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6th CIRP Conference on Surface Integrity

Surface integrity quantification in machining of aluminum honeycomb structure

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Abstract

This work outlines an analysis of the surface integrity of aluminum honeycomb after milling using specific tools. This is the most common core material used for aircraft honeycomb structures. The machining of these materials is accompanied by some difficulties related to structural properties due to the weakness of local bending stiffness of the cell walls and the lightweight of material. This influences the surfaces quality after machining. Our analysis aims to show the link between the surface integrity (burr, walls folding and tearing) and the machining conditions. To meet this objective a specific method based on microscopic observations is developed.

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Keywords: Type your keywords here, separated by semicolons ; Honeycomb structures, machining, burr formation

1. Introduction

The use of sandwich composite structures based on honeycomb core has grown considerably in recent years, especially in the aeronautic, aerospace and automotive industries. Recent development projects for Airbus A320neo or Boeing 787 Dreamliner confirm the increasing use of the honeycomb material. With increasing applications, the production techniques of sandwich structures are subject to constraints and very high requirements from manufacturers. An important aspect of production technology is honeycomb core machining. Aluminum honeycomb is the most metallic honeycomb core used in aerospace applications. This structure combines lightweight and a good mechanical behavior. It is characterized by high out-of-plane compression, shear properties and outstanding energy absorption characteristics. Nevertheless, this material presents a forming challenge because of the geometric properties of honeycomb structure [1]. First of all, the uses of honeycomb material in sandwich composite are limited by the difficulty of designing structures with complex

geometries. Indeed, the two existing methods for the manufacture of honeycomb allow to have only structures with parallelepiped shape [2, 3]. Thus, a forming step by machining is necessary to obtain complex geometrical shapes making the use of honeycomb materials possible in various fields. However, there are some factors limiting honeycomb machining, particularly the weakness of local bending stiffness of the cell walls and the low density of honeycomb material. This shows the fragility of each wall of the honeycomb, which influences the quality of obtained surfaces after machining [4]. In order to ensure the assembly of honeycomb core and the skins to form a sandwich structure, it is necessary that the machined surface is flawless. A good machined honeycomb surface is a crucial criterion in the cutting of this type of material. Its use in sandwich material requires a good surface quality to be able to stick the walls on either side of honeycomb.

In our study we are interested in the machining of aluminum honeycomb cores by milling. In the literature several publications focus on the use of methods to fix the honeycomb

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core during cutting. The authors use methods to stabilize the honeycomb structure, either by freezing water in the cells or by using iron powder in the presence of a strong magnetic field. Wang [5] studied the effect of cryogenically freezing water in the honeycomb cells to both increase the compressive strength and maintain the cutting stiffness. This study found that average machining forces increased significantly with ice, as well as a limited effect on defect reduction. However, this method is only feasible for open-cell honeycomb and not for sandwich material. Who [6] conducted a study on the interaction of the workpiece with the tool for individual aluminum honeycomb cell walls with frozen water stabilization. The study analyzes the resulting cutting forces as a function of tool positions and wall angle. In modeling the interaction of a cutter tooth with the walls, the author assumes wall shear, and the absence of deformation and material wrapping around the tool.

Other studies have focused on the machining of composite honeycomb materials. Jaafar et al. [7] present a study on the use of finite element modeling to predict the impact of cell structure and cutting tool geometry on the machining of Nomex® honeycomb cores. However, Nomex® is a material with very different mechanical properties than aluminum. Gill et al. [8], Yip-Hoi and Gill [9] also address the issues of machining Nomex® honeycomb, and when it is bonded as a core material to fiberglass skin sheets. The study [9] presents the mechanisms related to how the cells break and collapse during cutting. The geometry of the milling tool is one of the most critical factors in cutting efficiency. Many patents have been filed on milling cutters designed specifically for machining honeycomb structures [10,11]. However, defects, such as distortion and burrs, are easily generated during the machining of aluminum honeycombs due to the low stiffness caused by the cellular structure and thin walls [3]. In order to solve these problems, studies have been conducted. Mendoza et al [12] developed a new tool to machine both honeycomb and solid aluminum. He demonstrated an improvement in the surface quality of honeycomb machining. An et al. [13] also conducted studies on the defects during milling of aluminum honeycomb, including the burr formation mechanism, distribution characteristics and cutting process of honeycomb cell walls. Regarding innovation in machining, ultrasonic assistance is a rapidly developing method. Ultrasonic cutting technology has been used in honeycomb machining due to its advantages of reduced cutting forces, accuracy and environmental friendliness [14]. Sun et al [15] also indicates that ultrasonic machining is one of the ways to ensure efficient high-quality machining for aluminum honeycomb.

However, the reviews of literature do not exhibit studies related to the optimization of machining of aluminum honeycomb core. In this paper, the objective is to determine the optimal machining setting to ensure the integrity of the machined surfaces. For this purpose, an original method is developed to characterize the defects on the surfaces of aluminum honeycomb materials.

2. Milling of aluminum honeycomb materials

2.1. Aluminum honeycomb core materials and milling tool

The aluminum honeycomb studied is made of 5056 series of aluminum alloy sheet. The honeycomb is fabricated by bonding together aluminum foils which are then expanded to form a hexagonal cellular configuration. The geometric characteristics of the aluminum honeycomb core are shown in fig. 1 and table 1.

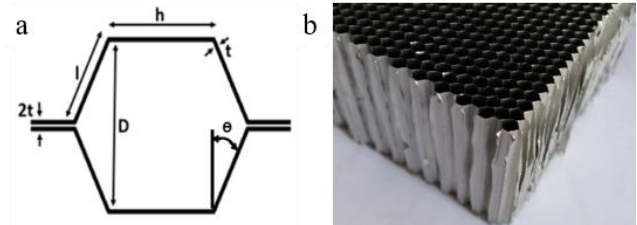


Fig. 1. Study aluminum honeycomb configuration (Density 49 kg/m³): Designation 3.1-1/8-07.

Table 1. Honeycomb geometric parameters.

D (mm)	t (μm)	θ (°)	h (mm)
3.175	17.78	120	1.4

Due to the increasing use of this type of material in industry, manufacturers have developed efficient and specific tooling solutions for different honeycomb machining operations (grooving, facing, routing, drilling). The tool used in this study is a combined tool. It consists of two parts mechanically assembled by a screw: A circular cutting blade made of tungsten carbide and characterized by a cutting edge with 55 teeth, a diameter of 18.3 mm, a cutting angle of 22° and a clearance angle of 2.5°. The upper part of the tool is a cylindrical body made of high-speed steel with a diameter of 16 mm, consisting of ten helices containing chip breakers, see fig. 2.

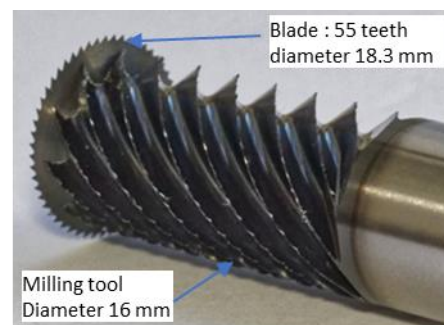


Fig. 2. Combined tool for milling aluminum honeycomb.

2.2. Milling tests and surface characterization

A parametric study is conducted to identify the influence of the main cutting parameters on aluminum honeycomb milling. Table 2 summarizes the different levels of the parameters in the

study. The milling of aluminum honeycomb materials is performed according to the grooving configuration, see Fig. 3. A monitoring of the surface quality evolution was performed according to the cutting conditions.

Table 2. Factors and levels of the honeycomb milling design of experiments.

Levels	Feed rate, V_f [mm/min]	Rotation speed, N [rpm]
1	150	2000
2	1000	15000
3	3000	23000

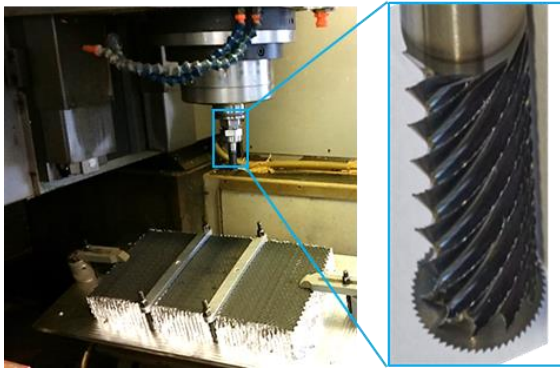


Fig. 3. Grooving operation of aluminum honeycomb. (Workpiece size 400mm x 250mm)

The surface integrity of the aluminum honeycomb after milling is linked to the burr formation. The ductility and the thin thickness of the aluminum wall constituting the honeycomb favor the formation of this defect during the machining of this type of structure. Generally, the burr is accompanied by a plastic deformation of the cells and their geometrical change, see fig. 4.

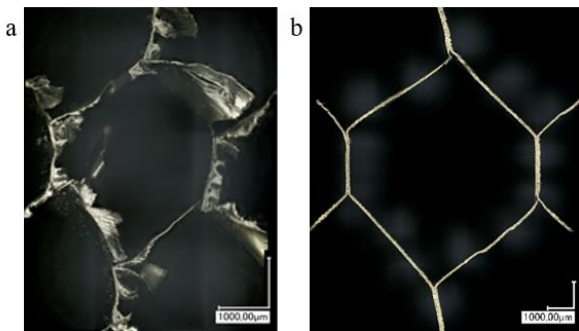


Fig. 4. Machined aluminum honeycomb cells; (a) cells with burrs and plastic deformation of the walls; (b) cells without burrs and without plastic deformation.

Burr is defined as the excess material observed outside the ideal geometric shape. In the case of honeycomb, the desired geometric shape is the one that is closest to the initial cells. The burr is quantified by measuring its geometric parameters (length, width, thickness) or by measuring the area occupied by its profile. In this study, we opted for the second method, which

is more significant in terms of burr distribution, especially since the burr tends to close the alveolar cells. The difficulty encountered in quantifying the burr is the definition of the boundary between the cell geometry and the burr. This separation is even more difficult when the plastic deformation experienced by the cell is more pronounced. This results in the fact that it is not possible to use the initial geometry of the cells before machining as a reference due to the geometric change of the cells after the machining operation.

Thus, the method used here is based on a digital processing of 2D images of cells after machining. To overcome the problems mentioned above, this method uses the principle of skeletonization. The objective is to extract the average line representing the general shape of the honeycomb cell. Then a reconstruction of the cell is performed. From the skeleton obtained previously, the reconstruction of a cell without burrs is possible. It is sufficient to identify the cell walls according to their type (single wall or double wall) and to add the appropriate thickness on the image. A width t is assigned to the single walls and $2t$ to the double walls. The reconstruction of the cell eliminates the burrs and preserves the plastic deformation undergone by the walls during machining.

Finally, a superposition of the two images: At this stage two images of the same cell are available, a first one containing the original cell with the burrs and a second one after treatment excluding the burrs and respecting the thickness of each wall. In order to localize the burrs, a superposition of two images is carried out which allows to observe the excess of material on the walls. Thus, the delimitation of the burr surface is possible.

3. Results and discussions

3.1. Chip formation process in aluminum honeycomb milling

The formation of chips during the machining of aluminum honeycomb is done in several steps. The circular cutting blade cuts the walls which slide on the upper face of this one until reaching the upper part of the tool which has the role to shred and to push back the chips, see fig. 5.

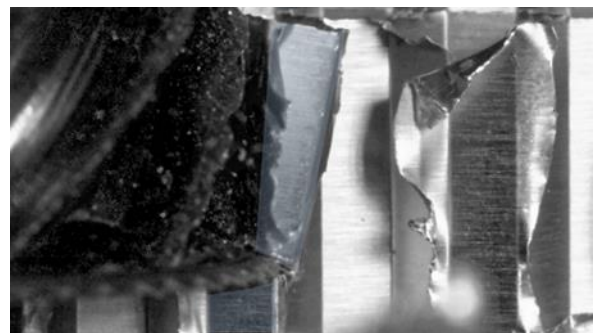


Fig. 5. Chip formation mechanisms when machining aluminum honeycomb, cutting conditions: $V_f=1000$ mm/min, $N=2000$ rpm, cutting depth=10 mm.

The cutting of the walls is done by micro impacts conditioned by the thin thickness of the walls and the feed speed per tooth. The morphology of the generated chips

depends strongly on the cutting conditions. Their size and shape change according to the tool rotation speed and the feed rate. The smallest chip is observed at low feed rates (200 mm/min) and high rotational speeds (23000 rpm). The chip size is on the order of 1 mm, see Fig. 6-b. As the rotational speed decreases, the chip size increases. Chips consisting of honeycomb walls of 6 mm in length (machining depth) and 1.4 mm in width (width of honeycomb walls) are observed, see Fig. 6-a.

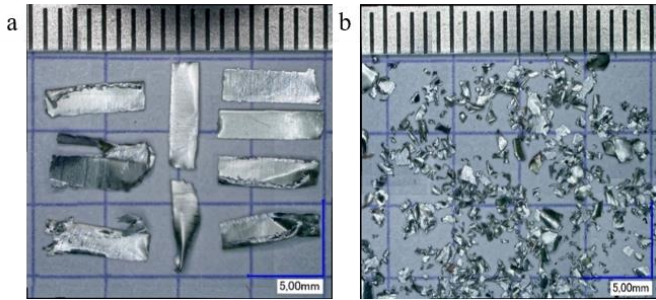


Fig. 6. Chips morphology during machining of aluminum honeycombs; (a) Vf=200 mm/min, N=2000 rpm; (b) Vf=200 mm/min, N=23000 rpm

3.2. Evolution of the machined surface according to the milling conditions

The major defect encountered when machining aluminum honeycombs is the formation of burrs. They tend to close the cells and enlarge the thickness of the walls, see Fig. 7. These burrs have sizes of about ten micrometers and are mainly formed in double walls because of their thickness. Depending on the machining conditions, other forms of burrs of larger sizes may appear.

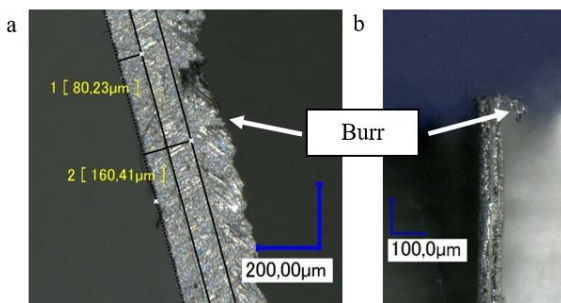


Fig. 7. Burrs at the double walls: (a) front view; (b) cross-sectional view.

Fig. 8 shows the evolution of the burr rate as a function of the cutting conditions. The best surface finish is observed for a feed rate of 200 mm/min and a rotation speed of 2000 rpm with a burr rate that does not exceed 4%. Fig. 9 shows an optical image of the machined cell under this condition. In this image the burr is identified in pink color and the reconstructed cell walls in white color. A small amount of burr is observed on the machined cell and it is located near the junction area on a double wall. For the same feed rate (200 mm/min), the surface quality deteriorates by increasing the rotation speed until reaching a burr rate of 34%. Fig. 10 shows the burr distribution

on the machined cell from the image processing. More burrs are observed at the single walls due to the bending of the walls. However, the double walls show a low level of burrs.

A different behavior is observed for the other feed rate. Contrary to the 200 mm/min feed, a decrease of the burr rate is observed with the increase of the rotation speed for the 3000 mm/min feed rate. A decrease of 70% is observed for this feed rate. A decrease in the burr rate is also observed with a change from 36% for the 2000 rpm speed to 11% for the 23000 rpm speed. For the feed rate of 1000 mm/min and 1500 mm/min, a change of pace point is observed at 10000 rpm and 15000 rpm respectively. For the 1500mm/min feed rate, the burr rate decreases from 22% to 18% between 2000 rpm and 15000 rpm before increasing to 27% at 23000 rpm. For the feed rate of 1000 mm/min, the burr rate decreases from 20% to 13% between 2000 rpm and 10000 rpm and then increases to 18% at a rotation speed of 23000 rpm.

The opposite trend of the burr rate observed in Fig. 8 are linked to the cutting mechanism for the cells walls by the tool. Indeed, the difference in diameter between the two parts of the tool makes it possible for walls to accumulate in front of the tool upper part. This accumulation depends on the machining conditions, it is greater for high feed rates and low rotational speeds. this generates a bad surface finish on the parts which results in a high burr rate. This accumulation is accentuated with the increase in the rotation speed for a feed rate of 200 mm/min, this results in an increase in the burr rate.

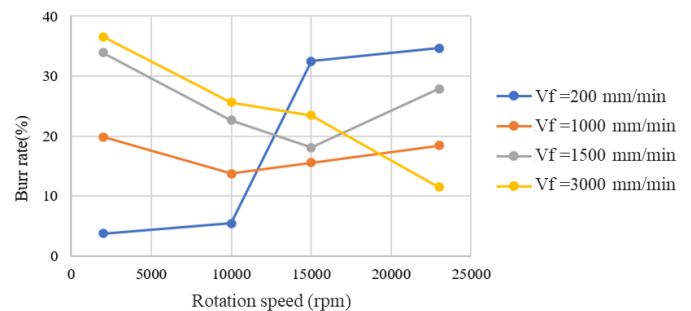


Figure 8. Evolution of the burr rate according to the cutting conditions.

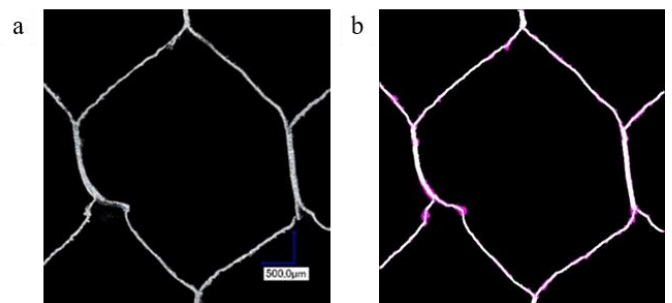


Fig. 9. Optical imaging and processing for burr limitation, cutting condition: Vf= 200 mm/min, N= 2000 rpm.

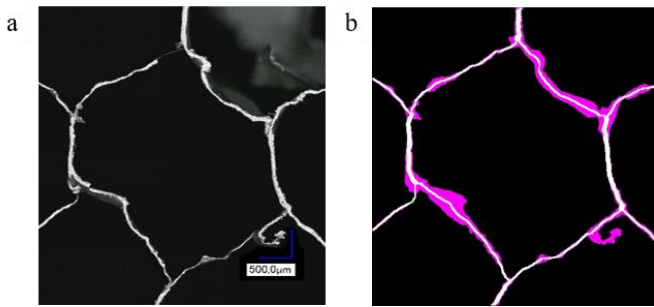


Fig. 10. Optical imaging and processing for burr limitation, cutting condition: $V_f=200$ mm/min, $N=3000$ rpm.

4. Conclusion

The machining quality of aluminum honeycomb materials is highly dependent on the amount of cut-induced defects. The defect evaluation faces methodological difficulties due to the absence of standardized techniques for this type of material.

For aluminum honeycomb, defects of walls tearing and plastic deformation of the cells are mainly observed. The ductile property of the aluminum honeycomb sheets means that their machining causes the formation of burrs that tend to close the cells. In order to characterize the importance of the rate of these burrs generated on the walls during milling, a protocol of identification and quantification was set up. It is based on the processing of images of the machined cells in several stages and allows a reconstruction of the cell to locate the burr and calculate its rate. This method allowed us to identify the optimal parameters for cutting the aluminum honeycomb. Milling with low feed rates and low rotation speeds reduces the amount of burr and thus guarantees a better machining quality. Under these conditions, the machined cells show a burr rate of less than 5%. Finally, it is shown that an optimal combination of cutting parameters can reduce or even eliminate machining defects.

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