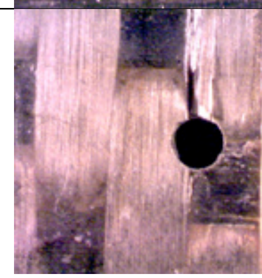
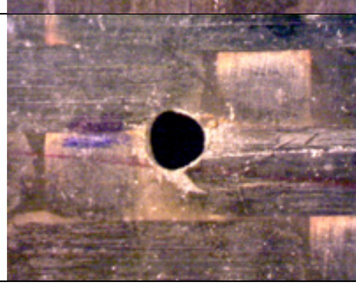
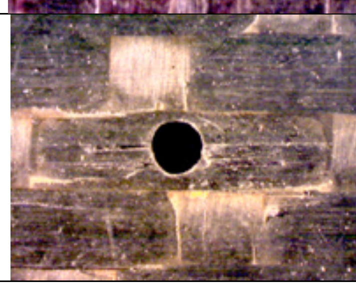
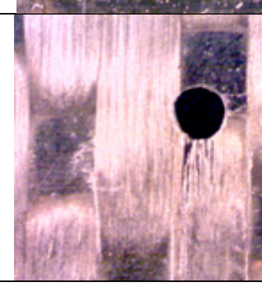
<table>
<tr><td colspan="3">Material Thickness</td><td colspan="3">4.5 mm</td></tr>
<tr><td colspan="3">Abrasive Flow rate (g/s)</td><td colspan="3">200MPa(supply pressure) → 11.9 gm/s, 350MPa(supply pressure) → 14.3 gm/s</td></tr>
<tr><td colspan="3">Std.</td><td>2 mm</td><td>3 mm</td><td>4 mm</td></tr>
<tr><td rowspan="4">Supply pressure</td><td rowspan="2">200 MPa</td><td>Ent.</td><td></td><td></td><td></td></tr>
<tr><td>Exit</td><td></td><td></td><td></td></tr>
<tr><td rowspan="2">350 MPa</td><td>Ent.</td><td></td><td></td><td></td></tr>
<tr><td>Exit</td><td></td><td></td><td></td></tr>
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Figure 8 Typical AWJ Drilled Entry and Exit Surfaces for varied Process Conditions

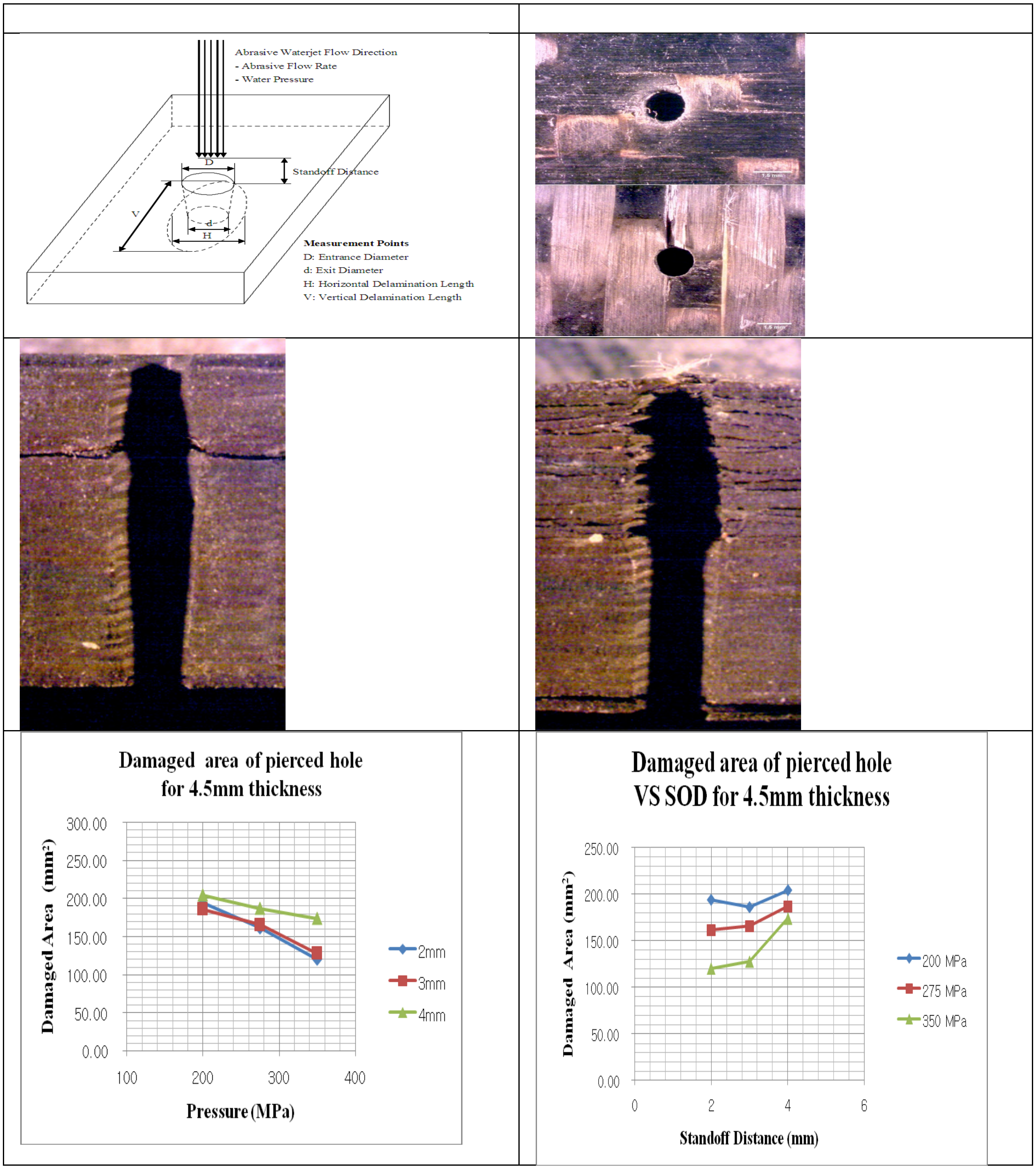
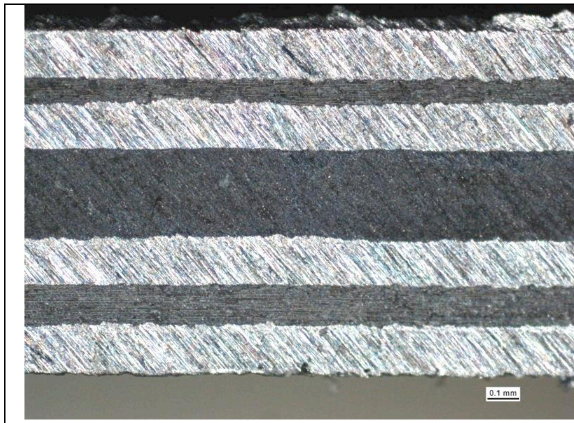
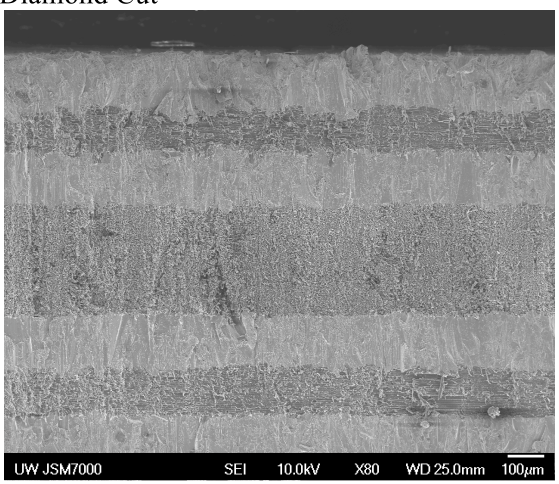


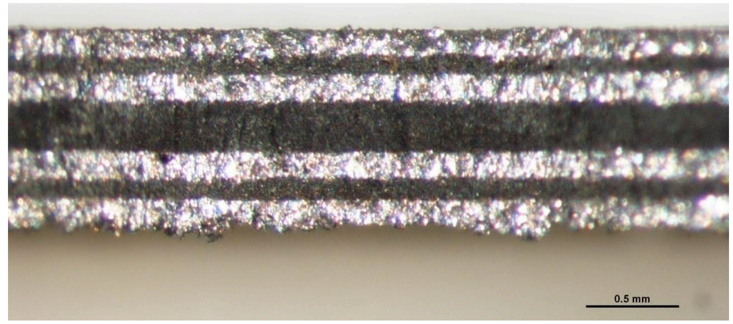
Figure9 Summary of the drilling damage and delaminations



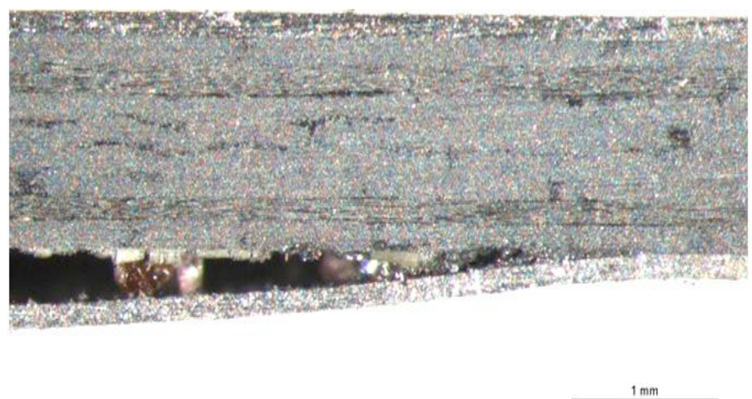
Diamond Cut



SEM Micrograph of AWJ machined Surface



AWJ Cut



Abrasive Embedment and Delamination at the Jet Exit

AWJ Trepanned holes

Figure 10, Cutting and Drilling Characteristics in Fiber-Metal Composite Laminate