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THE INFLUENCE OF MACHINING CONDITIONS ON THE MILLING OPERATIONS OF NOMEX HONEYCOMB STRUCTURE

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ABSTRACT

Nomex honeycomb structures are attracting increasing interest from many industrial sectors and their use is becoming more widespread. These structures are widely used in sandwich materials as lightweight structures having good mechanical properties. Due to its manufacture the machining of Nomex honeycomb structures present many technical and scientific problems, specifically the low thickness of the walls constituting the honeycomb cells, the composite nature of the paper forming the Nomex and low density of this type of these structures. The objective of this work is to implement a scientifically rigorous approach to predict and analyze the machinability of this type of material. A validation of the model was made through experimental studies with different cutting conditions. Then, a follow-up of the cutting forces and observations of the machined surface quality, using the isotropic elastoplastic approach.

1 INTRODUCTION

Machining, which is a forming process by removing material, is the most widely used process in the production of mechanical parts (automotive, aeronautics and aerospace) (Jonsons et al. 2012). It is the latter who is interested in our study, in particular the machining of Nomex honeycomb structures. These structures have many advantages, in particular a better mass / rigidity ratio, a better mechanical response out of plane and reduced maintenance. Their use varies according to the needs in industrial fields such as boating, sports and automotive, (Cognard 2012; Reyne 1998). Specific manufacturing processes are used in order to develop the closest possible shape to the desired final part, with specific mechanical properties. However, it may be necessary to complete all shaping operations with finishing operations, in most cases this is machining by cutting tool. Indeed, the main machining operations performed on composites are surfacing and milling. The machining of Nomex structures presents many: The Nomex is characterized by a low thickness of its walls, it is made of a composite material consisting of aramid fibers and phenolic resin in addition to the alveolar geometry of the nest structure bee. To avoid these problems, builders use ice water or a thermosetting resin to solidify the structure and overcome cell deformation and vibration (Norville et al. 1968; Hirayama 2004). The machining of honeycomb structures presents various formatting defects, specifically, the tearing of the walls and the name fibers cut. Machining faults can be classified according to their location and the affected component. For defects located on the machined surface, damage comes down to uncut fibers, material tearing and thermal degradation of the resin, (Geng et al 2015; Teti 2002). These defectsessentiallydepend on the used cuttingconditions.Manystudies have been experimentally investigated the influence of cutting conditions on cutting forces and surface quality for this type of material, (Karpat et al. 2012 ; Jaafar et al.2017 ; Yaozhi 2019 Xiang et al. 2019 ; Fang 2013). Several experimental studies show that Nomex honeycomb structures support out-of-plane load (Garam et al. 2018; Suchao et al. 2020). to produce complex high-quality parts, it is necessary to optimize the machining conditions. This optimization is generally based on experimental designs that are very expensive and slow to achieve. The use of modeling and numerical simulation facilitates the understanding of this interaction. Aramid paper can be modeled as an orthotropic or isotropic material (Seeman et al. 2014; Kilchert 2013; Fischer et al. 2009), the latter remains complex and requires the determination of the mechanical properties of each direction of Nomex paper, for this we have chosen the isotropic elastoplastic approach. This modeling is known for its simplicity and its reduction in terms of computing time. In this study, a finite element modeling approach of the Nomex honeycomb cutting process is proposed. the main objective is to establish a correlation between the experimental and numerical results using the elastoplastic-isotropic approach. this work provides a fairly robust numerical tool capable of modeling the mechanical behavior of Nomex honeycomb structures during milling processes. The goal is to reproduce the material removal process using a three-dimensional approach by allowing to analyze both the effect of the alveolar structure and that of the tool / wall interaction on the overall behavior.

2 STUDIED MATERIALS AND TOOLS

The milling studies were performed on the core material of the sandwich structures. The honeycomb material used is Nomex which is composed of aramid fibers and a phenolic resin. Each cell has a regular hexagonal shape with an angle of 120 °, a wall thickness of 0.06mm, and a cell size of 3.2mm. The modeled Nomex honeycomb structure consists of 10 rows and 9 columns with a total of 86 cells (Figure 1).

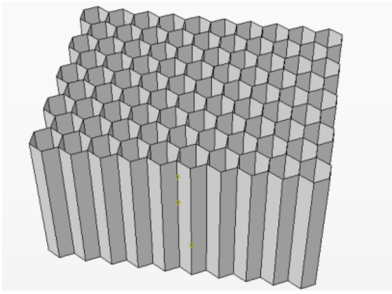

Figure 1: Diagram of the honeycomb structure.

The tool proposed for this study is the CZ10 combination tool (Figure 2) consisting of two parts mechanically assembled by a screw, a smooth circular hill with a diameter of 18.3 mm and the shredder has a 16 mm diameter which consists of ten propellers with chip breakers.

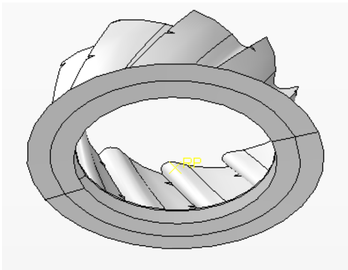

Figure 2: Combination Tool, Smooth Circular Blade and Ten Helix Chipper with CZ10 Chipbreaker.

3 DIGITAL PROCESS OF THE MILLING OPERATION

To fullyunderstand the milling process and phenomenasuch as the mechanisms of chip formation, damage and cutting forces, weused a digital machining model of the honeycomb developed by using the finite elements ABAQUS / EXPLICIT code. Our studiesfocused on the work of Foo (Foo et al. 2007) and Roy (Roy et al. 2014)attributed to the Nomex paperconstituting the honeycomb structure an isotropic elastoplastic behavior. The tool is modeled as a rigid material, whichmeans the non-attribution of mechanical and thermal properties to it. The feed rate f and the rotational speed N wereapplied the reference point where the cutting forces are calculated (Figure 3).

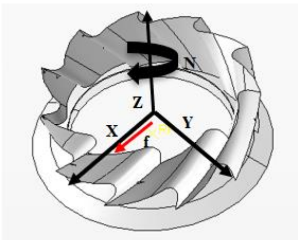

Figure 3: Cutting conditions assigned to the cutting tool, N is the speed of rotation, f is the feed rate.

The cells of the Nomex honeycomb are meshed using conventional shell elements with 4 nodes of type “S4R”, The elements size is taken about 5mm. On the other hand, the tool is meshed using 4-node quadrangular rigid elements used for three-dimensional analyzed, (R3D4). Regarding the tool / part contact, two contacts are to be considered when simulating the machining of the Nomex. The first, with the honeycomb that come into contact with the tool during its movement, this contact is defined by a surface-to-surface contact with penalty contact method. The second contact that occurs between the honeycomb walls, this contact is modeled by assigning it a general contact with the penalty contact method. The boundary conditions are adopted according to the experimental setup carried out. To prevent the part from sliding during milling, an embedding is applied (Ux = Uy = Uz = URx = URy = URz = 0). The symmetry stresses around the Y plane are applied to the walls of the honeycomb (Uy = URx = URz = 0), this eliminates all displacements of the part in the Y direction, therefore the symmetry stresses around the X plane are applied (Ux = URy = URz = 0) to the surface of the normal $\vec{x}$.

4 BIHABIOR LAW AND THE ADOPTEDBRIAKIN CRITERIA

Several works have been attributed to the Nomex paper the elastoplastic-isotropic behavior, [Nasir et al. 2015; Roy et al. 2014; Heimbs 2009]. The elastoplastic isotropic behavior is characterized by the decomposition of the total strain into an elastic strain and a plastic strain. Generally, the elastic behavior is described by Hooke's law as a linear elasticity model, Eq.1. This law describes the relationship between stresses and strains and is expressed as follows:

$$\{\varepsilon\}=[S]\{\sigma\} \quad (1)$$

Where S is the tensor of order 4 complacencies. For isotropic materials, the law is written:

$$\begin{pmatrix}\varepsilon_{11}\\ \varepsilon_{22}\\ \varepsilon_{33}\\ \varepsilon_{23}\\ \varepsilon_{31}\\ \varepsilon_{12}\end{pmatrix}=\begin{pmatrix}\frac{1}{E} & -\frac{\upsilon}{E} & -\frac{\upsilon}{E} & 0 & 0 & 0\\ -\frac{\upsilon}{E} & -\frac{1}{E} & -\frac{\upsilon}{E} & 0 & 0 & 0\\ -\frac{\upsilon}{E} & -\frac{\upsilon}{E} & \frac{1}{E} & 0 & 0 & 0\\ 0 & 0 & 0 & \frac{1}{G} & 0 & 0\\ 0 & 0 & 0 & 0 & \frac{1}{G} & 0\\ 0 & 0 & 0 & 0 & 0 & \frac{1}{G}\end{pmatrix}\begin{pmatrix}\sigma_{11}\\ \sigma_{22}\\ \sigma_{33}\\ \sigma_{23}\\ \sigma_{31}\\ \sigma_{12}\end{pmatrix} \quad (2)$$

The elastic properties are completely defined by the Young's modulus E and the Poisson's ratio υ. Thus, the shear modulus G can be expressed as a function of these two terms using the following equation:

$$G=\frac{E}{2(1+\upsilon)} \quad (3)$$

Assuming that the elastic behavior of the material is isotropic, i.e. the material has the same elastic properties in all directions, we get:

$$\sigma = 2\ \mu\varepsilon^{el} + \lambda\ \mathrm{tr}\ (\varepsilon^{el})\ \mathrm{Id} \quad (4)$$

Where μ (alsocalled G, Coulomb'smodulus) and λ are the Lame coefficients defined as followsaccording to the Young'smodulus E and the Poisson's ratio ν:

$$\lambda = \frac{\upsilon\ E}{(1+\upsilon)(1-2\upsilon)} \quad (5)$$

$$\mu = \frac{E}{2(1+\upsilon)} \quad (6)$$

The formulation of the elastoplastic behavior rests on an assumption of partition of the total strain into an elastic strain and a plastic strain. In a general three-dimensional framework, they are linked by the following relation:

$$\varepsilon = \varepsilon^{el} + \varepsilon^{p} \quad (7)$$

Where ε is the total straintensor, εel the elasticstraintensor and εp the plastic straintensor.

The mechanical propertiesattributed to Nomex paper T410 determeted by Foo (Foo et al. 2007) and Roy (Roy et al. 2014), are density ρ = 1.4 g / cm3, Young'smodulis E = 3400 MPa, and Poisson's ratio 0.3. The breakage of Nomex paper is controlled by its plastic deformation, as soon as the latter reaches the value 0.1208, the damaged element is removed to giverise to the chips.

5 CALCULATION OF MACHINING FORCES

The machining studiescarried out relate to the operation of dry milling of the Nomex honeycomb structures. In order to improve the understanding and machinability of honeycomb structures, the evolution of cutting forces is monitored during milling. This monitoring willallow us to understand the cutting mechanisms and more precisely to study the effects of cutting conditions on the forces, the machinability of the part, the chip formation and the quality of the surfaces obtained. Usuallythere are twoways to measure and identify cutting forces. The first identifies the components of the cutting force: the cutting force Fc, the feed force Ft, and the crushing force Fz in the case of milling (Figure 4). The second method is to follow and observe the overall machining cutting force generated during milling FAvg, this force is oftencalculatedaccording to the following equation (Jenarthanan et al. 2013 ; Davim et al.2004 ; Dolatabadi 2010):

$$Favg = \sqrt{F_x^2 + F_y^2 + F_z^2} \quad (8)$$

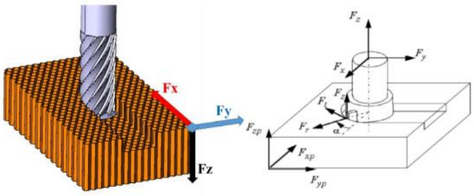

Figure 4: Diagram of the distribution of cutting forces for a milling operation.

6 RESULT AND DISCUSSION

The goal of modeling honeycomb structures is to analyze the interaction between tool and structure when machining honeycomb cells. In order to validateour model, a comparison of the cutting forces obtained by the isotropic elastoplastic approach with those obtained experimentally. The main objective is to correlatebetweennumerical and experimental studies during milling of Nomex honeycomb structures.

6.1 Effect of rotational speed on cutting forces:

A comparative study between the cutting forces measured experimentally (Jaafar 2018), and the cutting forces determined numerically with the finite element model. Figures5,6,7 and 8 shows the evolutions of the average cutting force FAvg and the different components of the cutting force (Fx, Fy and Fz) obtained experimentally and numerically as a function of the feed rate, during the milling process with the CZ10 combination tool.

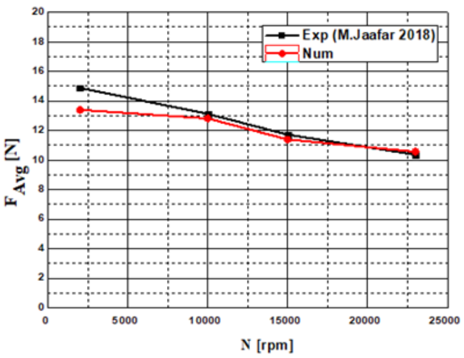

Figure 5 : Evolutions of cutting forces $F_{Avg.}$

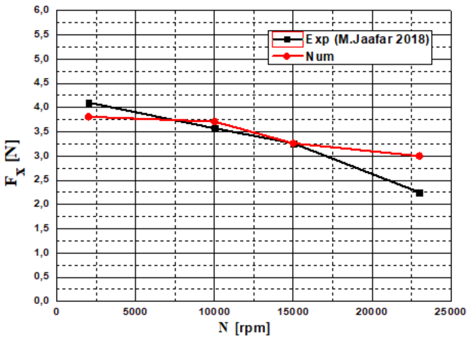

Figure 6 : Evolutions of feed forces, $F_{x.}$

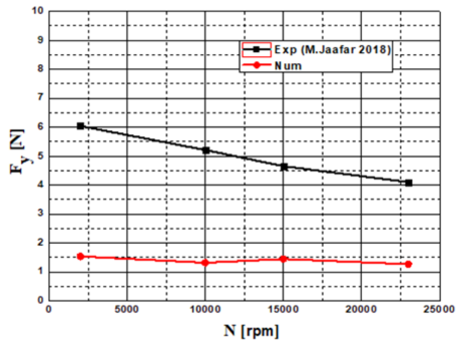

Figure 7 : Evolutions of tangential forces, Fy.

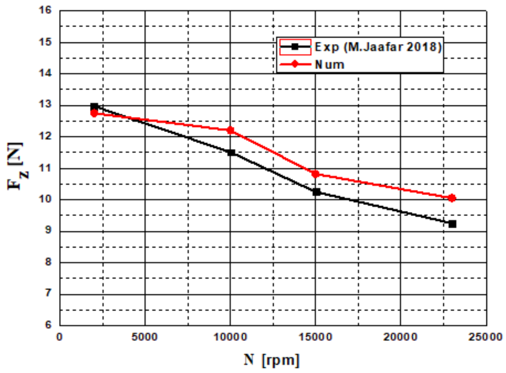

Figure 8 : Evolutions of thrust forces Fz.

For the forces Fx and Fz, the numerical model is in agreement with the experimental results where the reduction of the forces with the increase in the speed of rotation is observed. Wenoticedthat the Fy force predicted by the simulation remains far from experimental reality, this is due to the removal of damagedelements and the loss of contact of the tool associated with the failure criterion in the Abaqus code. We have noticedthat the most important component Fz for modeling and experiment, it is three times higherthan Fx and Fy, this is explained by the mechanical behavior of the honeycomb structure which is characterized by the good wall resistance in the vertical direction. Finally, our ABAQUS code with the isotropic elastoplastic approach gives a better trend with the experimental results and especially for the Fx and Fz forces.

6.2 Effect of depth of cut on cutting forces:

One of the parameters thatplays the most important role in machining forces is the depth of cut, regardless of the material beingmachined (composite or metallic) [Jaafar 2018]. Indeed, it has been shown that forces increase with increasing the depth of cut. A numerical study wascarried out to verify the effect of the depth of cut on the machining forces. In fact, a series of simulations werecarried out during milling whoseused conditions are: (f = 200mm / min N = 2000 rpm), the tool proposed for this study is the combined tool CZ10. The depths of cut studied are 2mm, 6mm, and 12mm. Figures9,10,11 and 12 shows the evolutions of the average cutting force FAvg and different components of the cutting force (Fx, Fy and Fz) obtained numerically as a function of the depth of cut.

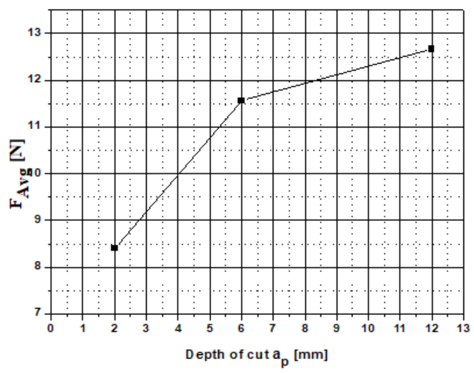

Figure 9 : Evolutions of cutting forces F_{Avg}

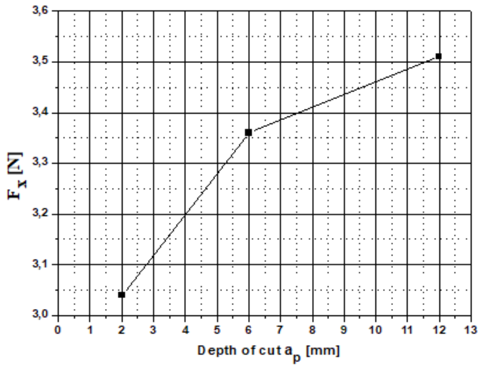

Figure 10 : Evolutions of feed forces, F_x

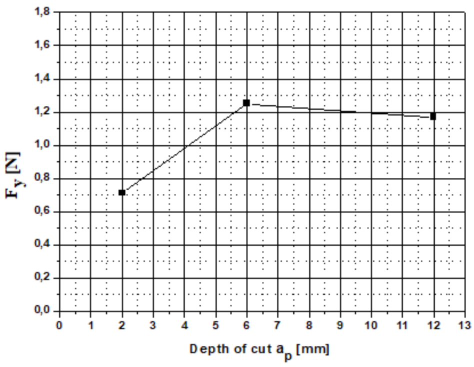

Figure11:Evolutions of tangential forces, F_y

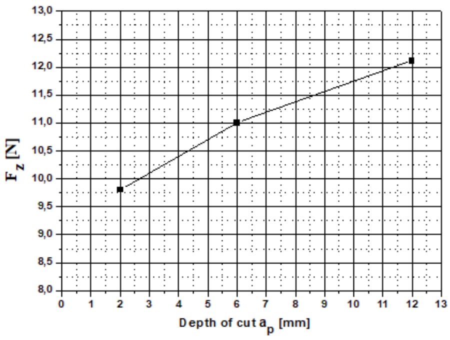

Figure 12 :Evolutions of thrust forces F_z

The main observation is that the cutting force components Fx, Fy and Fz increase with increasingdepth of cut ap almostconstantly. Generally, these results are wellcorrelated with the results obtained experimentally (Jaafar 2018, Jenarthanan et al. 2013).

6.3 The influence of machining conditions on surface quality:

The quality of the machined surface is of primary importance for the use of these sandwich material structures. However, the machining of the Nomex honeycomb is characterized by two surface quality defects, uncut aramid fibers along the machined surface and tearing of the walls. The appearance of uncut fibers is a machining defect specific to the composite material which depends on the type of fibers and their orientation (Wang and Zhang 2003). Figures 13,14and 15 shows a comparison between the machined surface resulting from the experimental tests (Jaafar 2018) and the machined surface obtained numerically according to the machining conditions. By comparing the obtained results, we note that by increasing the speed of rotation from 2000 rpm to 23000 rpm, or by reducing the speed of advance from 3000mm / min to 200mm / min the quality of the surface machined improves. Uncut fibers are observed for all cutting conditions see Figures13,14 and 15, but they are less important for the rotation speed 23000 rpm. The low speed of rotation of the tool causes the thin walls of the Nomex to bend until they tear. These defects directly influence the use of Nomex honeycomb in sandwich materials. Machining defects cause a reduction in the bond strength between the skin and the honeycomb core, (Rion et al. 2008,Tchoutouo and Gandy 2012). Generally, experimental tests seem to correlate with numerical studies (Jaafar et al. 2017; Jaafar 2018).

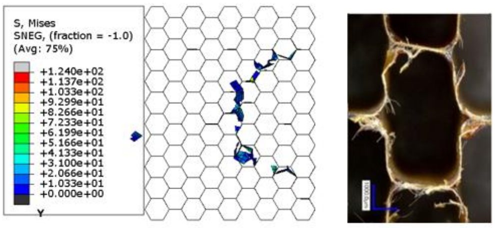

Figure 13: Comparison between the surface quality obtained during the machining of the Nomex honeycomb (Jaafar 2018)and the surface quality resulting from the digital simulation, the cutting conditions are: f = 3000 mm / min and N = 2000 rpm

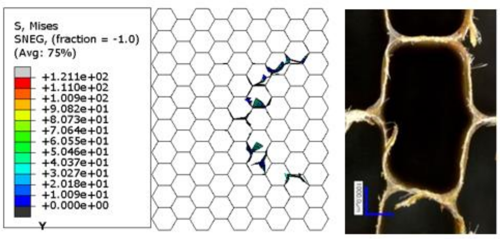

Figure 14: Comparison between the surface quality obtained during the machining of the Nomex honeycomb (Jaafar 2018) and the surface quality resulting from the digital simulation, the cutting conditions are: f = 200 mm / min and N = 2000 rpm.

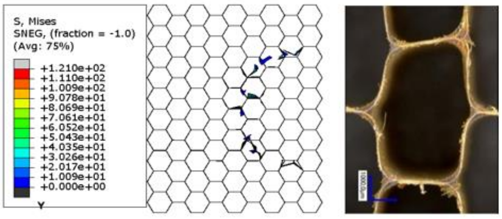

Figure 15: Comparison between the surface quality obtained during the machining of the Nomex honeycomb (Jaafar 2018)and the surface quality resulting from the digital simulation, the cutting conditions are: f = 3000 mm / min and N = 23000 rpm.

7 CONCLUSION

This article is dedicated to the 3D finite element modeling of the milling of honeycomb structures. The main contribution is to show the capacity of a global mechanical approach, integrating the couplingbetween the damage and the elastoplastic behavior of the Nomex material. Numerical modeling takesintoaccount the complex interaction between the cutting tool and the honeycomb structure. The isotropic elastoplastic approach shows Very good correspondance with those obtained experimentally, in terms of levels of cutting forces and surface quality. Cutting forces increase with depth of cut. The surface quality improves as rotational speed increases and feed speed decreases. Finally, with this model it is possible to approach a complete parametric study, thusoptimizing the milling process.

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