ROBOTIC TRIMMING, CUTTING AND SANDING OF CARBON FIBER BODY STRUCTURES

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Abstract

Stamped steel body structures set a benchmark for construction and aesthetics that any alternative including carbon fiber body structures must meet. The challenge to carbon fiber body structure manufacturers is to achieve the traditional body structure standards while maintaining the most competitive possible per part manufacturing costs. Fortunately for these manufacturers there is a great deal of accumulated experience in composite manufacturing including the finishing and trimming processes that can be among the most challenging to automate. This paper will discuss some of the robotic technologies that have been adopted from other composite finishing and trimming processes to meet the needs of carbon fiber body structure manufacturers. Specific examples will be discussed including robotic sanding of Class A surfaces and abrasive waterjet cutting of holes and features on various carbon fiber body structures, both of which are or will soon be in full production. For abrasive waterjet cutting, this paper will elaborate on a unique approach that was developed using robots to manipulate parts while secondary robots manipulate the abrasive waterjet media. The paper will also discuss the advantages of these robotic solutions vs. other approaches including lower running costs and the flexibility to quickly adapt to product or model changes.

Background

Robotic trimming, sanding and other material removal processes for carbon fiber components have been in production use for some time. To date, some of the larger markets for these processes have been in aerospace and non-structural automotive components. There have been some successes, and there have also been some installations where in retrospect a different approach might have been more appropriate. This evolution of manufacturing processes is a critical part of any market where new product technology drives changes in the manufacturing processes.

Fortunately for automotive body structures manufacturing, a great deal has be learned from the accumulated experience in aerospace, automotive component and other carbon fiber markets. This includes what type of a manipulator is best (robot vs. a CNC style gantry) and what is the most appropriate process (waterjet vs. router trimming). However, the process requirements for body structures pushes the state of the technology in several ways over the more established aerospace, non-structural automotive components and other carbon fiber markets. This is primarily due to the large size of the parts combined with the sharp changes in contours that is unique to body structure components.

Automotive Component Experience – Case 1

Since carbon fiber body structures have emerged only recently, experience within the automotive market has been limited to non-structural components such as fenders, hoods and roofs. These components are smaller, have simpler geometries, and have far fewer cut outs when compared to body structure components. However, they are produced in high volumes, have similar tolerances, and face the same cost pressures that any automotive or automotive
component supplier must deal with. So this is a good place to look at for lessons in processing carbon fiber automotive components.

One of the first companies to implement robotic automation in the manufacturing of carbon fiber automotive components was Plasan USA. In 2005 Plasan started producing front fenders for the Chevrolet Corvette. Initially Plasan relied on manual labor spending about an hour to drill holes and trim each fender. They recognized that they needed to look at automation as a means of reducing their per part production costs while maintaining high quality standards. One of the first operations Plasan considered automating was post molding operations including deflashing, trimming and drilling. This is a difficult process that generates undesirable carbon fiber dust and if not done properly will directly impact production quality. All of these factors make for a strong case to for automation.

The first step was to determine the best process to handle the required operations. Plasan partnered with KMT Robotic Solutions to first evaluate available options with quality as the most critical criteria as Plasan’s customer would not tolerate any loss in quality for a Class A surface for a premium vehicle. The testing included abrasive waterjet cutting and router trimming.

Each process has its strengths and challenges. For waterjet creating small holes without any de-lamination or blistering tends to be the most challenging process. For router trimming cutting an edge without fraying of the fibers tends to be the most challenging. These issues are discussed in more detail latter in this paper, but for Plasan it was a practical matter of finding a process that minimized any issues associated with the selected process. In Plasan’s case, the challenge of drilling the large number of small holes required was difficult for the waterjet process to handle without blistering. There will always be a small amount of fraying of the carbon fibers on the edges of the parts for router trimming, but by finding the right combination of router tool (titanium coated carbide), feed rates and spindle speed KMT was able to keep the fraying to a minimum. Figure 1 shows a picture of the router trimming cell.

![Figure 1: Router Trimming of a Carbon Fiber Fender](image)
One important advantage of router trimming is that it provided a lower capital investment to achieve the required production rates. A single robot cell was able to complete each fender in less than 25% of the time required to trim a fender manually. To maintain high spindle utilization, two part fixtures were located on opposite sides of a 180° rotating wall. While one part was being trimmed a completed part outside of the cell was being unloaded and then a new part was loaded onto the second fixture.

**Automotive Component Experience – Case 2**

BMW decided to give their customers the option of a carbon fiber roof on their 2008 M3 coupe. The new roof would give the car significant weight savings while also giving it a refined look. However, in order for their new carbon fiber roof to obtain the aerodynamics and distinct look they desired, BMW needed a precise surface finishing process for the clear coat varnish. They found that manual finishing led to high cycle times, inconsistencies in quality and worker safety concerns.

BMW worked with KMT Robotic Solutions to development of a robotic sanding solution to meet their requirements. As with the trimming case study, KMT went through an extensive testing process to identify the proper media, feeds/speeds, head design and other criteria necessary to achieve a high quality finish.

The production system featured a robot guided compliant grinding head that can adapt automatically to the curvature of the roof. To facilitate cost and time effective robot programming, the system features a KMT developed programming tool that can generate complex robot paths from 3D-CAD-data in under two minutes. This allows the robot to move at a constant speed while the grinding head makes all necessary adaptive movements in real-time. These technologies working together allow for constant grinding conditions over the entire surface of the roof, resulting in the constant surface quality required.

![Figure 2: Sanding of Carbon Fiber Roof](image)

With the automated grinding system it takes BMW just 50% of the manual cycle time to finish a roof and the level of precision KMT’s system offers simply isn’t possible though manual processing. Also, since the physical challenges inherent in manual grinding are delegated to the robot, employee safety is significantly increased.
Waterjet vs. Router Trimming

The automotive case studies are examples of valuable building blocks for robotic automation of carbon fiber body structures, however, there are unique requirements to this market that make automation more challenging. Probably the biggest challenge is the relatively large size and varying geometry of body structure components. As structural components they tend to be made up of more layers creating new processing challenges. Also, an automated system would be expected to have the flexibility to handle the wide mix of parts that make up the various body structure components.

One of the most critical needs is handling the trimming and cutting of features on the various panels. Over time, a variety of technologies have been investigated for cutting, trimming and drilling of carbon fiber parts. Some options such as using lasers have not proven to be viable both due to cost and complications in handling the fumes. Some options such as using straight water (no garnet media) are unable to provide the required part quality due to excessive delamination and blistering. Two technologies have emerged as the best alternatives for cutting and trimming carbon materials; router trimming and waterjet cutting.

Router trimming is essential a means of machining material in the same way that a mill would machine a metal part. In the case of robotic router trimming in the typical application the robot holds an electric spindle motor with a router trimming tool that is used to cut, trim or drill holes. One major difference between metal, plastic or other components that are milled or router trimmed is that carbon fiber is made up of layers of fibers woven together vs. a contiguous material. This creates a special challenge for a router tool that is designed to shave away the contiguous material. When cutting directly across the fibers there is generally no problem, but cutting in the direction of the fibers can be more challenging as they tend to fray when cut. This becomes more of an issue as the tool begins to dull and more tearing occurs. Even so, with the proper parameters the amount of fraying can be minimized as shown in figure 3.

![Figure 3: Variations in Router Trimming Results with Different Cutting Parameters](image)

Abrasive waterjet cutting does not have this problem. Instead a high speed stream of water carries an abrasive garnet that grinds off the fibers and bonding materials. Because the stream of water is always pointed at the panel, it is always perpendicular to the fiber strands. The garnet moves at such high speeds that it cleanly cuts the fiber material. Waterjet has the added advantage that it does not generate heat or dust.
One of the biggest challenges of waterjet is its tendency to spread into any gaps as the stream penetrates the material. This is particularly an issue with the top layer where delamination or blistering can be an issue. However, like router trimming this issue can be mitigated through techniques such as dynamically adjusting the pressure and always start at the interior of a feature and work your way to the outside. Figure 4 shows holes pierced with the proper pressure schedule blistering and delamination can be significantly reduced if not eliminated.

![Image of variations in Abrasive Waterjet Piercing]

**Figure 4: Variations in Abrasive Waterjet Piercing**

There is no clear cut advantage to one process over the other and it is always best to perform testing to determine what process is best. Table 1 compares some of the tradeoffs between the two processes.
### Table 1: Waterjet vs. Routering

<table>
<thead>
<tr>
<th>Criteria</th>
<th>Advantage</th>
<th>Background</th>
</tr>
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<tbody>
<tr>
<td>Capital Costs</td>
<td>Router</td>
<td>A clear advantage to router trimming. Router systems require additional equipment to contain and collect dust, but a larger investment is required for the intensifier and filtration equipment required for waterjet</td>
</tr>
<tr>
<td>Running Costs</td>
<td>Waterjet</td>
<td>For waterjet the largest running costs are water, garnet (abrasive media), and wear items like nozzles.</td>
</tr>
<tr>
<td>Throughput</td>
<td>Waterjet</td>
<td>Throughput depends on the material and cutting path, but for longer trim paths waterjet can be three times faster than router trimming</td>
</tr>
<tr>
<td>Capability</td>
<td>Depends</td>
<td><strong>Small Holes</strong> – De-lamination or blistering on the surface makes small holes challenging for waterjet.</td>
</tr>
<tr>
<td></td>
<td></td>
<td><strong>Small Slots</strong> – For router trimming the slot size is limited by the size of the smallest tool</td>
</tr>
<tr>
<td>Quality</td>
<td>Depends</td>
<td><strong>Loose Strands</strong> This in particular is an issue with router trimming, but can often be minimized with the proper speeds and feeds</td>
</tr>
<tr>
<td></td>
<td></td>
<td><strong>Blistering</strong> This in particular is an issue with waterjet, but can be addressed by proper programming path and pressure settings</td>
</tr>
<tr>
<td>Secondary Issues</td>
<td>Waterjet</td>
<td><strong>Dust</strong> This is an inherent issue with router trimming but can be controlled by enclosing the system with proper ventilation</td>
</tr>
<tr>
<td></td>
<td></td>
<td><strong>Heat</strong> This is also an issue with router trimming but with proper speeds, feeds and tooling can be mitigated</td>
</tr>
<tr>
<td></td>
<td></td>
<td><strong>Tool Wear</strong> Wearing tools can impact quality, but a proper maintenance schedule can mitigate this issue</td>
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Implementing with a Robot

Although 6 axis articulated robots are extensively used in automotive body shops they should not by default be considered the right manipulator for processing carbon fiber body structures. In fact 5 axis gantry robots are widely used for cutting, trimming and drilling for aerospace and other industries. Gantry style manipulators have 2 major advantages over articulated style robots; their ability to cover large spans and achieve extremely high accuracies. For aerospace these are both critical requirements when covering a fuselage, wing or other large structures with extremely high precision. This however is not the case for body structures. In fact articulated robot suppliers have tailored their designs specifically to meet the needs of the automotive body structure market. All of the major robot suppliers offer cost effective models with the proper reach and payload for processing body structures.

Accuracy is more challenging, but robot suppliers have made great strides in the last few years in the development of high accuracy solutions. All of the major robot suppliers now offer calibration packages that enable the accuracies required for cutting, trimming and drilling carbon fiber packages. Each of these suppliers also offers simulation and design packages that allow CAD part drawings to be used to generate robot paths and then have these paths downloaded directly to the robot. These packages also allow for accurate design of the workcell and validation of cycle times to minimize the implementation risks. Figure 5 shows a model of a concept for a abrasive waterjet cutting cell for processing carbon fiber body structures.

Figure 5: Multi-Robot Concept for Carbon Fiber Body Panel Abrasive Waterjet Cell
Abrasive waterjet has an additional challenge for the robotics, or for that matter a CNC gantry solution. This is because the waterjet stream contains a high amount of energy that must be dissipated by the part or if not by some other means or it could cut its way through the system. The ideal way to dissipate this energy is with a tank with water that captures the waterjet stream. This means that the robot must position the waterjet nozzle over the part and direct the stream down so that any air moves or stream that works its way through the part is captured by the tank below. In most cases this is sufficient, but there are two complications. The first complication is due to any variation in the geometry of the part that is far outside of a plane. This can be compensated for by using one robot to hold the part and a second robot to hold the nozzle. The robot that is holding the part makes sure that the part is oriented so that the second robot can aim the waterjet stream into the tank below.

The second complication is that in some instances the patterns to be cut may force the waterjet stream to be in line with a second area of the part. This means that without dissipating the energy after it passes through the feature to be cut the area of the part in line with the cut may also be unintentionally cut. This problem can be addressed with a catcher or protection plate designed into either the tooling or fixturing that catches any portion of the waterjet stream that is not dissipated. This is typically done with some type of a sacrificial media that is worn away over time and replaced as a regular maintenance item. Figure 6 shows an example of including catcher details in the fixturing. The catcher plate can also be added to the End of Arm Tooling so that it moves with the waterjet nozzle, but this can restrict the motion of the robot.

![Figure 6: Method of Avoiding Abrasive Waterjet Over Spray Damage](image)

**Production Implementation**

Production implementation of carbon fiber body structures is in the early stages, and those OEMs who are implementing them in their designs consider their manufacturing processes to be a competitive advantage. So because of this details on the production systems has not been released, but there are some good lessons learned and related information that are helpful to other OEMs considering this technology.
A key finding is that in addition to the quality, elimination of dust and other issues previously discussed, abrasive waterjet has shown to have a running cost advantage over router trimming. When comparing running costs per meter of trimmed surface testing of production Carbon Fiber body panels has confirmed close to a 3:1 advantage for waterjet running costs:

- Router Trimming: $0.26/m
- Waterjet: $0.09/m

Another finding is the importance of performing sufficient testing to dial in the proper parameters for the parts to be processed. Variables to be set include:

- Material thickness (min/max)
- Entry process to minimize de-lamination
- Water Pressure
- Orifice diameter
- Focusing tube diameter
- Garnet quantity
- Cutting speed

As the market develops and field experience increases less effort up front effort will be required, but for now anyone planning to move forward with CARBON FIBER body panels should plan on a stage 1 test effort.

A final finding is that for abrasive waterjet systems a multi-robot solution where one robot manipulates the part and additional robot(s) (the number depending on the throughput requirements) performs the cutting appears to be the best configuration. This approach has proven to have 2 advantages. The first advantage is that the robot that the part holding robot handles 2 tasks; loading and unloading parts into the cutting area and positioning the parts so that the waterjets can always cut down into the collection tank.

**Summary and Next Steps**

This is an exciting time for those involved in the production and ramp up of technologies such as carbon fiber that are critical enablers for electric vehicles or other highly fuel efficient vehicle programs. One of the key challenges facing greater use of carbon fiber body structures is how to drive down the manufacturing costs to be competitive with traditional sheet metal body structures. A critical component in meeting this challenge is how to drive down the manufacturing costs, including the requirement to cut, trim and drill features into the panels. Robotics with abrasive waterjet or router trimming are both viable technologies, but abrasive waterjet has shown that it has advantages that will over time lead to its more widespread use. As OEMs and tier 1 suppliers develop plans for new vehicle programs with carbon fiber body structures they should make sure that they work closely with and as early as possible with those that supply solutions to key processes including the cutting, trimming and drilling of their body panels.

**References**