



HAL
open science

The Influence of Machining Conditions on The Milling Operations of Nomex Honeycomb Structure

Tarik Zarrouk, Jamal-Eddine Salhi, Samir Atlati, Merzouki Salhi, Mohammed Nouari, Najim Salhi

► **To cite this version:**

Tarik Zarrouk, Jamal-Eddine Salhi, Samir Atlati, Merzouki Salhi, Mohammed Nouari, et al.. The Influence of Machining Conditions on The Milling Operations of Nomex Honeycomb Structure. PalArch's Journal of Archaeology of Egypt/ Egyptology , 2020. hal-03325776

HAL Id: hal-03325776

<https://hal.univ-lorraine.fr/hal-03325776v1>

Submitted on 25 Aug 2021

HAL is a multi-disciplinary open access archive for the deposit and dissemination of scientific research documents, whether they are published or not. The documents may come from teaching and research institutions in France or abroad, or from public or private research centers.

L'archive ouverte pluridisciplinaire **HAL**, est destinée au dépôt et à la diffusion de documents scientifiques de niveau recherche, publiés ou non, émanant des établissements d'enseignement et de recherche français ou étrangers, des laboratoires publics ou privés.

PalArch's Journal of Archaeology
of Egypt / Egyptology

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

*Tarik Zarrouk¹, Jamal-Eddine Salhi¹, Samir Atlati², Merzouki Salhi¹, Mohammed
Nouari³ and Najim Salhi¹.*

¹Laboratory of Mechanics and Energy, Faculty of Sciences, First Mohammed University,
Oujda/60000, Morocco.

²ESTO, First Mohammed University, BP 473, Oujda, Morocco.

³LEMETA, Mines Nancy ET Albi, GIP-InSIC, France

**Tarik Zarrouk¹, Jamal-Eddinesalhi¹, Samir Atlati², Merzouki Salhi¹, Mohammed
Nouari³ and Najimsalhi¹. The influence of machining conditions on the milling
operations of nomex honeycomb structure– Palarch's Journal Of Archaeology Of
Egypt/Egyptology 17(2) (2020), 1-11. ISSN 1567-214X.**

**Keywords: Honeycomb, Nomex, Milling, isotropic elastoplastic, Numerical modeling,
surface quality.**

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 defects essentially depend on the used cutting conditions. Many studies have been experimentally investigated the influence of cutting conditions on cutting forces and surface quality for this type of material, (Karpal 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).

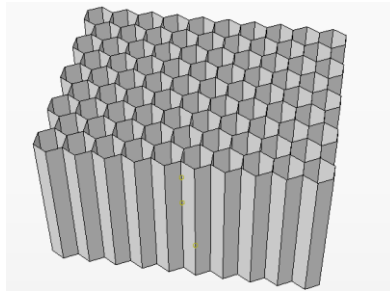


Figure 1: Diagram of the honeycomb structure.

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.

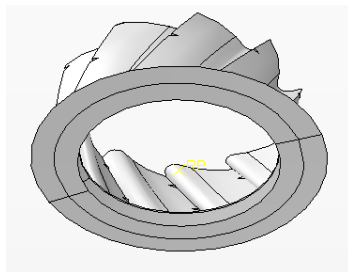


Figure 2: Combination Tool, Smooth Circular Blade and Ten Helix Chipper with CZ10 Chipbreaker.

3 DIGITAL PROCESS OF THE MILLING OPERATION

To fully understand the milling process and phenomena such as the mechanisms of chip formation, damage and cutting forces, we used a digital machining model of the honeycomb developed by using the finite elements ABAQUS / EXPLICIT code. Our studies focused on the work of Foo (Foo et al. 2007) and Roy (Roy et al. 2014) attributed to the Nomex paper constituting the honeycomb structure an isotropic elastoplastic behavior. The tool is modeled as a rigid material, which means the non-attribution of mechanical and thermal properties to it. The feed rate f and the rotational speed N were applied the reference point where the cutting forces are calculated (Figure 3).

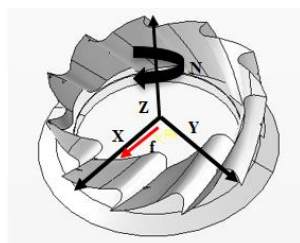


Figure 3: Cutting conditions assigned to the cutting tool, N is the speed of rotation, f is the feed rate.

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 ($U_x = U_y = U_z = U_{Rx} = U_{Ry} = U_{Rz} = 0$). The symmetry stresses around the Y plane are applied to the walls of the honeycomb ($U_y = U_{Rx} = U_{Rz} = 0$), this eliminates all displacements of the part in the Y direction, therefore the symmetry stresses around the X plane are applied ($U_x = U_{Ry} = U_{Rz} = 0$) to the surface of the normal x^{\rightarrow} .

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:

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

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

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

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

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

Where μ (alsocalled G, Coulomb's modulus) and λ are the Lamé coefficients defined as follows according to the Young's modulus E and the Poisson's ratio ν :

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

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

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 strain tensor, ε^{el} the elastic strain tensor and ε^p the plastic strain tensor.

The mechanical properties attributed to Nomex paper T410 determined by Foo (Foo et al. 2007) and Roy (Roy et al. 2014), are density $\rho = 1.4 \text{ g / cm}^3$, Young's modulus $E = 3400 \text{ MPa}$, 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 give rise to the chips.

5 CALCULATION OF MACHINING FORCES

The machining studies carried 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 will allow 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. Usually there are two ways to measure and identify cutting forces. The first identifies the components of the cutting force: the cutting force F_c , the feed force F_t , and the crushing force F_z in the case of milling (Figure 4). The second method is to follow and observe the overall machining cutting force generated during milling F_{Avg} , this force is often calculated according to the following equation (Jenarathanan et al. 2013 ; Davim et al. 2004 ; Dolatabadi 2010):

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

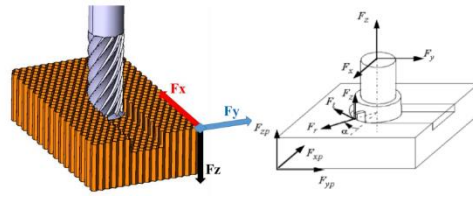


Figure 4: Diagram of the distribution of cutting forces for a milling operation.

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 validate our model, a comparison of the cutting forces obtained by the isotropic elastoplastic approach with those obtained experimentally. The main objective is to correlate between numerical 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. Figures 5, 6, 7 and 8 shows the evolutions of the average cutting force F_{Avg} and the different components of the cutting force (F_x , F_y and F_z) obtained experimentally and numerically as a function of the feed rate, during the milling process with the CZ10 combination tool.

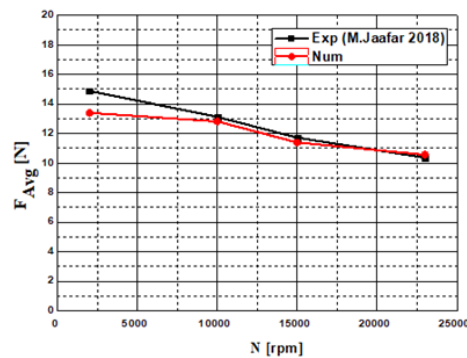


Figure 5 : Evolutions of cutting forces F_{Avg} .

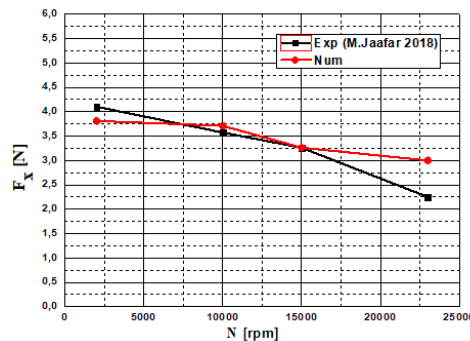


Figure 6 : Evolutions of feed forces, F_x .

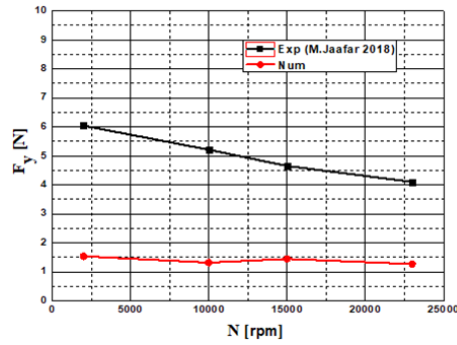


Figure 7 : Evolutions of tangential forces, Fy.

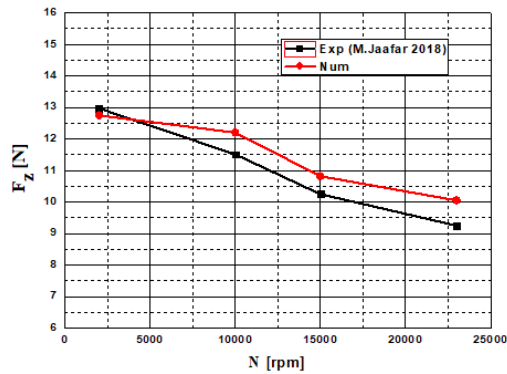


Figure 8 : Evolutions of thrust forces Fz.

For the forces F_x and F_z , 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. We noticed that the F_y force predicted by the simulation remains far from experimental reality, this is due to the removal of damaged elements and the loss of contact of the tool associated with the failure criterion in the Abaqus code. We have noticed that the most important component F_z for modeling and experiment, it is three times higher than F_x and F_y , 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 F_x and F_z forces.

6.2 Effect of depth of cut on cutting forces:

One of the parameters that plays the most important role in machining forces is the depth of cut, regardless of the material being machined (composite or metallic) [Jaafar 2018]. Indeed, it has been shown that forces increase with increasing the depth of cut. A numerical study was carried out to verify the effect of the depth of cut on the machining forces. In fact, a series of simulations were carried out during milling whose used conditions are: ($f = 200 \text{ mm} / \text{min}$ $N = 2000 \text{ rpm}$), the tool proposed for this study is the combined tool CZ10. The depths of cut studied are 2mm, 6mm, and 12mm. Figures 9, 10, 11 and 12 shows the evolutions of the average cutting force F_{Avg} and different components of the cutting force (F_x , F_y and F_z) obtained numerically as a function of the depth of cut.

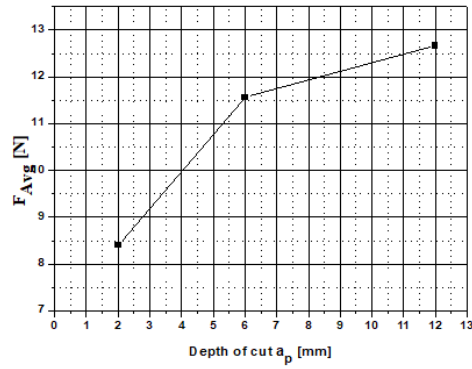


Figure 9 : Evolutions of cutting forces F_{Avg}

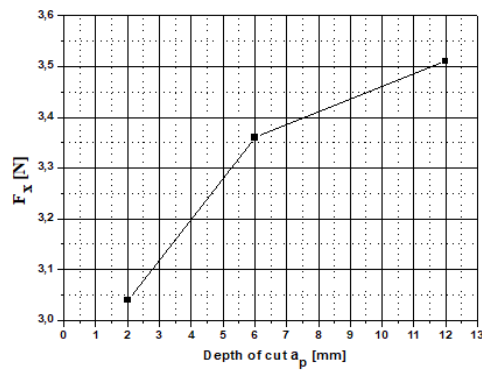


Figure 10 : Evolutions of feed forces, F_x

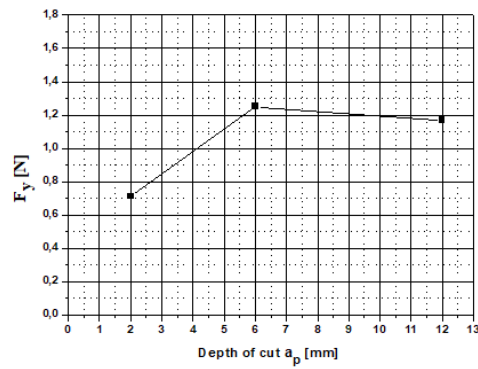


Figure11:Evolution of tangential forces, F_y

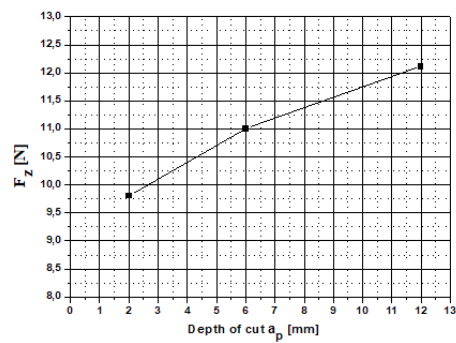


Figure 12 :Evolutions of thrust forces F_z

The main observation is that the cutting force components F_x , F_y and F_z increase with increasing depth of cut ap almost constantly. Generally, these results are well correlated 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 13,14 and 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).

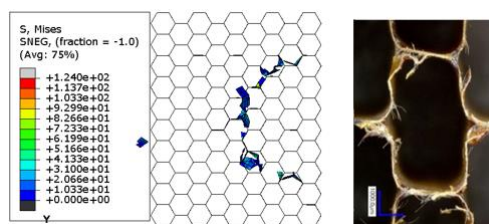


Figure 13: Comparison between the surface quality obtained during the machining of the Nomex honeycomb (Jaafar 2018) and the surface quality resulting from the digital simulation, the cutting conditions are: $f = 3000 \text{ mm / min}$ and $N = 2000 \text{ rpm}$

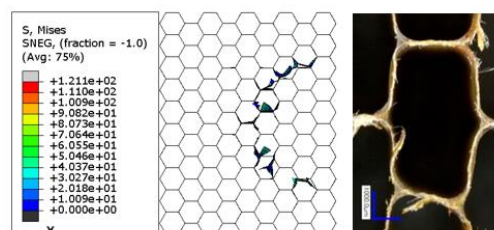


Figure 14: Comparison between the surface quality obtained during the machining of the Nomex honeycomb (Jaafar 2018) and the surface quality resulting from the digital simulation, the cutting conditions are: $f = 200 \text{ mm / min}$ and $N = 2000 \text{ rpm}$.

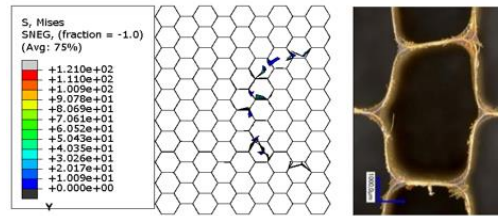


Figure 15: Comparison between the surface quality obtained during the machining of the Nomex honeycomb (Jaafar 2018) and the surface quality resulting from the digital simulation, the cutting conditions are: $f = 3000 \text{ mm / min}$ and $N = 23000 \text{ rpm}$.

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 coupling between the damage and the elastoplastic behavior of the Nomex material. Numerical modeling takes into account the complex interaction between the cutting tool and the honeycomb structure. The isotropic elastoplastic approach shows very good correspondence 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, thus optimizing the milling process.

REFERENCES

- J. Jansons, V. Kulakov, A. Aniskevich, A. Lagzdins. 2012. Structural Composites - From Aerospace To Civil Applications. Innov Technol News.
- P. Cognard. 2012. Collage des composites - Secteur aéronautique, Tech. L'ingénieur. BM7626 V1.
- M. Reyne. 1998. Les composites dans les sports et les loisirs, Tech. L'ingénieur - Matériaux / Plast. Compos (33) : 1-2.
- H. Norville, C. Madera and E. Tibor. 1968. Process for machining expanded honeycomb, U S Patent, N° 3,413,708.
- A. Hirayama. 2004. Methode for cutting honeycomb core, U S Patent, N° 6,740,268 B2.
- D. Geng, D. Zhang, Y. Xu, F. He, D. Liu, Z. Duan. 2015. Rotary ultrasonic elliptical machining for side milling of CFRP : Tool performance and surface integrity, Ultrasonics (59) : 128-137.
- R. Teti. 2002. Machining of Composite Materials, CIRP Ann. - Manuf. Technol. (51) : 611-634.
- Y. Karpat, O. Bahtiyar, B. Deger. 2012. Mechanistic force modeling for milling of unidirectional carbon fiber reinforced polymer laminates, Int. J. Mach. Tools Manuf (56) : 79-93.

- M. Jaafar, S. Atlati, H. Makich, M. Nouari, A. Moufki, B. Julliere. 2017. A 3D FE modeling of machining process of Nomex® honeycomb core: influence of the cell structure behaviour and specific tool geometry, *CIRP* (58) :505-510.
- X. Yaozhi. 2019. Study on cutting tool design and processing technology of ultrasonic-assisted cutting of honeycomb composites. (Master degree thesis) Tsinghua University, Beijing China.
- D. Xiang, B. Wu, Y. Yao, Z. Liu, H. Feng. 2019. Ultrasonic longitudinal torsional vibration-assisted cutting of Nomex® honeycomb-core composites, *Int. J. Adv. Manuf. Technol.*
- L. Fang. 2013. Development of ultrasonic milling circular tool made of NOMEX cellular materials[D]. Hangzhou, China : Hangzhou Dianzi University.
- Garam Kima. 2018. Ronald Sterkenburga, Waterloo Tsutsuib, Investigating the effects of fluid intrusion on Nomex® honeycomb sandwich structures with carbon fiber face sheets, *Composite Structures*, *compos struct* (206) : 535-549.
- Suchao Xie, Hao Wang, Chengxing Yang, Hui Zhou, Zhejun Feng. 2020. Mechanical properties of combined structures of stacked multilayer Nomex honeycombs. *Thin-Walled Structures* (151) :106-729.
- R. SEEMANN, D. KRAUSE. 2014. Numerical modelling of nomex honeycomb cores for detailed analyses of sandwich panel joints, 11th World Congr. Comput. Mech. (WCCM XI).
- S. Kilchert. 2013. Nonlinear finite element modelling of degradation and failure in folded core composite sandwich structures, Thesis, Faculty of Aerospace Engineering and Geodesy of the Universität Stuttgart.
- S. Fischer, K. Drechsler, S. Kilchert, A. Johnson. 2009. Mechanical tests for fold core base material properties, *Compos. Part A* (40) :1941-1952.
- C.C. Foo, G.B. Chai, L.K. Seah. 2007. Mechanical properties of Nomex material and Nomex honeycomb structure, *Compos. Struct* (80) :588-594.
- R. Roy, S. Park, J. Kweon, J. Choi. 2014. Characterization of Nomex honeycomb core constituent material mechanical properties, *Compos. Struct* (117) :255-266.
- M.A. Nasir, Z. Khan, I. Farooqi, S. Nauman, S. Anas, S. Khalil, A. Pasha, Z. Khan, M. Shah, H. 179 Qaiser, and R. Ata. 2015. Transverse shear behavior of a nomex core for sandwich panels (50) :733-738.
- S. Heimbs. 2009. Virtual testing of sandwich core structures using dynamic finite element simulations, *Comput. Mater. Sci* (45) :205–216.
- M.P. Jenarathanan, R. Jeyapaul. 2013. Optimisation of machining parameters on milling of GFRP composites by desirability function analysis using Taguchi method, *Int. J. Eng. Sci. Technol* (5) :23–36.
- J.P. Davim, P. Reis, C. Conceic. 2004. A study on milling of glass fiber reinforced plastics manufactured by hand-lay up using statistical analysis (ANOVA), *Compos. Struct.* (64) :493–500.
- F. Dolatabadi. 2010. Étude de l'influence du mode de lubrification sur les performances d'usinage du composite à matrices d'aluminium (Doctoral dissertation, École Polytechnique de Montréal).
- Mohamed Jaafar. 2018. Étude expérimentale et simulation numérique de l'usinage des matériaux en nids d'abeilles : application au fraisage des structures Nomex® et Aluminium. *Matériaux*. Université de Lorraine. Français. (NNT : 2018LORR0303).
- X. M. Wang and L. C. Zhang .2003. "An experimental investigation into the orthogonal cutting of unidirectional fibre reinforced plastics.pdf," *Int. J. Mach. Tools Manuf* (43) :1015–1022.
- J. Rion, Y. Leterrier, and J. E. Manson. 2008. "Prediction of the adhesive fillet size for skin to honeycomb core bonding in ultra-light sandwich structures," *Compos. Part A* (39) :1547-1555.