Process Speeds for Drilling and Reaming CFRP and CFRP/Metallic Stacks

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John Barry
Electroimpact Inc.

Zan Uffelman
Electroimpact Inc

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ABSTRACT

Drilling of carbon fiber reinforced plastic (CFRP) components in aircraft production presents many challenges. Factors including layup material, layup process, layup orientation, hole tolerance, surface finish, delamination limits, and inspection methods result in a wide range of process times. The purpose of the paper is to provide a framework to understanding the drilling process in CFRP and the resulting hole tolerance, surface finish and delamination. The paper will investigate drilled hole diameters from 3/16″ (5 mm) up to 1″ (25.4 mm) drilled thru CFRP/CFRP and CFRP/metallic stacks with automated drilling machines using single sided clamping.

INTRODUCTION

Any discussion of how fast a hole can be produced must begin with the hole quality that is required in the finished product. Hole quality definition evolves thru several stages. In the aerospace industry the process usually begins with the stress engineers designing the aircraft. With metallic components, there is an extensive design history for the engineer to draw upon. Many of the basic design rules are taught in engineering schools. This is not the case with CFRP. While widespread military use and commercial use on smaller components have provided a baseline for design, use on large commercial components is a recent development. The matrix material supplied by BASF, Cycom, Hexcel, and other suppliers are continually being improved. The designers also have a choice of layups from quasi-isotropic to uniaxial, all which can affect the final hole quality. The stress engineers use OEM-supplied data along with extensive testing to determine hole quality requirements. This information is then passed to the manufacturing engineers where qualification documents are written along with inspection procedures. Inspection procedures will vary in extent depending on whether it is for initial qualification of a machine, production line test coupons, or the aircraft component. Communication is critical to ensure the designers intent is achieve and to keep designers from specifying the near impossible. This paper will present an overview of certain hole quality requirements, examine how they are interpreted, and consider the implications on process time.

SURFACE FINISH

For metallic components the effect of surface finish on fatigue life is well documented. Composite materials are typically chosen over metallic structures for their superior strength to weight ratio and better fatigue life. In C/AL fatigue tests, it is expected that the aluminum will fail before the CFRP. In CFRP/CFRP fatigue tests, the titanium lock bolt has been observed to fail first. The effect of surface voids in a lightning strike of CFRP has also been raised as a concern (1). The stress engineer will consider these behaviors and ultimately define surface finish requirements which the manufacturing engineer must understand and interpret.

To discuss surface finish it is necessary to outline the standard methods of quantifying surface roughness. The most common surface finish measurement is Ra (see Figure 1). Ra is the average roughness of the profile about a mean line. Other important values when measuring CFRP surface finish are Rt and Rz. Rt is the height difference between the highest and lowest point within the sampling length of a profile. It can be used to measure the depth of a CFRP defect. Rz is the ten-point height value of a surface and is the distance between the average of the five highest points and the average of the five lowest points on a digitized profile(2). Some researchers have proposed Rz and Ry as better indicators of surface for CFRP and have raised concerns that Ra does little to describe the amount of surface damage due to fiber pull-out or matrix smearing (3).

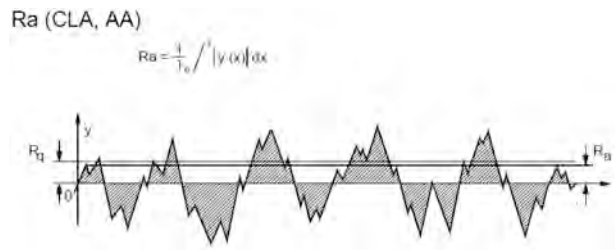

Figure 1. Calculation of average surface roughness (Ra) per ISO 25178-2.

A profilometer is commonly used to measure surface finish (see Appendix). A profilometer drags a small radius stylus across the work piece to measure the surface. A probe radius of 5 micron (0.005 mm) is typically used which allows for the probe to detect surface flaws across a typical 0.25 mm thick ply. (see Figure 2) As the probe moves relative to the surface, the stylus moves up and down recording the profile of the surface. To separate roughness from waviness, a sample or cut-off filter is used. The profile is divided up in lengths of the cut-off filter and assessed individually. Typically, the cut-off filter is 5 times smaller than the measurement length. For all subsequent measurements, a measurement length of 4mm was used with a cut-off filter of 0.8mm.

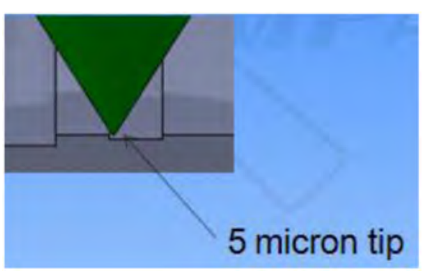

Figure 2. Five micron probe tip shown with 0.25 mm ply thickness and 25 micron deep tear out.

Material Effects on Surface Finish

Within the bore of the hole, CFRP is prone to surface defects at certain locations with respect to their fiber orientation. Fiber pullout is a common surface defect in unidirectional CFRP compositions. It occurs as the cutter moves across the top of the long slender fiber bundles, pulling the fiber out of the resin matrix instead of cutting. See Figure 3 for location. Another surface defect occurs parallel to the fiber orientation when the cutting edge peels the fiber from the matrix before shearing it. Other factors that affect the type and number of surface defects are fiber material, fiber diameter, resin material, whether it is woven or unidirectional, and ply layup. Note that these zones are localized over small areas of the bore. These areas typically are not in line with the primary load direction on the fastener. This is in contrast to a metallic flaw such as rifling which is axisymmetric revolving around the bore of the hole.

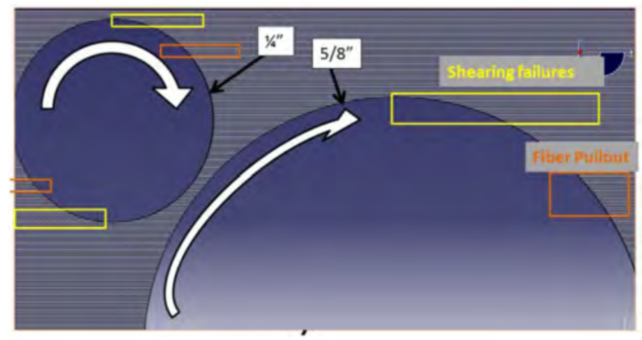

Figure 3. Location of surface defects

The profile of a CFRP surface is much different from a metallic surface. Taking a surface finish measurement at areas with surface defects will result in a Ra measurement that is significantly higher than in other parts of the hole. Figure 4 shows the profile of aluminum in a CFAL/AL stack (Blue), a calibration plate (Red), CFRP in a CFRP/AL stack (Green), and CFRP in a CFRP only stack (Purple). The CFRP measurements are taken in areas with surface defects which are represented by the deep valleys represent surface defects. The surface defects are made worse when aluminum is present, because the aluminum chips are pulled up through the flutes during drilling and increases the depth of the defects.

HOLE DIAMETER MEASUREMENTS

On aluminum aircraft most of the fasteners are installed with an interference fit to provide improved fatigue life of the component. Interference fasteners require tight control of hole diameter to control amount of deformation in the structure. For CFRP the use of interference fasteners like slug rivets will cause delamination of the plies. For this reason, clearance fit bolts and sleeved bolts are more common and hole tolerances can be widened.

Types of Measurement Equipment

Hole diameter is often measured using one of the probe styles shown in Figure 5 (also see Appendix). The 3-point probe (5a) is a popular choice because a range of several millimeters can be measured with a single probe tip. The 2-point probe (5c) can be used to measure ovality of the hole but the stroke of the gage is less than 0.5 mm and the body of the probe tip must be closely matched to the hole for best

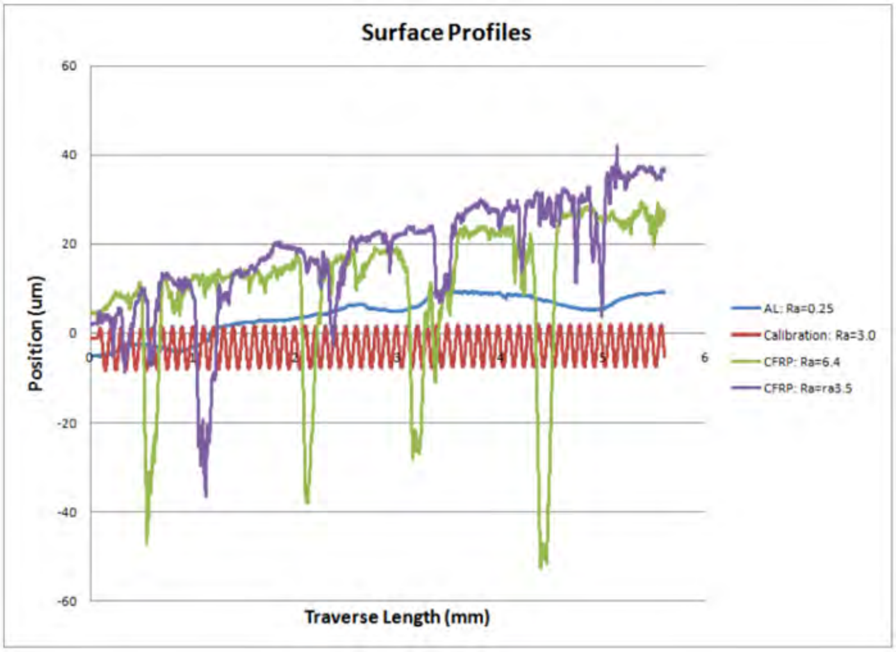

Figure 4. Surface profile of CFRP drilled hole.

accuracy. The 3-point probe self centers in the hole, however, the 2-point probe requires a diameter close to that of the hole to measure true diameter.

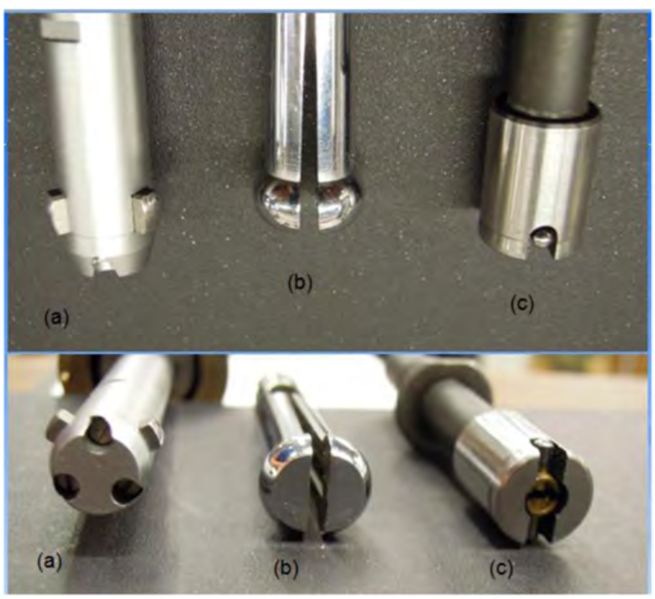

Figure 5. Hole probe types for 11.11 mm. (a) 3-point (b) split ball (c) 2-point ball plug.

When measuring CFRP, the radius of the probe along the axial direction can influence the readings. The 3-point probe (5a) has a large radius of 5 mm that contacts the part whereas the 2-point probe (5c) has a radius of 1.25 mm. The split ball (5b) has a radius of 4 mm. The small radius of the 2-point probe results in increased sensitivity to areas of tear out as shown in Figure 6. A ball radius of 1.25 mm, would drop into 0.25 mm wide flaw (corresponding to tear out of a single ply) as much as 6 microns. If the radius of the probe is 5 mm, this distance drops to 1.6 microns. These factors could increase diametral measurements by 12 and 3.2 microns respectively.

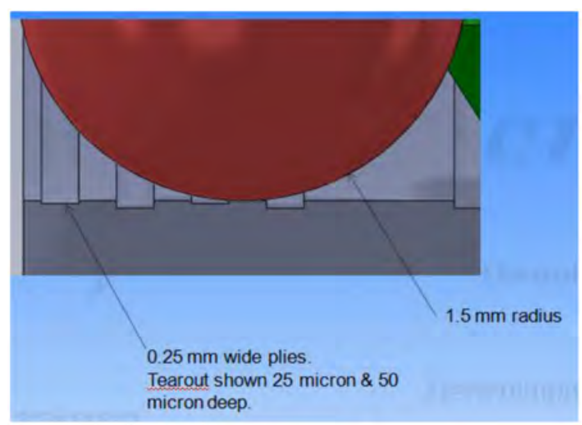

Figure 6. Hole probe diameter size effects.

Effects of Measuring Methods on Data

When deciding on a measuring procedure, it is important to choose your method and equipment in order to properly measure the features of interest. Figure 7 shows the difference in diameter measurements of the same holes measured with two different 2-point ball plug gauges (Figure 4c) with different contact diameters. The small contact diameter has larger maximum measurements because it falls in surface voids, but the conclusion drawn might be that the

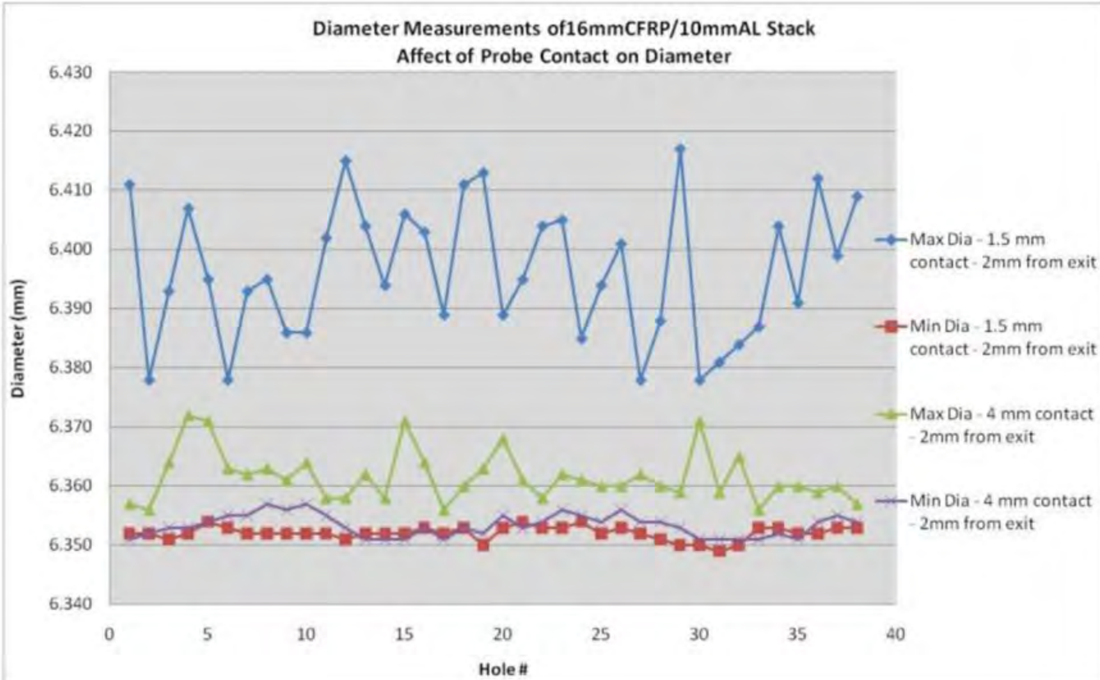

Figure 7. Hole probe diameter size effects.

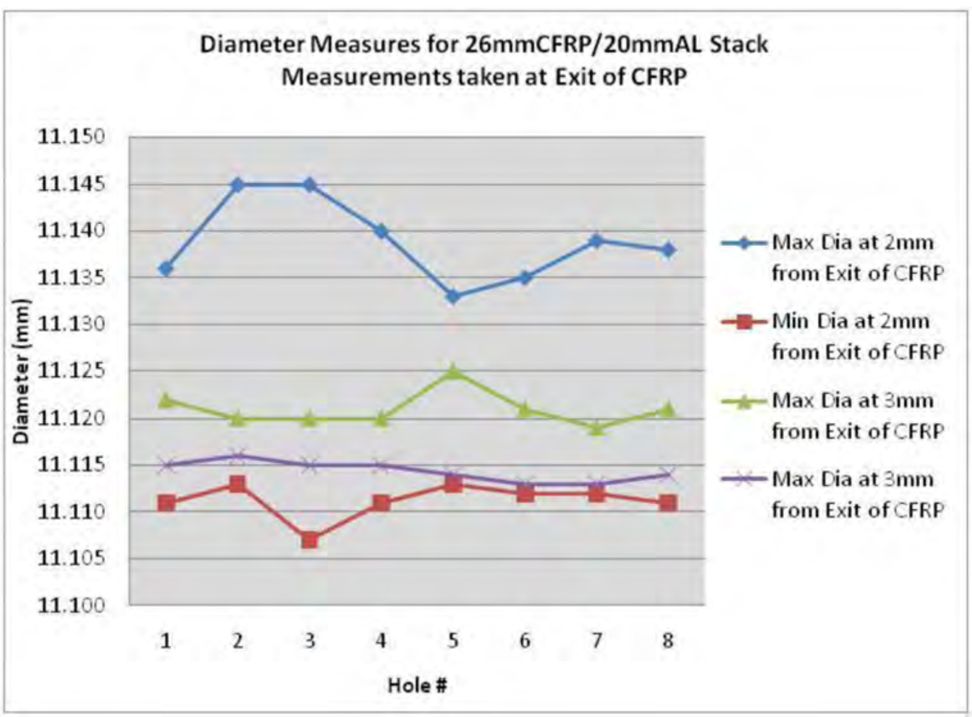

Figure 8. Axial location affects diameter measurements.

holes are oval. Figure 8 shows the difference in diameter measurements measured at the exit of CFRP in a CFRP/ Aluminum stack. Measuring at 2mm from the exit rather that 3mm results in an average of 0.020mm larger diameters due to defects caused by chip erosion. It is important to choose locations to measure that properly represent the hole. Unnecessarily stringent measuring procedures result in unnecessary increases in production time.

CUTTING PROCESS

The cutting process of metals is primarily a function of plasticity. Machining of thermoset composites, however, involves very little plastic deformation (4). To better visualize the cutting process, the authors sectioned round blanks from a 45 mm thick layup. Cutting action of CFRP was demonstrated using these blanks, PCD tooling, engine lathe, and high speed camera. The layup is 50% 0°, 20% +45°, 20% −45°, 10% 90°. A schematic representation was drawn on the end of the blank - five horizontal lines representing the 0-degree axis, one vertical line representing the 10% of the fibers in the 90° axis. The areas of tear out in a drilled hole for anisotropic layup have been shown by previous authors to occur approximately 45° from the 0° axis. This behavior was also observed on the OD of the blank as shown in Figure 9.

Thermal conductivity of CFRP materials is in the range of 5 w/m.K which is 10% that of steel. Therefore, very little of the heat is conducted out thru the part. With a glass transition temperature of 200 C, melting of the matrix can happen quickly when drilling thick stacks. Heat management can be thru air blast, minimum quantity lubrication, or water based flood. Of the three, water based flood lubrication thru the bit has the highest capacity for heat transfer out of the cutting edge. Table 1 shows some example process times and how thinner stacks can often be drilled many times faster than thick stacks where heat buildup at the cutting edge is more likely to occur.

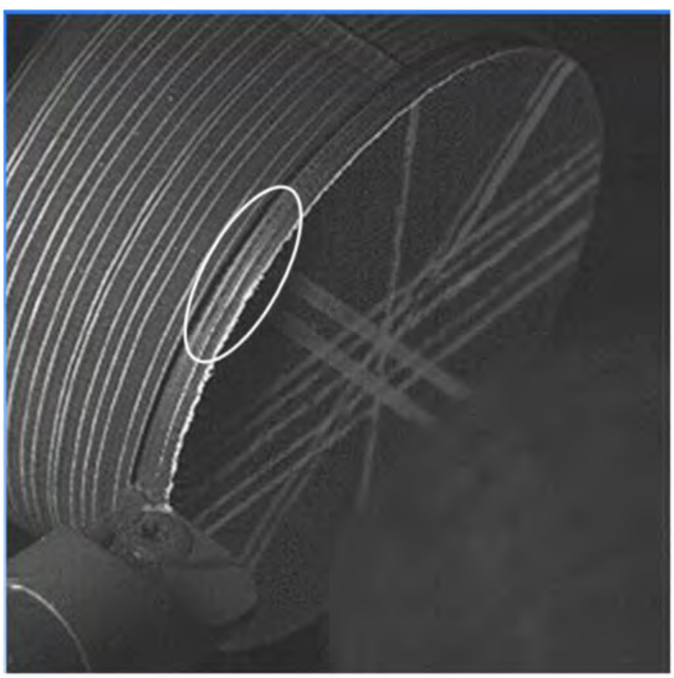

Figure 9. Cutting action investigated by turning CFRP on lathe.

The material and layup can have a large effect on the quality of the hole. To determine the impact that material has on hole quality, two different samples were drilled with a 14.28 mm PCD cutter using identical parameters. Sample A (Figure 10) is symmetric but not balanced. 50% of the fibers in sample A are in the 0 deg direction while only 10% are in the 90deg direction. Sample B (Figure 11) is quasi-isotropic. The hole in sample B was drilled immediately after sample A to negate tool wear. The surface finish of sample A is significantly worse than sample B. Since surface defects are a result of fiber direction and are not randomly distributed around the hole, a layup with 50% of the fibers in one direction will be significantly worse than a layup with 25% in one direction. The order of stacking of the layup plies can also influence hole quality results. For example, if multiple 0° plies are stacked coincidently, tear out effects will also be concentrated over a smaller area and are more likely to bias measurements.

Figure 10. Magnification of Sample A

Figure 11. Magnification of Sample B

Taking into account the hole quality factors discussed above, some manufacturers are able to drill CFRP at 18,000 rpm at a fraction of a second while others will drill and ream the same size hole at 1500 rpm in a process that spans minutes.

Table 1. Range of process times for C/C stacks. (*process is drill/ream)

Dia. (mm)	Stack (mm)	Process time (sec)	Mm/min (effective feed rate)
5.090	4.95	0.34	873
5.090	11.5	0.62	1113
6.35 "fast"	10	0.7	857
6.35 "slow"	25	25	60
9.98	30	19	94
15.87	65	17	229
19.05	71	130*	33
25.40	71	148*	29
25.40	71	253*	17

There are several factors that cause such wide variation. Hole diameter tolerance may be 50 or 75 micron, or may be specified as H8, H9, or H10 depending on customer and load transfer requirements of the joint. Statistical process requirement of Cpk of 1.3 or 1.6 or higher also drive up process time. Even in cases where the tolerance requirements are identical, the process time may vary widely depending on the methodology chosen to measure and validate. If diameter is measured as a full swept circle, layup factors which result in increased tear out at off axis positions will decrease process time exponentially. This is especcially critical when working with CFRP components and training personnel who may only have familiarity with metallics.

CFRP/METALLIC STACK

Drilling of CFRP/Metallic stacks is again driven by hole quality requirements. The working process parameters developed for CFRP may need to be altered. The metallic chips drawn thru the CFRP material will often result in chip erosion of the composite. One typical example is bellmouth of the composite panel at the metallic interface. Note that the process times shown in the table below are meant to exhibit the extreme range of times that can result from material, stack, and hole quality choices. The fact that the largest holes are present in much smaller quantities and in some cases these holes could take multiple shifts of machinists when performed manually should be kept in mind.

Table 2. Range of process times for C/AL stacks. (*process is drill/ream)

Dia. (mm)	Stack (mm)	Process time	Mm/min (effective)
4.763	2.9 C/4.5 AL	0.94	472
5.090	2.9 C/4.5 AL	1.78	250
9.98	20 C/10 AL	28	64
15.87	42 C/19 AL	130*	28
25.4	25 C/15 AL	65*	37
25.40	75 C/25 AL	420*	14

To further reduce the size of the chip, a stepped reamer can also be used. The volume of metallic chips to be removed past the CFRP will strongly effect hole quality. When drilling out piloted holes, there are fewer chips which has a positive effect on CFRP hole quality, but adds issues of alignment affecting cutter stability if using a 2 flute cutter. Unfortunately, use of a reamer does not guarantee success for CFRP hole quality. In some cases, the cutting action of the reamer acts to propagate the surface flaws initiated by the drill. As shown in Figures 12 and 13, the area of tear out in the hole which was 0.4 mm undersize, is still apparent in the finish reamed hole.

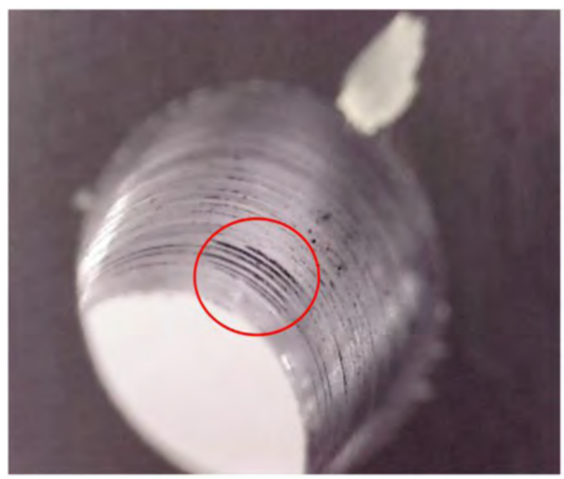

Figure 12. Surface finish defects in under-sized drilled hole

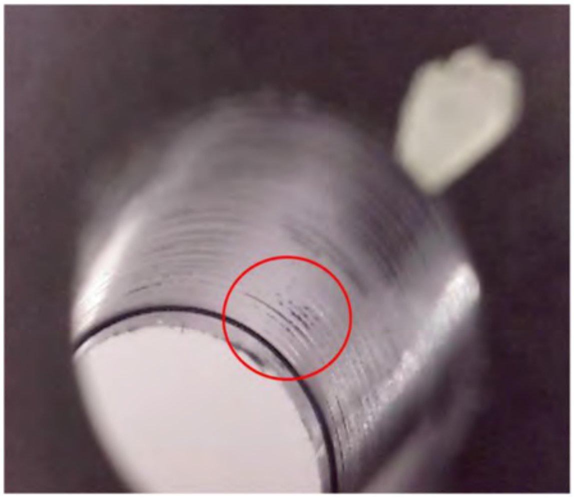

Figure 13. Surface finish defects in reamed hole.

The profile of the surface of the undersized drilled hole was measured using a contact probe profilometer. The tear out areas were less than .050 mm deep indicating that the reamer should have cleaned up any surface defects. However, in this case, it is shown that the reamer cutting edge is prone to tear out of the laminate similar to the drill bit.

SUMMARY/CONCLUSIONS

It is well understood that drilling process times of CFRP stacks will be driven by cutter choice, spindle speed, coolant/ lubrication, and machine stiffness. However, hole diameter tolerance, surface finish limits, and inspection methods also drive process times as well as tool cost. How fast you can go may be ruled by the old racing proverb, how much do you want to spend? In some cases, an investment in higher purchase price of cutters and machine can reduce cost per hole. More important than how much money is spent will be the level of understanding of the material and the machining and inspection processes that will be required.

Drilling CFRP/metallic stacks introduces issues with chip erosion. The thicker/stiffer/larger the chip, the more erosion. In most cases the desired hole quality can be achieved with a drill process using feed, speed, and peck. In the worst case, a drill ream process is required where the quantity of chips driven past the CFRP surface is significantly reduced.

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CONTACT INFORMATION

John Barry, PE
Electroimpact, Inc
4413 Chennault Beach Road
Mukilteo, WA 98275
johnb@electroimpact.com

Zan Uffelman
Electroimpact, Inc
4413 Chennault Beach Road
Mukilteo, WA 98275
zanu@electroimpact.com

DEFINITIONS/ABBREVIATIONS

CFRP
Carbon Fiber Reinforced Plastic.

PCD
Poly-crystalline Diamond.

Quasi-Isotropic layup
Fiber layup that is balanced and symmetric for similar strength and stiffness in all directions of the panel.

Anisotropic layup
Fiber layup that is symmetric but unbalance for greater strength in one direction

Symmetric layup
Layup of unidirectional plies such that ply direction is symmetric about the mid ply of the panel

Balanced layup
Layup where equal number of plies in each ply direction 0/90 or 0/90/+45/−45 etc

APPENDIX

PROFILOMETERS

- Mahr PS1, www.mahr.com
- Diavite, www.diavite.com

HOLE PROBES/ BORE GAGES

- Diatest, www.diatest.com
- Bowers, www.bowersmetrology.com
- Mitutoyo, www.mitutoyo.com

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