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ISSUES IN MACHINING OF HOLLOW CORE HONEYCOMB SANDWICH STRUCTURES BY ABRASIVE WATERJET MACHINING

Machining of hollow core honeycomb sandwich materials is a challenging job as the mechanical properties of various layers (skin, core) are quite dissimilar, and the conventional solid cutting tool experiences a sudden change of conditions while machining that might lead to damage on the tool/part. Although, abrasive waterjets (AWJs) is highly efficient in the machining of advanced composite materials due to their unique characteristics, efficient machining of sandwich structures by AWJs needs many challenges to be addressed. This work presents various issues observed in AWJ machining of carbon- and glass- fiber skin based, aluminum sandwich structure composite materials, and the limitations of AWJs in processing these exotic materials. Finally, possible strategies for efficient machining of honeycomb structures were proposed for future investigation.

1. INTRODUCTION

Recently, the use of various types of advanced engineering composite materials (AECMs: fiber reinforced-, sandwich-, and particulate- composite materials) in high value added industries, such as aerospace, automotive and spacecraft, is increased significantly as a structural material due to their high strength-to-weight ratio, modulus-to-weight ratio compared to metals. Various composite materials represent 50% by weight of the new Boeing 787 and Airbus 350XWB frames [1],[2],[3]. Replacing the aluminum based top conical portion (95% of the material is removed by the expensive conventional machining) of space shuttle structure by composite material, reduces the weight by 30%.

When the flexural rigidity of a composite material is not sufficient, the sandwich concept offers an alternative *without a significant weight penalty*; the core (wood, honeycomb, corrugated or expanded polymer foams) supports the lateral loads experienced by the sandwich component through shear - shear strength and modulus are the most relevant properties of a core material. The faces of the sandwich are placed at a constant distance from each other to stipulate high compressive modulus for the core – a small degree of compression cause to a significant decrease in flexural rigidity. Some core

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materials provide good thermal and acoustic insulation properties to the sandwich. On the other hand, the global trend for commercial AECMs in aero-structures is - *large components and increased use of integrated co-cured parts*, by aiming at reduction in the cost by minimising the (i) number of part assembly steps, and (ii) problems with tolerances.

Although, few components can be produced by near-net-shape manufacturing, they usually require secondary machining to attain desired geometry, tolerances and features for assembly. Mechanical fasteners are opted when periodic disassembly is present, which requires feature machining. Although, the AECMs have excellent complementing properties of individual constituents, machining them with conventional solid cutting tools is a challenging job - due to its (i) constituents which have low machinability that come from their superior mechanical properties, and (ii) heterogeneity - sudden change of properties of constituents those come in contact with the cutting tools in a short time gap. Furthermore, anisotropy, low thermal conductivity and heat sensitivity, matrix cracking, inter-laminar voids, and resin melting due to heat generated during the process, high cutting forces, generated vibration and noise, pose severe challenges to the conventional machining processes. The high-strength fibers in composites do not break easily, and tend to be pulled by the cutting tool, leading to microcracking and delamination along the cut. In the case of aramid, the tough fibers are very hard to shear and result in fuzziness along the machined surface. Overheating at the machining zone can heat the resin above its glass transition temperature and locally damage the cured laminate. The polymer composite materials can outperform any other materials in all respects except temperature tolerance. When fluid is used to cool the local machining zone, the fibers may absorb moisture, also degrading the laminate properties. In addition, the tools themselves are put to the test when cutting AECMs. The heterogeneous combination of fiber and matrix resin means that a cutting tool encounters varying resistance due to the interlayered hard abrasive fibers and softer resin, which puts stress on the tool drive mechanism; fibres (carbon, glass, aramid, metal) are abrasive and can lead to rapid wear on the costly dedicated tools. Furthermore, machining with conventional machine tools is not environmentally friendly as solid tools generate dust and carbon powder which can wreak havoc on electrical systems and personnel. In addition to this, conventional machining leads to removal of material in the form of chips which increases the under utilisation of the workpiece material.

Holes drilled in a component serve as areas of stress concentration and can have a detrimental effect on the strength, stiffness and reliability of the composite by disrupting the fiber load path - the method of hole making can itself damage the composite. Frequent tool change is required when using routers/drills due to the abrasive nature of the composite. Frayed/delaminated edges requires costly rework and slowdown of production cycles. Hence, selection of machining method for composites is of utmost important. In spite of encouraging aspects of orbital drilling (lower axial cutting forces; efficient chip and heat extraction; and single drill tool to generate various sized holes), it has the following limitations: (a) the drill tool will be in contact with abrasive fibers, (b) sudden exposure to materials with quite different properties, (c) bending the thin vertical walls of the honeycomb structures, (d) hazardous airborne dust, low machinability and delamination. With the conventional machining processes, tool geometry/materials and operating conditions must be adopted to reduce mechanical/thermal damage to the workpiece/tool;

this might lead to impractical operating conditions due to unacceptable MRR and delamination.

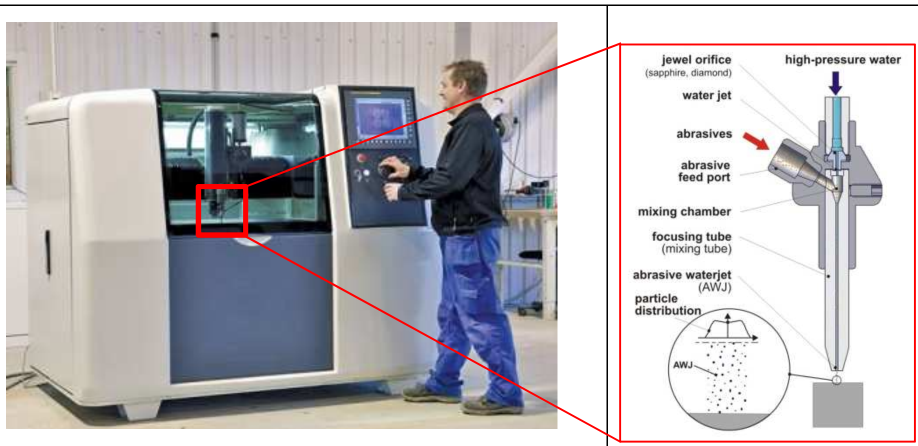
Among the wide range of unconventional machining processes, abrasive waterjet (AWJ), laser beam (LB), electro discharge (ED) machining approaches are found successful in machining of composites. However, AWJ being by far the most widely used approach due to the following reasons: LB technology for polymer matrix composites results in extremely poor cut quality with excessive burr formation, large dimensional errors, large HAZ, severe thermal damage, forms charred matrix residues and protruding fibers [4], FRPs have greatly different physical and thermal properties and thus behave differently when exposed to the laser beam. CFRPs are more difficult to cut with lasers because of high vaporization temperature and high thermal conductivity. Aluminium has always been a difficult material to cut with CO_2 lasers due to the material reflection of the LB, but it exhibits the best results of all materials on AWJs. Mass spectroscopy and gas chromatography analysis of fumes from the LB machining of various composites indicated the presence of powders of fiber materials and high concentration of CO, CO_2 and low molecular organic compounds, hydrogen cyanide which are of considerable health risk [5]. On the other hand, ED machining strongly dependent on the conductivity of the composite material; Glass and Kevlar FRPs are poor electrical conductors. ED machining provides the lowest MRR among the three unconventional machining approaches (LB, ED and AWJ). As a holistic comparison, AWJ can cut up to 60 cm (virtually any materials) where as lasers can go up to 7cm (depending on material properties) and ED can go up to 30cm (depending on material properties). Capital investment (in USD) for AWJ is from 60K-300K where as 200K-1M for lasers and 100K-400K for EDM. Same machine and workpiece setup for different jobs can be used in AWJ machining where as different gases and parameters in the case of lasers, and different wire types in case in ED machining have to be used. The proven superiority and tremendous productivity gains (high cutting speeds of 5 times to traditional methods) of AWJs against other processes, due to its unique properties - can cut virtually any material, low temperature at the machining zone prevents damage to the constituents and delamination, low cutting forces (<7N), small kerf width (0,3mm), and low vibration - made to consider this unconventional machining process to investigate its machining capability of sandwich honeycomb structures.

2. SCOPE OF WORK

In the present work, an attempt was made to investigate various issues involved in abrasive waterjet machining of advanced sandwich honeycomb composite material used in high value added aero-, space- and automotive- and space shuttle- industries. Furthermore, it addresses the limitations of the state-of-the-art AWJ machine tool for efficient manufacturing of sandwich composite materials with high dimensional accuracy; for this purpose two types of manufacturing operations by abrasive waterjet machining were considered in this study: (i) through cutting, and (ii) radial drilling. Finally, potential strategies to address the issues observed in the considered manufacturing operations were proposed for future consideration.

3. EXPERIMENTAL SETUP AND METHODOLOGY

Through cutting and drilling trials were conducted on a Finecut abrasive waterjet machine tool, which has 3-axis machining capability that enables maneuvering the focusing nozzle, by which the jet plume, along the three primary axes by gantry router (X-axis: 1,9m, Y-axis: 1,2m and Z-axis: 0,78m). The ultra-high pressure pump is capable of supplying water at a maximum pressure ($\boldsymbol{P}$) of 414MPa. The abrasive mass flow rates ($\boldsymbol{m_f}$) and jet feed rates ($\boldsymbol{v}$) can be achieved in the range of 0-1kg/min and 0-20,000mm/min respectively. Figure 1 presents the photograph of the abrasive water-jet machine setup used in this study; Figure 1b presents the close up view of the AWJ cutting head with the description of various elements those generate the high velocity jet plume for erosion. Garnet abrasive media with 120 mesh size was employed throughout the experimentation in the machining of carbon fiber- and glass fiber- skin based aluminum honeycomb core sandwich structure (100mmX100mmX10mm).



(a) (b)

Fig. 1. Experimental setup for abrasive waterjet machining of sandwich materials [6]

In this study, experimental trials were conducted in two stages to evaluate the performance of AWJs in machining carbon fiber-aluminum honeycomb sandwich composite materials. Stage 1 of experimentation involves the comparative study between the conventional and the abrasive waterjet cut sandwich structure surfaces. Stage 2 of experimentation, further divided into two modes:

(i) Mode 1: *U-shaped through cutting* – includes machining of both the linear feature, and arc features. The two linear cut feature of 30 mm are connected (in a perpendicular direction) to the linear feature of 20mm, on either side, by an arc feature cut of radius 5mm.

(ii) Mode 2: *Radial hole drilling* - The holes of various diameters (15mm, 20mm, 30mm, 35mm) were achieved by abrasive waterjet radial drilling mode by first piercing the honeycomb structure by the jet at the center of the hole, and then traversing along the hole periphery.

All the experimental trials were performed by considering the following AWJ process parameters: waterjet pressure = 350MPa, abrasive flow rate = 0,035kg/min, jet traverse rate= 500mm/min, diameter of orifice = 0,12mm, and diameter of focusing nozzle = 0,3mm. The experimental results were analyzed to identify the potential reasons for the resulted behavior. Based on the identified issues from the comprehensive analysis, possible strategies were proposed to address these issues identified with abrasive waterjet machining of sandwich honeycomb composite materials.

4. RESULTS AND DISCUSSION

4.1 PILOT TRIALS CONDUCTED ON CARBON FIBER-ALUMINUM HONEYCOMB SANDWICH STRUCTURE COMPOSITES

Figure 2 presents the results of the stage 1 of the experimentation where the through cut surfaces were produced on sandwich honeycomb structures by the conventional machining (carbon fiber based skin – Fig. 2a) and abrasive waterjet machining (carbon fiber- and glass fiber- based skin – Fig. 2b). From the results it can be seen that the thin wall section of the honeycomb structure is severely damaged, which can be attributed to the very high forces exerted by the conventional solid tool. On the other hand, there is no damages observed on the abrasive waterjet through cut surfaces of carbon-fiber and glass fiber- based structures that can be explained as follows: as the abrasive waterjet exerts negligible forces (<7N) while cutting on the thin walls of the structure, it cannot result in any sort of damage to the thin wall structure of the honeycomb. Furthermore, the top skin layer of the cut surface is of very high quality without any delamination.

In general, the top surface of the glass fiber skin layer will be covered by a layer to protect from the damage caused by the red hot chips spill onto the top surface in the conventional machining operations. Laying the protective layer before machining, peeling it after machining and cleaning the top skin increases the manufacturing cost drastically, and also increases the down time. However, abrasive waterjet has generated damage free surface on the top skin of the glass fiber material after machining - both in the cutting and radial drilling operations (Fig. 2b). This encouraging result contributes towards reduction of the manufacturing cost of unit component and down time.

Before proposing strategy for dynamic compensation of the jet divergence effects to generate high quality machined surfaces and to maintain the tolerances, the observations made from the pilot trials (stage 2 of experimentation) conducted (Finecut, Sweden) in two modes, to see the possibility of machining carbon fiber-aluminum honeycomb sandwich structure composites (HSC) were discussed in the following: Figures 3 and 4 presents a typical abrasive waterjet machining: through cutting (Fg. 3) and radial drilling (Fig. 4) of HSC. In the feature generation operation by AWJs, while the jet traversing perpendicular to the composite material surface, various regions (top skin, honeycomb, bottom skin) of the HSC respond differently to the AWJ due to their individual material properties, physical

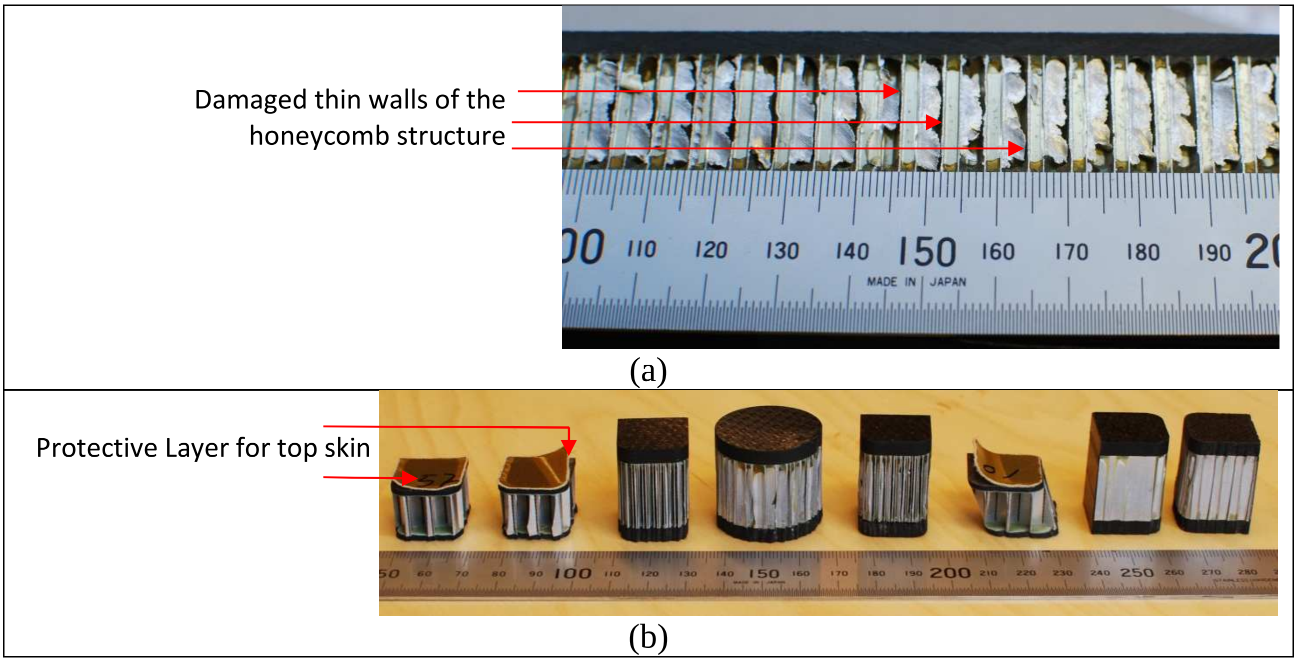


Fig. 2. Cut surface produced by the conventional and unconventional machining approaches: (a) conventional method, (b) abrasive waterjet method

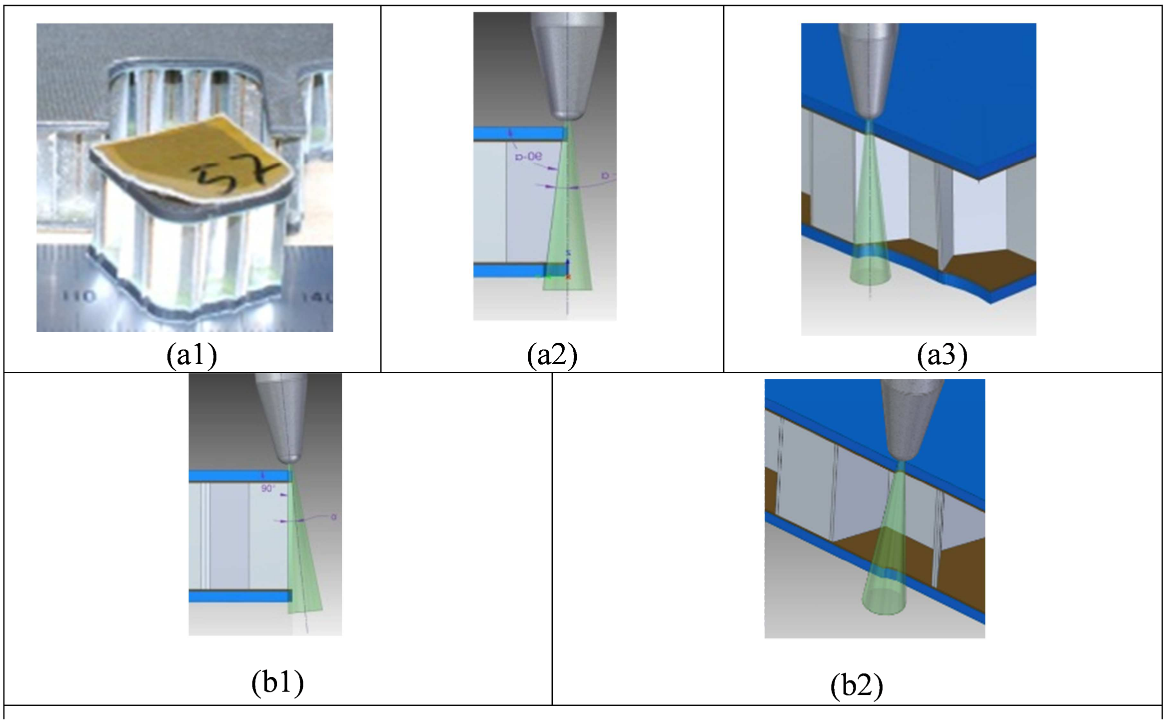


Fig. 3. Through cutting of hollow core honeycomb sandwich structures: (a1) AWJ through cutting trial, (a2, a3) schema tic illustration of conventional AWJ through cutting, (b1) proposed dynamic jet compensation – side view, (b1) – isometric view

structure, distance from the focusing nozzle tip (jet divergence), that generate different surface quality on the top skin, bottom skin layers and the honeycomb structure.

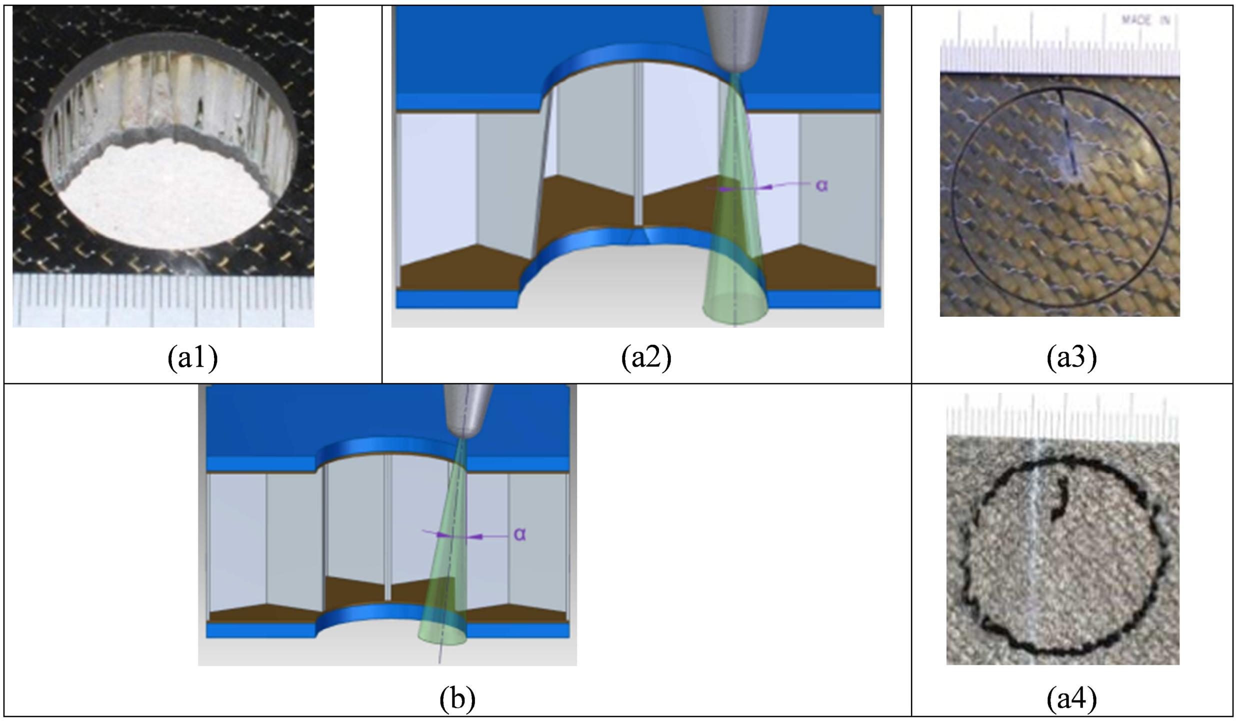


Fig. 4. Radial drilling of hollow core honeycomb sandwich structures: (a) conventional AWJ approach: (a1) AWJ radial dilling trial, (a2) schematic illustration of radial drilling, (a3) top skin layer, (a4) bottom skin layer, (b) proposed dynamic jet compensation

As the top skin of the composite is near to the tip of the focusing nozzle, the divergence of the jet is negligible (Fig. 3-a2 and Fig. 4-a2) that results in smooth top surface (Fig. 4-a3). When the jet progresses towards the core structure from the top layer, the solid core materials reacted differently to the hollow core composite materials, and pose challenges to the machining. When the jet passes through the void cell structure of the HSC, the jet diverged due to its inherent fluid dynamic characteristics and damaged the side walls of the cell structure and the bottom skin of the sandwich structure (Fig. 4-a4). In addition to the macro scale irregular surface on the bottom skin of the sandwich materials, there exists a meso scaled taper on the cut surface, after the AWJ based radial drilling. Similar behavior was observed in case of through cutting operation. This can be attributed to the characteristics of the diverged AWJ plume in the free air.

4.2. STRATEGY TO AVOID THE EFFECTS OF JET DIVERGENCE FOR THE GENERATION OF SMOOTH SURFACES

With the existing state-of-the-art design of cutting heads, the jet divergence is an integral part of the AWJ technology. As the jet divergence leads to deviation in the part final dimensions, attempts can be directed towards adopting the two stage procedure to reduce its undesired effects:

4.2.1. EMPLOYING LONG CHAIN POLYMERS

Mixing of the long chain polymers in the water leads to the formation of long chains of molecules, which cannot be broken down easily. This concept is exploited in WJ machining to form a coherent jet to reduce the divergence of jet emerging from the focusing nozzle. In the second stage, to reduce the effects of jet divergence further, the dynamic jet tilting mechanism is proposed as follows.

4.2.2. STRATEGY FOR DYNAMIC COMPENSATION OF THE JET DIVERGENCE EFFECT ON FEATURE QUALITY

To address the issue caused by jet divergence - taper and undulated surface on the bottom layer of AECMs- a strategy in which the impingement axis is tilted proportional to the jet divergence angle so that one edge of the jet will always be maintained normal to the machining surface (Fig. 3b and 4b). However, dynamic compensation of the jet according to the jet divergence depends on various parameters, such as the diameter of focusing nozzle, jet traverse rate, standoff distance, i.e. the distance between the workpiece and the tip of the focusing nozzle. Hence, generalisation of this concept needs development of an analytical model that takes into account above said AWJ process parameters, by considering this model, an optimization strategy suggests the process parameters to be employed for achieving the target (depth of cut, productivity, delamination etc.) by taking into account the type of AECM. A dynamic compensation strategy suggests the tilt of the jet required to compensate the divergence effects, by considering the shape of the feature to be machined and the basic process parameters employed for machining.

5. CONCLUSIONS

From the comprehensive experimental investigation on machining of carbon- and glass- fiber skin based aluminum sandwich structures, the following conclusions can be made:

- Although, excellent kerf characteristics - surface quality, width - can be achieved on the top skin of the honeycomb composite structure, the bottom skin will result with non-uniform surface.
- Top kerf width in machining is considerably different from the bottom kerf width due to the expansion of the jet in the cell or void of the honeycomb structure. There exists a micro scale taper on the bottom skin cut surface.
- By addition of long chain polymers to the water, the divergence of the jet can be reduced significantly by that, uniform bottom skin surface can be expected.

- By effective design of the mixing head, the mixing efficiency can be improved, and divergence of the jet can be reduced, which helps in achieving uniform bottom skin surface that is near to the quality of the abrasive waterjet cut top skin.
- An attempt can be made to eliminate the nonuniform surface issue on the bottom skin of the sandwich structure by maneuvering the jet.
- The cost of laying and peeling of the top skin protection layer on the honeycomb sandwich structure, and the machining down time, can be drastically reduced by employing abrasive waterjet based honeycomb structure machining.

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