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TRIMMING OF CFRP AIRCRAFT COMPONENTS

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ABSTRACT

This paper presents hardware and data on the use of AWJ for trimming aircraft carbon fiber reinforced plastic (CFRP) parts such as those used on the Airbus 350 and the Boeing 787. Generally, CFRP parts on an aircraft vary in size from large parts such as wings and fuselage sections to small size parts such as clips, brackets, and door stringers. The machinery that is most suitable for these parts is presented. Gantry systems with AWJ and routing end effectors have been the most commonly used machines for large parts while relatively small robotic arms are emerging for trimming small parts. In any of these systems, special sidefire cutting heads have been developed to access tight spaces such as trimming and beveling stringer flanges. Small catcher cups, mounted on the cutting end effector, have also been developed to catch the waste jet. Data are presented on taper, trailback, and surface finish to identify parameters meeting the required accuracy and surface finish.

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1. INTRODUCTION

Abrasive Waterjets (AWJ) have been one of the great enabling and timely tools that allowed expediting the use of composites since the early 1980s. This is because AWJs offer several advantages over conventional machining methods. Among these advantages are:

- Higher cutting speeds than routers
- No distortion due to limited jet forces and its nature of micromachining action
- No heat affected zones
- No delamination, splintering, fraying edges or any other integrity problems
- No subsequent processes are needed
- Reduced fixturing and tooling
- Process automation and multi-operations are possible
- No dust
- Versatile for different composites and laminated structures

Figure 1 shows the continuously rising trend in the use of carbon fiber composites in aerostructures. For example, the use of composites on the Boeing 787 and Airbus 350 is about 50% by weight and 90% by volume. In comparison, the Boeing 777, which entered service in 1995, contains only 10% composite structure by weight.

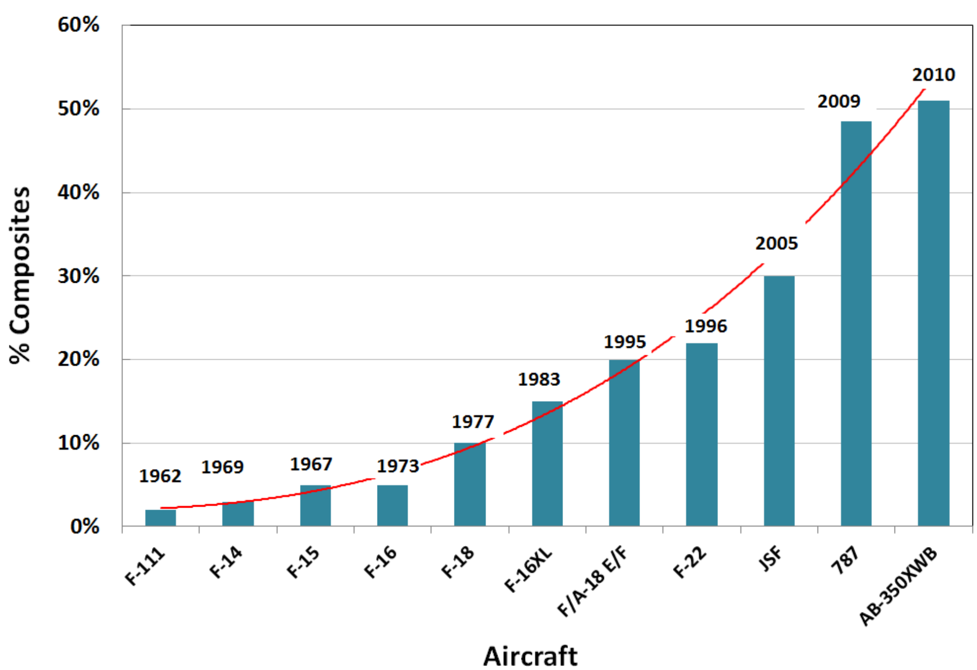


Figure 1. Composite use in aircraft

More and more parts are now being made out of carbon fiber reinforced plastics (CFRP) due to their superior, strength, and lightweight. These parts range in size from relatively large, such as the wing covers and fuselage, to small parts such as clips and doors. Figure 2 shows a list of the major CFRP parts on the Airbus 350.

- Fuselage
  - Skin
  - Frame
  - Keel beam
  - Rear fuselage
- Empennage
  - Fin
  - Rudder
  - Stabilizer
  - Elevator
- Center and outer wing boxes

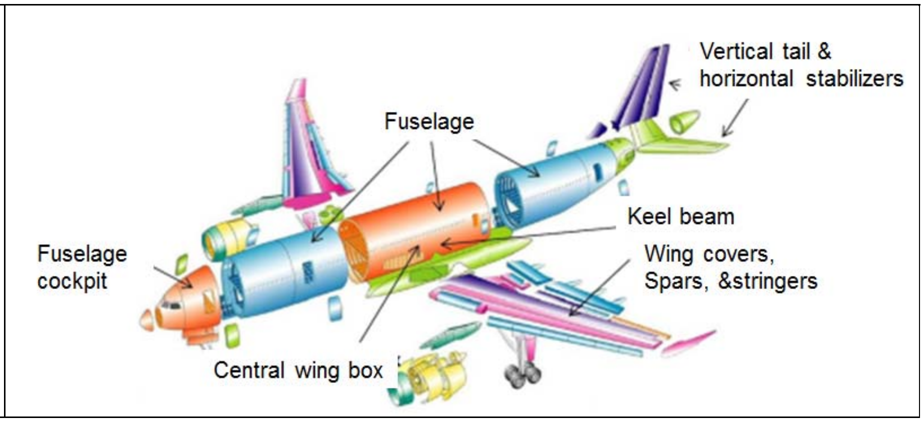
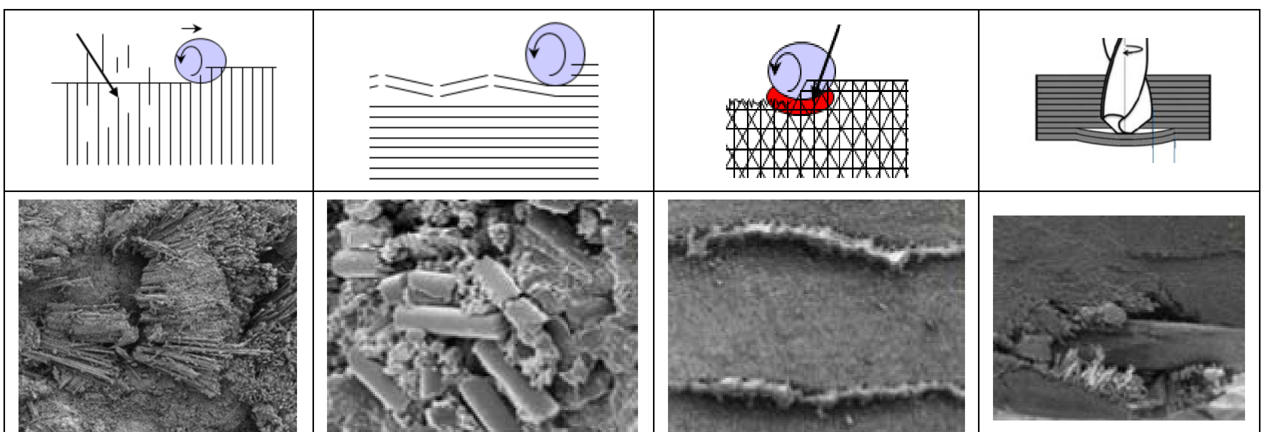


Figure 2: Major CFRP parts on the Airbus 350

In addition to the above, there is a wide range of clips and brackets that are used in assemblies. The above parts vary in thickness from a few millimeters to a few tens of millimeters. The required accuracy also varies from high precision parts within 0.15 mm to looser tolerances of 1.5 mm to 3 mm. Manufacturer's specifications such as the Boeing BAC 5578 and the Airbus AIPS03-03-006 identify the tolerances, surface finish, and composite integrity allowances.

Despite the significant growth in the use of composites and the advances in solid tools, using mechanical tools for routing and drilling has been problematic due to the anisotropic nature of the composite and the abrasive nature of the fibers. This results in lower tool life, longer downtime, and higher costs.

Typical problems that have been encountered when machining carbon fiber composites with conventional solid tools are both related to surface finish and integrity. Common integrity issues are shown in Figure (3) below (Hashish 2013). Environmentally, solid tools generate dust and carbon powder, which affect electrical systems and personnel. In addition, solid tools may not be able to access tight spaces as required due to the bulkiness of the spindles. Downtime is also associated with frequent tool change as routers and drills wear.



Fiber pull out	Fiber Breakage	Matrix smearing	Delamination

Figure 3. Potential integrity problems using solid tools (photos are from Miller et.al. 2013)

Briggs and Ramulu (2010) showed that diamond wheel saws might result in great sub-surface damage for CFRP. In a recent study, Miller et. al. (2013), studied PCD cutting, and recommended work on new tool geometries and process conditions to optimize material removable rates while reducing delamination and fiber pull out. Zhang (2009) proposed a common approach modeling to different composites where matrix deformation is typical with solid tools. Other machining technologies (Komanduri 1997) such as laser, ultrasonic machining, and EDM have been studied but with limited applications success. A study by Shanmugam, et. al. 2008 identified the mechanisms of delamination by waterjet. An electron microscopy study by Yu, Lacy, and Munn (2009), Figure 4, showed cuts made by a diamond saw and waterjet. The diamond saw cuts show clear damage and pull out of the carbon fibers.

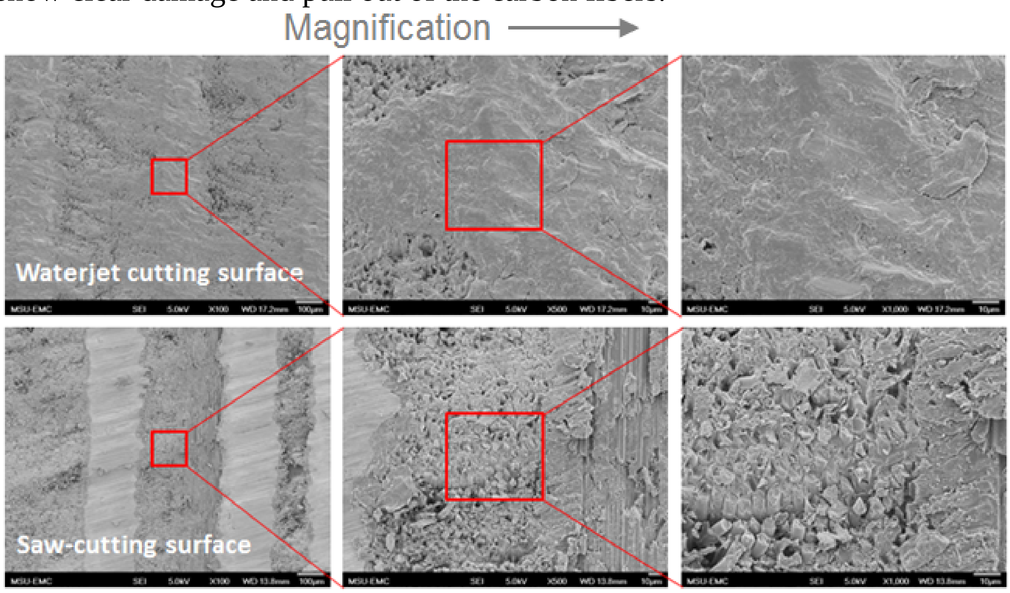


Figure 4. AWJ cut versus diamond saw cut composite surface (Yu et. al. 2009)

In the following sections, we will discuss AWJ composite trimming state-of-the-art and describe some of the hardware used on AWJ machining centers. Several applications will also be discussed at the end of the paper.

2. CUTTING PROCESS

When the abrasive waterjet (AWJ) cuts through and separates the material, three phenomena are observed. The first is that the jet is deflected opposite to the direction of the motion. This means that the exit of the jet from the material lags behind the point at the top of the material where the jet enters. The distance the exit lags the entrance is typically called the trailback, lag, or drag as shown in Figure 5. In this figure, the jet is moving from the left to the right. Observe that the jet-material interface is a curved surface but commonly straight for the range of thicknesses used in aero-structures (5 to 75 mm).

The second phenomenon is that the width of the jet varies along the cut from top to bottom. This difference in width is typically called the taper of the cut. A taper can be either positive or negative. That is, the width at the exit of the cut may be either smaller or larger than the width at the top. Typically, the kerf width at the exit side is smaller than that at the entry at practical cutting speeds. Figure 5 shows a cut with a taper. This taper can be compensated for in modern cutting systems (Knaupp et.al 2002, and Hashish 2007).

The third phenomenon is related to the surface finish of the cut. Due to the transient nature of the jet penetration process and jet instability, striations will form along a cut surface, especially near the exit. Figure 5 shows a striated surface cut by AWJ.

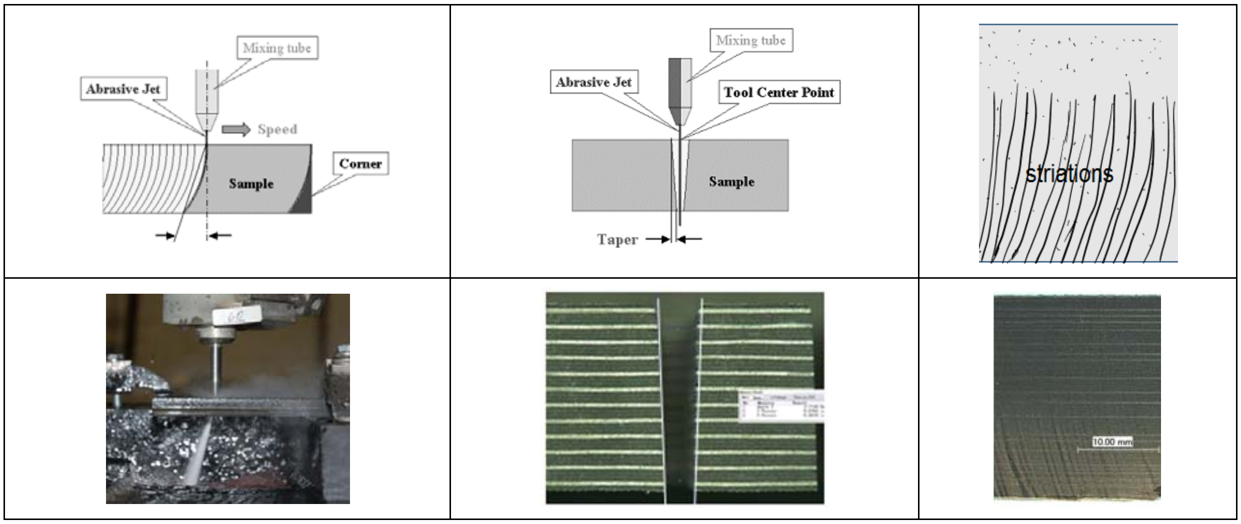


Figure 5. AWJ cut versus diamond saw cut composite surface

3. COMPOSITE TRIMMING SYSTEMS

AWJ composite trimming systems can be classifies into gantry (or Cartesian) and robotic systems. Gantry systems are the most common in the industry where two masts are used for both AWJ trimming and solid tool routing and drilling. Machine lengths are about 50 m. Figure 6 shows models of composite machining centers (CMC) used for trimming wings and fuselage sections of different shapes and sizes using a flexible fixturing system that adapts to the shape of the parts and holds it in place throughout the entire waterjet and mechanical processing.

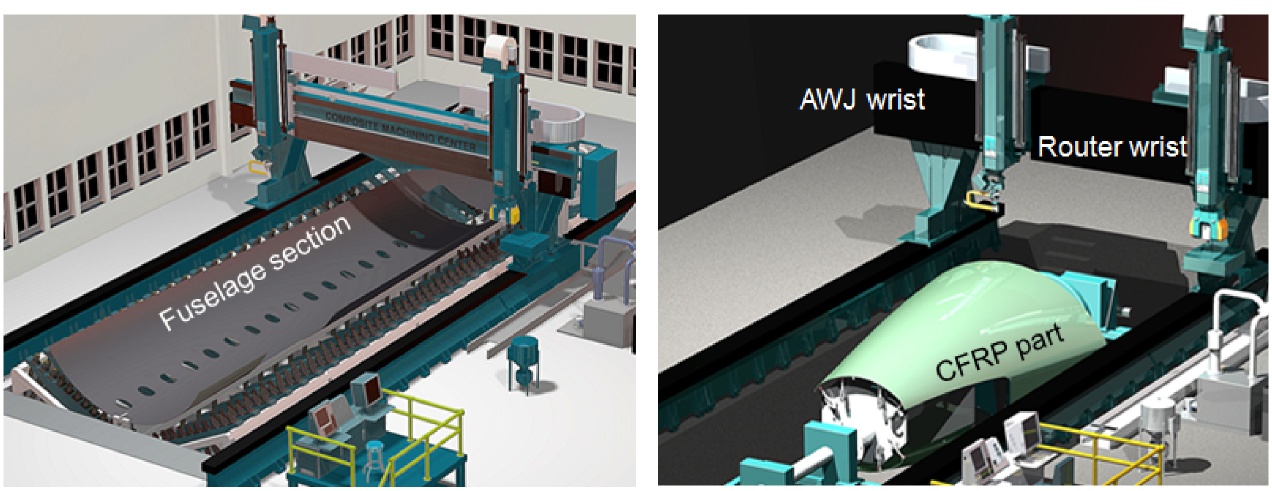


Figure 6: Hybrid composite machining center

Standard AWJ machines have also been adapted for cutting and drilling medium size (~4 m) relatively flat composite parts (Hashish 2013).

The design of the end effector used for trimming is critical because it is also used to hold a catcher cup for catching the AWJ and directing the waste back to a collection system. A catcher tank is not used due to the relatively large size and the shape of parts to be trimmed. It is also important that the tool center point (TCP) which, in this case, is the tip of the mixing tube, be at a known and specific position when focal point wrists are used.

Figure 7 shows a focal point wrist for wing trimming. Observe that the catcher cup arm needs to swing (sixth axis) so it does not collide with the structure being trimmed.

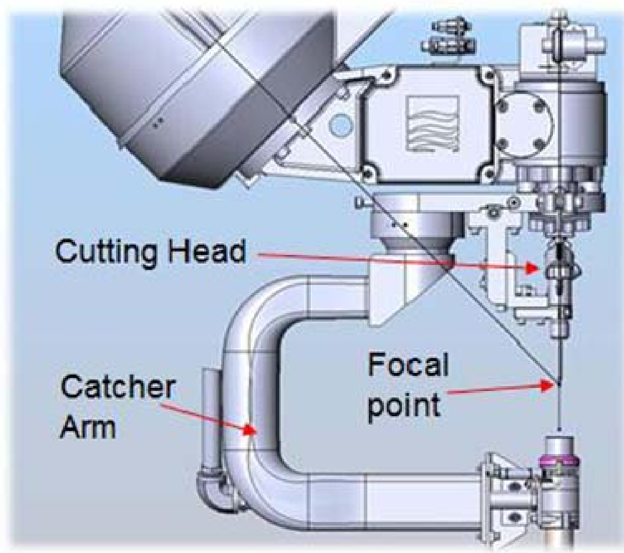


Figure 7. Focal point end effector with catcher arm

3.1 Robotic End Effectors

Robotic arm end effectors are emerging systems for the trimming of composite materials. Two kinematic methods have been developed:

- Moving AWJ - stationary part
- Moving Part - stationary AWJ

In the first approach, a robot arm is plumbed with UHP lines to feed a cutting head which is to be manipulated to cut the desired geometry. A catcher arm may or may not be used on the end effector. Figure 8 shows an example of this approach where a catcher arm is also mounted on the robot wrist. In this specific example, a sidefire cutting head is used to slit tubular sections and trim the ends of stringers. Accordingly, the sidefire cutting head is made to fit inside the geometry while the robotic arm moves the head and catcher assembly along the cut path. The accuracy of the cut is determined by the repeatability of the robot arm. A cut is first made and inspected to determine the error function, which is then used to compensate the cut path. This process may have to be repeated to obtain results that are more accurate.

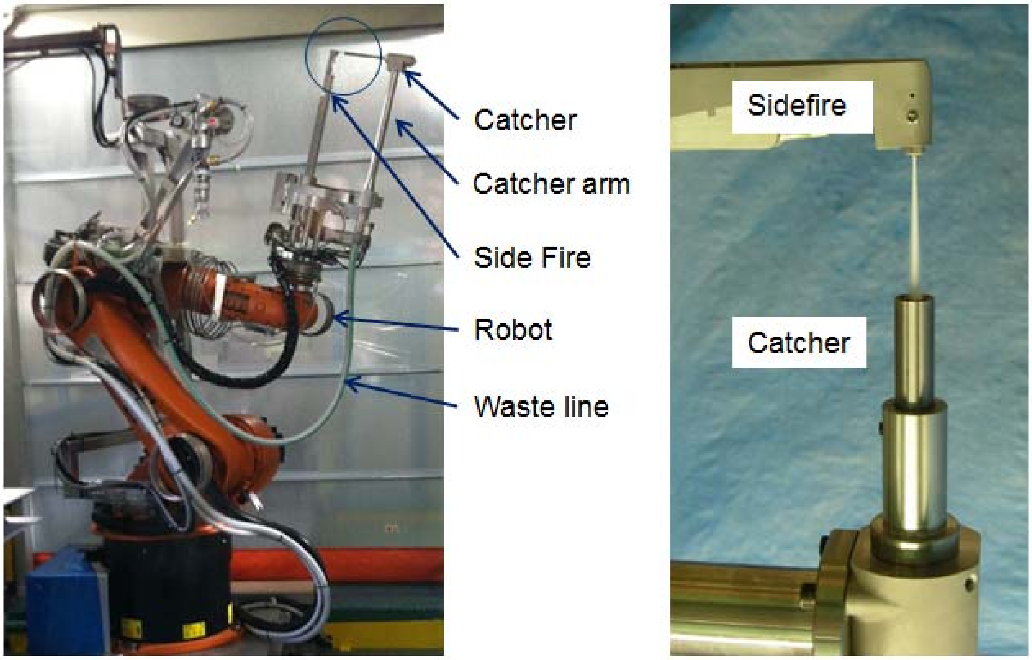


Figure 8. Robotic trimming end effector

There are a large number of small composite parts such as brackets and clips that need to be trimmed and shape-cut as mentioned above. For example, Figure 9 shows some composite clips that do not exceed in size over 150 mm in any direction that need to be shape-cut out of a plane surface corner parts. To cut these parts, it is advantageous to manipulate them under a stationary jet to avoid complex robot plumbing with UHP tubes.

Figure 9: Examples of small composite parts

A robotic trimming cell has been developed (by Genesis Systems and Flow International Corporation) for using a Kuka robotic arm to hold and manipulate the part to be trimmed under a stationary jet. Figure 10 shows a sketch of this system. A gripper is used to hold the part. Part and TCP referencing routines have been developed for quick trimming using offline programming. A small catcher cup has also been integrated into the cell for directing the waste into a collection drum.

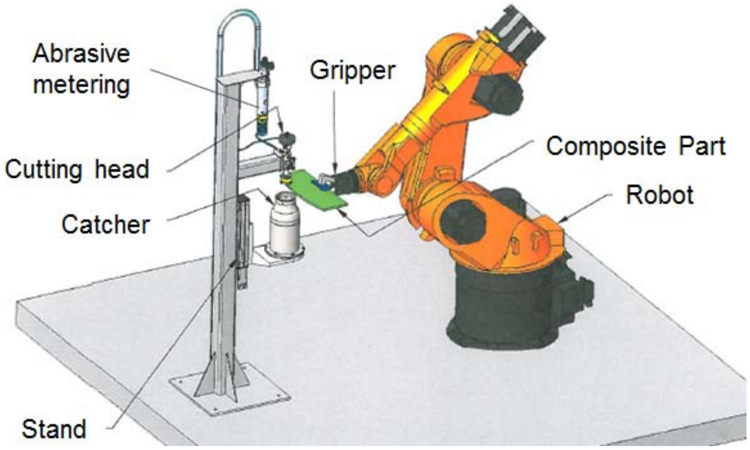


Figure 10. Robotic trimming of small composite parts

3.2 Special Trimming Heads and Catchers

In standard cutting heads, the water body is designed with enough length to provide high coherency waterjets while the lower sections for abrasive entrainment, mixing and accelerations are designed for producing high efficiency AWJs. To cut in tight spaces and to trim stringer flanges used on many structural components, a special cutting head was developed so cutting can be accomplished from the inside of the stringer, especially when beveling is needed. Figure 11 shows images of sidefire cutting heads for normal and bevel trimming. The geometry of a sidefire is not conducive to form a high-level coherency waterjet or to produce a high efficiency AWJ. However, the sidefire was demonstrated to effectively trim stringers and wing sections. In order to improve the robustness of the side-firing nozzle, a vacuum assist port was added. The vacuum assist port could be used to enhance the abrasives suction capability, especially when the abrasive feed lines are relatively long.

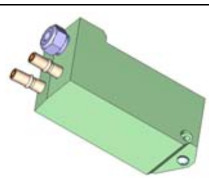
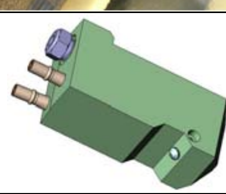
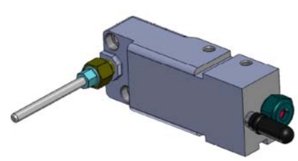
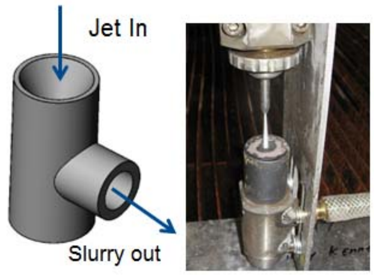
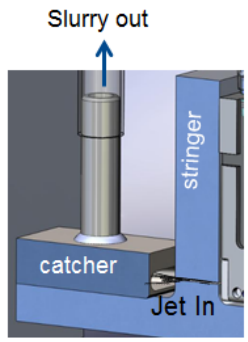
		
		
90 Degree Trimming	Bevel Trimming	Access to tight spaces

Figure 11. Small size AWJ sidefire cutting heads with vacuum assist capability

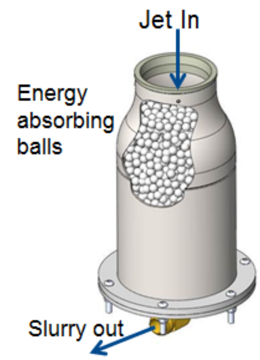
Catcher cups are also critical components for AWJ trimming, and they need to fit in tight spaces, allow manipulation, and be mounted on the end effector. Figure 12 shows pictures of some catcher cups used in the cutting of wing covers, stringers, and clips. These cups are typically 150 mm long and 75 mm in diameter. The ball-filled catcher is larger in diameter and is used when its weight is not an issue such as the case of using a stationary jet.



Edge trimming catcher



Cutting near stringer root



Ball-filled for stationary jets

Figure 12. Examples of catcher cups

4. DATA TRENDS AND OBSERVATIONS

A large database has been generated on trimming a wide range of composite materials and thicknesses used in aircraft structures. The typical requirements are:

- Surface finish: Not to exceed 10 micron Ra
- Accuracy: the minimum accuracy requirement is about 0.25 mm
- Edge quality: No adverse effects such as delamination

4.1 Composite Samples

An aircraft manufacturer provided five composite samples with different thicknesses. We named the materials A, B, C, D, and E because no material-specific information was provided other than being CFRP. The measured thicknesses for these samples were 5.1 mm, 5.2 mm, 20.2 mm, 25.2 mm, and 27.12 mm respectively for the above named samples.

4.2 Parameters and Data Trends

The AWJ parameters used were:

Parameter	**Value**
Waterjet orifice diameter:	0.33 mm
Nozzle diameter:	1.0 mm
Nozzle length:	100 mm
Pressure:	400 MPa
Abrasive:	80 mesh garnet
Abrasive flow rate:	7.5 g/s
Nozzle standoff:	2.5 mm

Figures 13 show the taper results for two sample materials as an example for the taper trends. Observe that the taper peaks at certain speeds due to jet divergence and instability. Plotting all the data for the five samples showed that the two thin material samples have a different trend. This is attributed to the possibility that these two samples are of different structure (Hashish 2013).

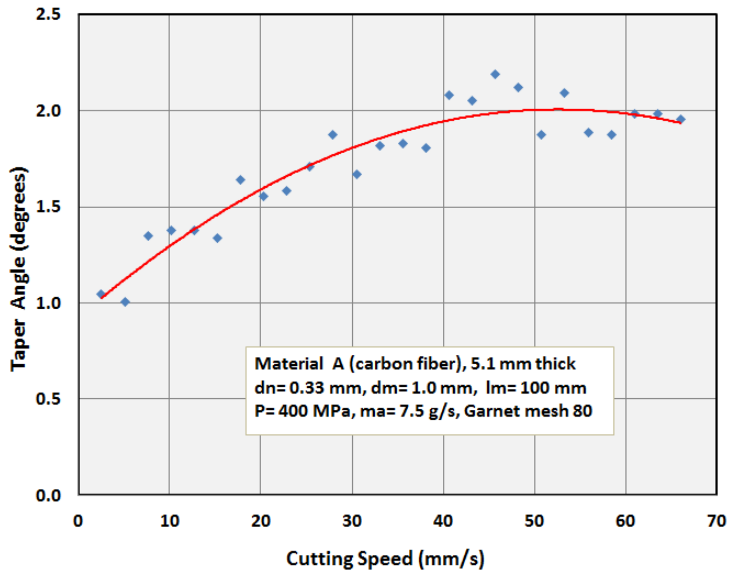


Figure 13. Taper angles for 5.1 mm thick CFRP

Figure 14 shows the widths of cut at the top surface at 2.5 mm standoff distance (SOD). This data may be used for cutter compensation. Observe that the kerf width narrows as the cutting speed increases. However, the sensitivity to speed is reduced with speed increase.

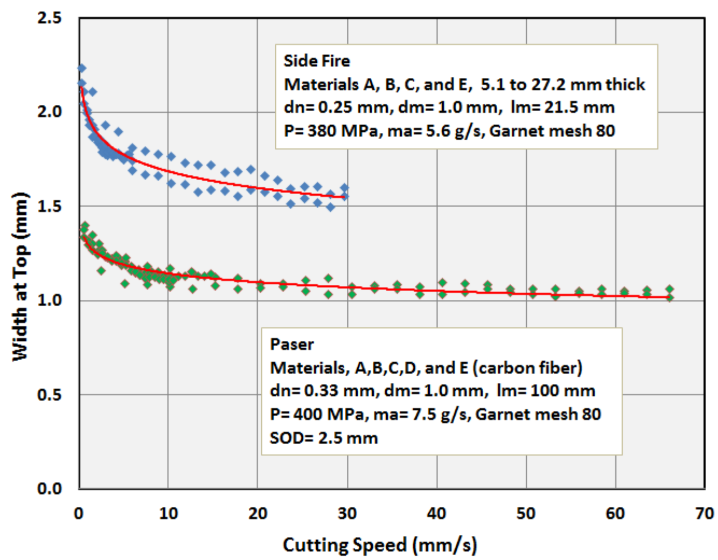


Figure 14. Kerf width at the top surface

The surface finish was measured as described above. Figure 15 shows a trend for the surface finish at the top and bottom of the cut. It is observed that the cutting speed effect on the surface finish at the top is insignificant, opposite to its effect at the bottom of the cut.

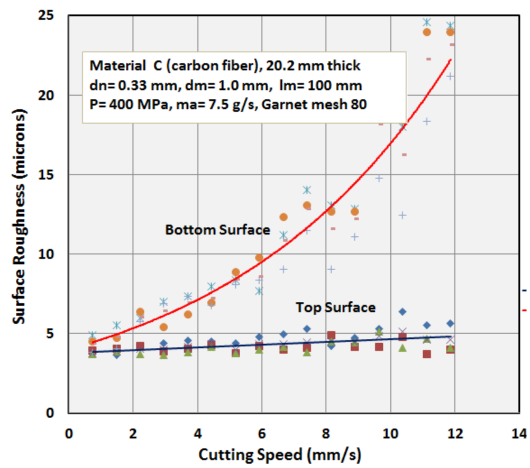


Figure 15. Surface finish at the top and bottom surfaces

Trailback is a critical phenomenon that affects the geometrical accuracy of the cut part at the bottom surface. However, for trimming using a catcher arm with a relatively small size catch cup, the trailback angle becomes highly critical in affecting the practical cutting speed. This trailback angle is a function of the process variables, cutting speed, and material thickness. Therefore, when cutting a variable thickness part, the trailback angle will change if the cutting speed is kept unchanged. Figure 16 shows the jet deflection as the cutting speed increases.

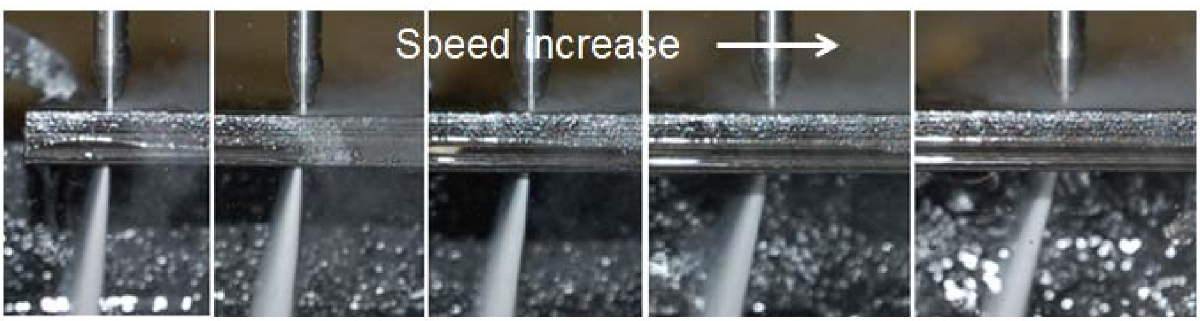


Figure 16. Increasing the trailback angle as speed increases

This suggests that the location of the catcher cup is of critical importance. To remedy this problem, the cutting speed must be reduced in order for the jet to enter the catcher, the catcher cup be of sufficient size to catch the jet, or its location must be automatically adjusted.

5. TRIMMING EXAMPLES

In this section, we present two examples of CFRP trimming applications. The first is on stringer trimming and the other is on fan blade trimming, although fan blades are parts of the jet engine rather than the aircraft body.

5.1 Stringer Trimming

Composite stringers are commonly I-Beam or T-Beam stiffeners used in the structure of aircraft wings, fuselage, floors, doors, and other parts, figure 17. These stringers needs to be trimmed and may be free standing or already attached to the part: a wing for example. The Boeing 787 wing stringers, for example, are trimmed before they are attached to the wing cover panels, while the Airbus 350 stringers are trimmed after they have been attached to the wing cover.

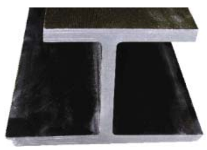
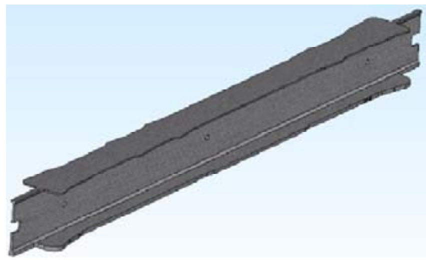
		
Free standing stringer cross section	Short stringer for an aircraft door	Stringers on a wing cover

Figure 17: Stringers

A special wrist, shown in Figure 7 is used to trim the stringers on wing covers using a machining composite center as shown in Figure 6. Figure 18 shows this application where a sidefire cutting head and a small catcher cup are used to fit between the stringers.

A special AWJ machine has been developed to trim the four edges of the flanges of the freestanding I-beam style stringers. In addition, the lower flanges were beveled at 45 degree angle. Six sidefire nozzles were simultaneously used to trim and bevel the stingers. Figure 18 (right) shows a travelling AWJ trimming system to trim stringers while Figure 18 (left) shows a special end effector for trimming attached stringers.

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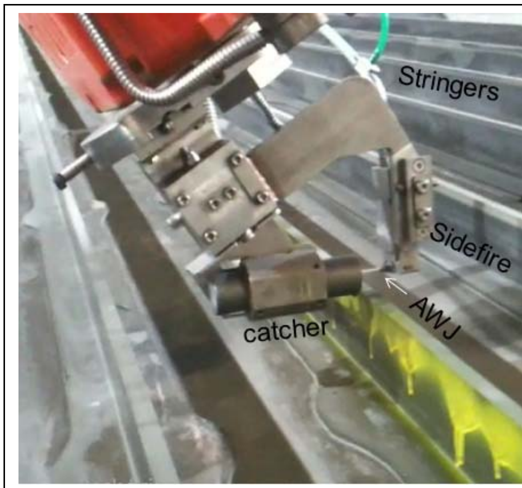
<td>
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<tr>
<td>Trimming stringers on a wing cover</td>
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Figure 18. Stringer trimming

5.2 Fan Blade Trimming

The weight of fan blades is a significant factor in propulsion system weight, causing weight increases to cascade throughout the engine system. The trend toward larger fans thus drove the need for CFRP materials for fan blades with added benefit of improved damage and defect tolerance (Black 2004). Accordingly, GE, for example, uses composite fan blades on the GEnx engine with larger and fewer composite blades. Figure 19 shows examples of fan blades.

		
Composite fan blade by GKN	GEnx fan blade with Titanium leading edge	AWJ trimming of composite fan blade edge

Figure 19. Geometry of fan blades and a test of blade trimming

Recent tests performed to trim fan blades with AWJ showed great promise for trimming around the entire blade which varies in thickness from a few millimeters at the tip to a few tens of millimeters at the root. The ability of multi-axis AWJ using focal point wrist as described above was demonstrated using offline programming (Cenit) and thickness-based cutting speed variation using advanced AWJ process models. Special attention to fixturing must be paid, and especially if the fan blade titanium cap is to be trimmed after mounting on the previously trimmed composite blade (as the case for the GEnx engine).

6 CONCLUSIONS

The following conclusions are drawn from this work:

- The use of CFRP is continuously rising and the AWJ is an ideal tool for trimming this material.
- AWJ composite machining centers have been used in the aircraft industry for trimming a wide angle of relatively large aero structures.
- Robotic trimming systems are emerging for loose tolerance applications.
- Sidefire cutting heads have been developed and used for trimming stringers and hard to access features on large parts.
- Small catcher cups have been developed and used for trimming applications on gantry and robotic arms.

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