EXPERIMENTAL INVESTIGATION OF COMPOSITE MATERIALS DRILLING USING A STEP GUNDRILL

P. Rahme[1,*], Y. Landon[2], F. Lachaud[2], R. Piquet[2] and P. Lagarrigue[2]

[1] Lebanese University, Faculty of Engineering, Mechanical Engineering Department;
P.O. Box : 27622319, Roumieh, Lebanon
[2] Université de Toulouse ; INSA, UPS, Mines Albi, ISAE ; ICA (Institut Clément Ader) ; Bât 3R1,
118 Route de Narbonne, F-31062 Toulouse cedex 9
[*] Corresponding author, email: prahme@ul.edu.lb

Key words: Composite plates, Drilling, Gundrill, Delamination, Pilot hole

ABSTRACT

The composite materials are nowadays widely used in the aeronautical field. Drilling of the aeronautical composite parts is required in the assembly process. The study of this operation is very important for composite materials since it generates a number of defects. These defects decrease the structure resistance against failure. A solution, to reduce these defects, is to drill using a special tool. In this paper, an experimental study on the drilling of thick composite plates using a step gundrill is conducted. This tool has a special geometry designed to drill thick composite materials and hybrid materials. More particularly, it allows the drilling chips to easily feed out of the hole. A number of drilling tests is performed in this paper. The drilling thrust force of each zone of the tool is measured, as well as the total drilling thrust force. The delamination at the exit of the hole is directly related to this thrust force. It is then interesting to decrease this drilling force. Moreover, a series of punching tests is realized on blind holes drilled using this step gundrill. The aim of these tests is to determine experimentally the critical thrust force at delamination. This force indicates the resistance of the last plies to delamination. It will be, in future works, compared to the drilling thrust force in order to find the critical cutting conditions at delamination. However, in this study, the measured drilling forces are compared to the ones of a twist drill of the same diameter. An important difference is found in the results of both tools. Delamination is relatively reduced in the case of the step gundrill when using a small feed rate per tooth.

1 INTRODUCTION

The composite materials are actually widely used in the aeronautical field. Indeed, this interest is due to the composite materials resistance/weight ratio, relatively high with respect to the other classical materials. The assembly of thick composite materials requires a drilling process. The drilling of composite materials generates a number of defects at the entry, on the wall and at the exit of the plate [1]. The defects generated at the vicinity of the hole diminish the resistance of the structure against failure [2]. Rahme et al. [3] identified the drilling defects and demonstrated that the defects at the exit of the plate are the major ones. In this context, it is interesting to conduct a study on the drilling of composite materials using a step gundrill in order to reduce these drilling defects.

In the field of the composite materials, many authors studied the defects when drilling composite laminates. Indeed, Rahme et al. ([3], [4]) and Hocheng et al. [5] showed that delamination at the hole exit is directly related to the drilling thrust force. To reduce delamination at the exit of the plate, the drilling thrust force must not exceed a critical thrust force. Several authors developed analytical models to determine the critical thrust force at delamination of the laminate. Hocheng et al. [6] used a linear elastic fracture mechanics method to find the critical thrust force at delamination. Tsao et al. [7] determined the critical thrust force at delamination for a composite plate by considering the laminate as an isotropic material. Alternatively, Rahme et al. ([8]-[13]) developed an analytical model for the critical thrust force at delamination of a composite orthotropic laminate, using a twist drill, with and without pilot hole. This model is based on the works conducted by Lachaud et al. [14]. In this model, the authors considered an embedded small-diameter circular plate and non-propagated cracks,

subjected to different load cases. The critical thrust force at delamination is then found as a function of the number of non-drilled plies remaining under the drill. On the other hand, Tsao et al. [15] showed the effect of the eccentricity of the chisel edge of a twist drill on the critical thrust force at delamination. Moreover, Tsao et al. [16] predicted the location of the delamination in the plate thickness. They found the critical thrust force as a function of the axial displacement of the tool. More recently, Tsao et al. [17] added to their model the induced bending moment in order to take into account the effect of the crack opening mode III on delamination.

When drilling a composite material, the critical thrust force at delamination must be related to the cutting conditions to find the critical drilling conditions. Jinhyuk et al. [18] showed the effects of single flute gundrill geometry on the force system through relevant theories and experiments. Further, several authors proposed empirical models to describe the drilling thrust force in relation to the cutting conditions. Few studies considered a drilling force decomposed along the cutting edge of the tool. Rahme et al. [19] proposed a cutting force model linear as a function of the feed rate per tooth. Yang et al. [20] proposed another model depending of the material of the plate, of the tool geometry and the tool material. Guibert et al. [21] developed a drilling force model by decomposing the active tool geometry into several parts. They broke down the active geometry of a twist drill without thinning of the chisel edge into three zones and determined for each zone the drilling force in relation to several parameters. Moreover, Langella et al. [22] showed a semi-empirical cutting force model with several coefficients experimentally determined.

In the present paper, an experimental study is performed on drilling thick composite laminates using a step gundrill. This case is usually used to drill a hybrid sequence of material, e.g. composite/aluminium/composite. The gundrill is nowadays widely used in the hybrid aeronautical assembly line. The cracks are first initiated under the central part of the tool and they are propagated under the effect of the main cutting edges. A series of punching tests is also realized on blind holes drilled using a step gundrill. These punching tests allow finding experimentally the critical thrust force at delamination for a given number of plies remaining under the drill. In future works, this critical thrust force should be compared to the drilling force in order to find the critical cutting conditions at delamination. In this study, the active geometry of the gundrill is divided into several zones. The drilling thrust force corresponding to each zone is experimentally measured for a given feed rate and spindle speed.

2 PRESENTATION OF THE USED STEP GUNDRILL

The used step gundrill in this work has a diameter of 16 mm (Figure 1). The tool is a single flute gundrill (V-shape) having three stages and coated cutting edges with polycrystalline diamond (PCD).

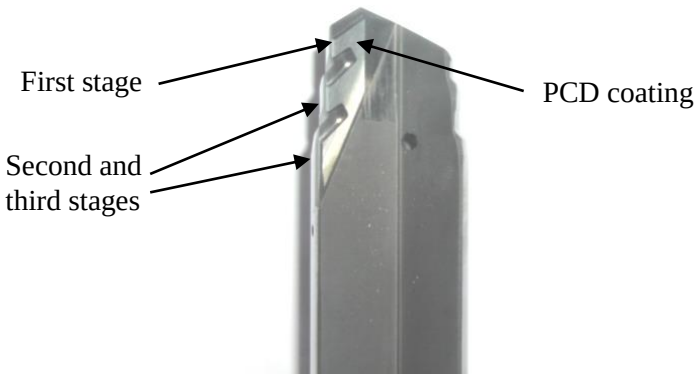

Figure 1: Gundrill geometry

This tool consists of a single step cutting edge, of tungsten (K15) coated with PCD. This type of tool is used for drilling all materials, and in particular the drilling of thick composite materials as well as of hybrid materials (composite - metal or vice versa). The gundrill is always guided by a drill bush since the tool tip is eccentric. The standard sharpening of the used gundrill is shown on Figure 2.

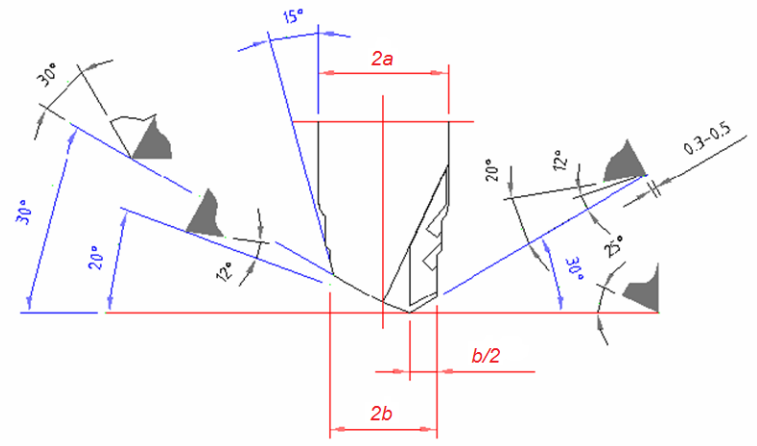

Figure 2: Standard sharpening of the used gundrill

3 PUNCHING TESTS

In this section, punching tests are performed to experimentally find the critical thrust force at delamination. Several blind holes are made and punched. A gundrill of diameter 16 mm (diameter of the third stage) is used to drill blind holes. The diameters of the first and the second stages are 13 mm and 14.5 mm, respectively. A cylindrical punch of diameter 4 mm equal to the length of the central part of the tool, that extrudes the materials, is used to punch the part of the plate located underneath the first stage (Figure 3). Also, the same gundrill is used to punch with pilot hole the part of the plate located under the second and the third stages (Figure 4). In both cases, the number of remaining non-drilled plies varies from 1 to 6 plies.

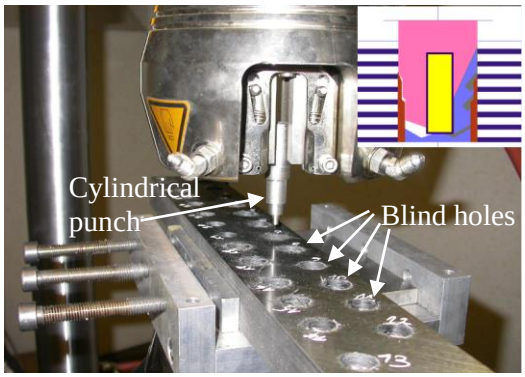

Figure 3: Punching of the part located under the first stage

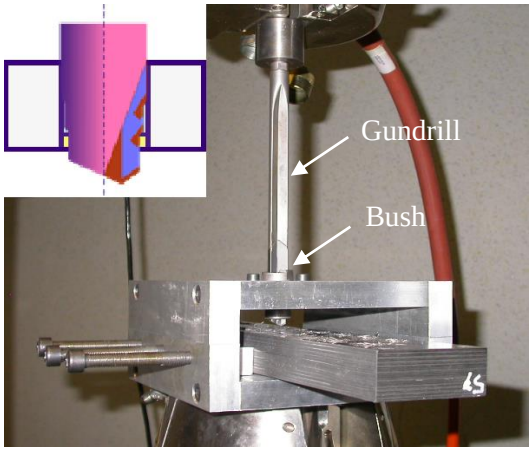

Figure 4: Punching of the plate located under the second and the third stages

The used plates are made of carbon epoxy T800/M21 of thickness 20 mm. The stacking sequence of these quasi-isotropic plates is $[90°, +45°, 0°, -45°]_{10S}$. The thickness of one ply is 0.25 mm. The forces and displacements are measured using a tension/compression Instron 8862 machine electrically operated with a maximum load of 100 kN. The critical thrust force at delamination is corresponding to the first drop in the force-time curve. Several tests are performed on blind holes, with different number of non-drilled plies. These tests are used in order to obtain the curve of the critical thrust force at delamination in function of the number of non-drilled delaminated plies. The repeatability of this test is verified and an uncertainty of 10% is found on the different measured values. The experimental results of these tests are presented in Figure 5.

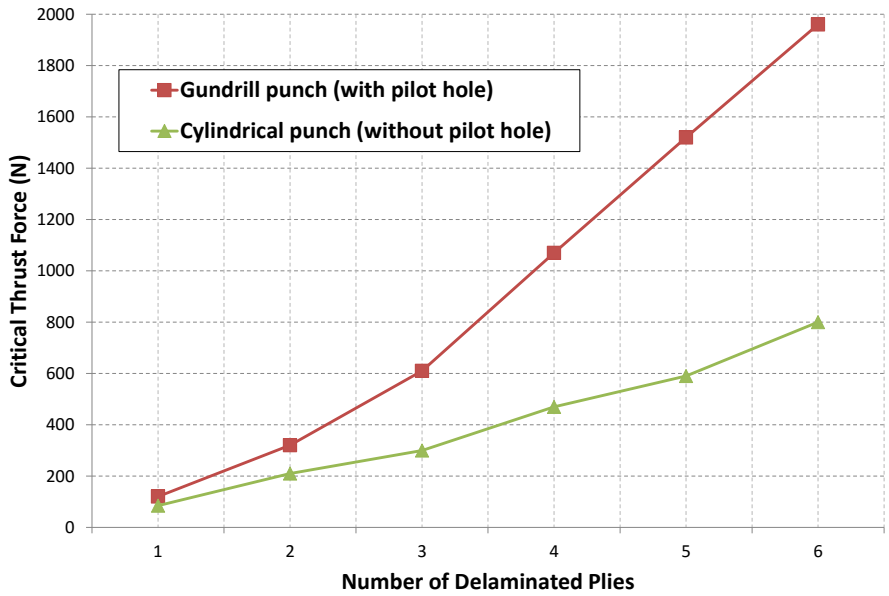

Figure 5: Critical thrust force as a function of non-drilled remaining plies, with and without pilot hole

As shown in Figure 5, the critical thrust force at delamination for drilling with pilot hole is higher than the one without pilot hole. This explains that drilling with pilot hole requires more thrust force to produce delamination. Alternatively, drilling without pilot hole, with small critical thrust force, is sensitive to delamination. Drilling with a thrust force higher than the corresponding critical force delaminates the laminate at the exit of the hole.

4 DRILLING TESTS

To relate the drilling thrust force to the feed rate in order to find the critical cutting conditions, a drilling thrust force model must be developed. To do so, the active part of the gundrill is decomposed into several zones. Since the effect of the central extrusion part of the gundrill is neglected, the different proposed zones are considered to be cutting zones. Figure 6 shows the different proposed zones of the gundrill as:

- Zone 1: the part located in the first stage between the central axis and the tool tip,
- Zone 2: the cutting edge of the first stage,
- Zone 3: the cutting edge of the second stage,
- Zone 4: the cutting edge of the third stage.

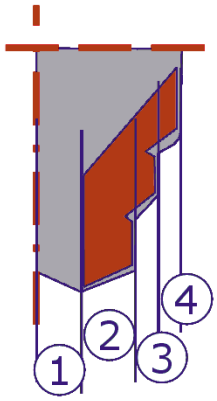

Figure 6: Decomposition of the gundrill active part into several zones

The drilling thrust force is experimentally found for each zone. A series of drilling tests is performed on multi-stage blind holes in order to measure the drilling thrust force of each zone of the gundrill. A CNC machining centre DMG DMU50eVo with a nominal power of 25 kW and a maximum rotation speed of 18,000 rev/min is used. Also, a 6-components force sensor is used to measure the drilling thrust force. The same gundrill and the same plates taken for the punching tests are used in these tests. Consequently, a gundrill having coated cutting edges with polycrystalline diamond, of diameter 16 mm, drills in these tests a carbon-epoxy composite laminate T800/M21 of 20 mm thickness and a quasi-isotropic stacking sequence ($[0°/+45°/90°/-45°]_{10S}$). The ply of this laminate has a thickness of 0.25 mm. A cutting speed of 75 m/min was chosen constant for all considered tests. In these tests, the drilling thrust force is measured by varying the feed rate per tooth. Three blind pilot holes are considered for every drilling test. These pilot holes allow determining the drilling thrust forces corresponding to the various considered zone. The diameters of the used pilot holes correspond to the diameters of zones 1, 2 and 3 of the gundrill. An example of drilling thrust force corresponding to a feed rate per tooth of 0.05 mm/tooth is shown in Figure 7.

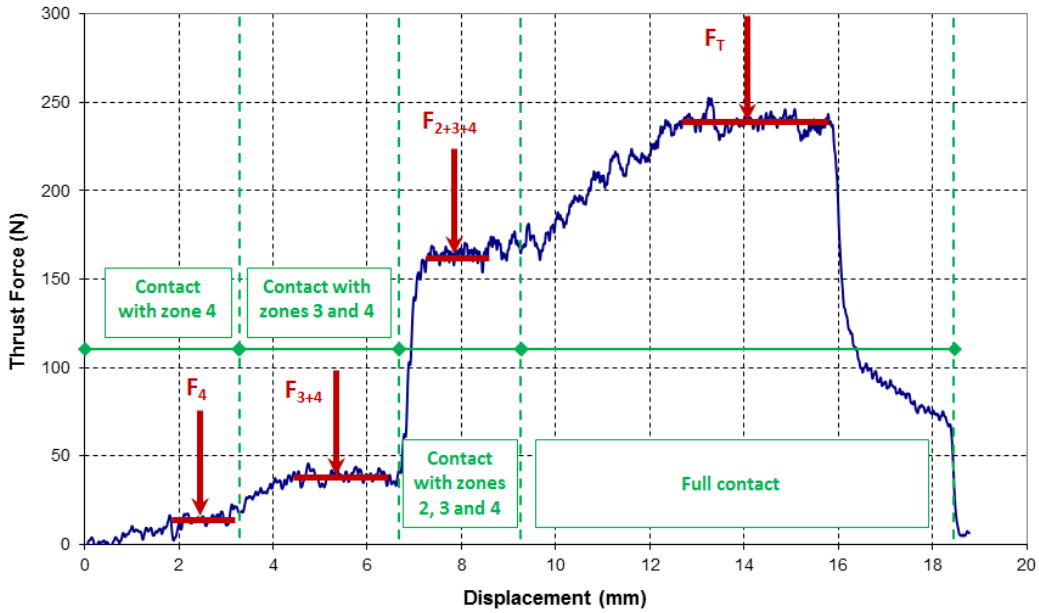

Figure 7: Drilling thrust force of different zones at 0.05 mm/tooth

The drilling thrust force of zone 4 (F_4) corresponds to the first plateau of the curve on Figure 7. This is obtained using the first pilot hole of diameter equal to the third stage diameter and the laminate is in contact with zone 4, only. When the first pilot hole is completely drilled, zone 3 is in contact with the plate. The measured drilling thrust force (F_{3+4}) corresponds to the force generated by zones 3 and

4. The thrust force corresponding to zone 3 (F_3) is, therefore, the difference of forces F_{3+4} and F_4. The same, when the gundrill comes out of the second pilot hole, zone 2 touches the material and the measured force (F_{2+3+4}) corresponds to zones 2, 3 and 4. Finally, when the gundrill is in full contact with the plate, without pilot holes, the measured force (F_T) is the total drilling force. By subtracting the different forces, the drilling thrust force corresponding to each zone of the gundrill is identified. This test is repeated by varying the feed rate per tooth. The drilling thrust force of different zones is drawn as a function of the feed rate per tooth, as shown in Figure 8. Since the drilling thrust forces corresponding to zones 3 and 4 are small, these two forces are combined and one zone is considered.

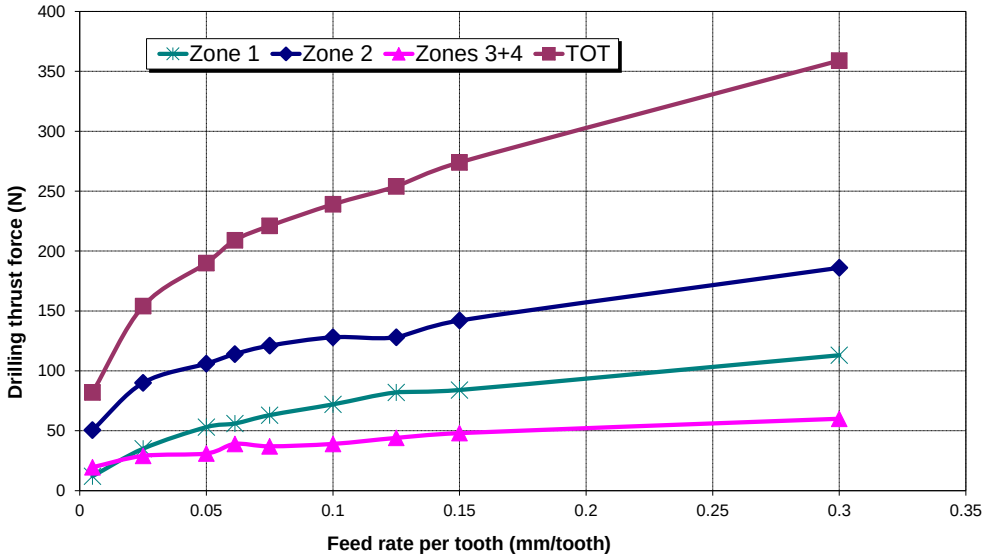

Figure 8: Experimental results of the different zone drilling thrust force in relation to the feed rate per tooth

According to the experimental drilling thrust forces, a power law curve can model the action of the different proposed cutting zone of the gundrill. While in the case of drilling using a twist drill in previous works [4], a linear model is used. A comparison of the drilling thrust force is presented on Figure 9 when using a gundrill and a conventional twist drill. The drilling thrust forces when using a gundrill are much lower than the forces generated by a twist drill. Since the defects at the exit of the hole are related to the drilling thrust force, delamination should be reduced when using a gundrill. However, a detailed study on delamination must be performed, in future works, at the exit of the hole when using a gundrill and a twist drill in order to compare the results.

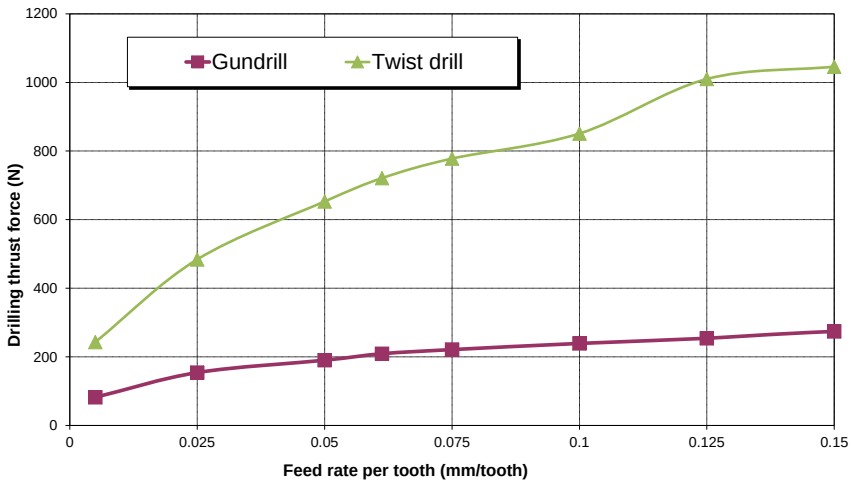

Figure 9: Comparison of drilling thrust force when using a gundrill and a twist drill

In future works, the found critical thrust force and the drilling thrust force will be related to find the critical cutting conditions when using this gundrill tool.

5 CONCLUSIONS

In this paper, an experimental study of drilling composite materials is performed when using a special step gundrill. The proposed gundrill is designed to drill thick composite materials as well as hybrid materials. The main objective of using this tool is to reduce delamination at the exit of the hole. This delamination is directly related to the drilling thrust force. Reducing the drilling thrust force will reduce accordingly delamination. A series of punching tests is made on blind holes drilled using the step gundrill. The critical thrust force at delamination is then experimentally found. The first important drop in the punching force corresponds to the critical thrust force. This force corresponds also to the resistance of the last plies to delamination. The critical thrust force is found for both cases, with and without pilot hole. More, a number of drilling tests is performed in this paper. Pilot holes are used to determine the drilling thrust force of each zone of the active tool geometry. The diameters of these pilot holes is taken equal to the diameters of the different stages of the gundrill. The total drilling thrust force is also measured. This measured total drilling thrust force is compared to the force obtained when drilling with a twist drill of the same diameter. An important difference is found in the results. The results of drilling when using the proposed gundrill are then promising. In future works, the critical cutting conditions at delamination will be found by relating the critical thrust force and the drilling thrust force for this tool.

ACKNOWLEDGEMENTS

We are grateful for the materials resources provided by AIRBUS Toulouse France. We thank Cédric Leroy, Benoît Marguet and Jacques Bourriquet for helping and supporting us in this work.

This work was carried out within the context of the working group Manufacturing 21 which gathers 18 French research laboratories. The topics approached are:

- The modelling of the manufacturing process,
- The virtual machining,
- The emerging of new manufacturing methods.

This project has been funded with support from the Lebanese University.

REFERENCES

[1] R. Piquet, B. Ferret, F. Lachaud and P. Swider, Experimental analysis of drilling damage in thin carbon/epoxy plate using special drills, *Composites: Part A*, **31**, 2000, pp. 1107-1115.

[2] H. Hocheng and C.C. Tsao, The path towards delamination-free drilling of composite materials, *Journal of Materials Processing Technology*, **167**, 2005, pp. 251-264.

[3] P. Rahme, Y. Landon, F. Lachaud, R. Piquet and P. Lagarrigue, Study into causes of damage to carbon epoxy composite material during the drilling process, *International Journal of Machining and Machinability of Materials*, **3**, No. ¾, 2008, pp. 309 – 325.

[4] P. Rahme, Y. Landon, F. Lachaud, R. Piquet and P. Lagarrigue, Delamination-free drilling of thick composite materials, *Composite Part A: Applied Science and Manufacturing*, **72**, 2015, pp.148 – 159.

[5] H. Hocheng and C.C. Tsao, Comprehensive analysis of delamination in drilling of composite materials with various drill bits, *Journal of Materials Processing Technology*, **140**, 2003, pp. 335-339.

[6] H. Hocheng and C.K.H. Dharan, Delamination during drilling in composite laminates, *ASME Journal of Eng. Ind.*, **112**, 1990, pp. 236-239.

[7] C.C. Tsao and W.C. Chen, Prediction of the location of delamination in the drilling of composite laminates, *International Journal of Materials Processing Technology*, **70**, 1997, pp. 185-189.

[8] P. Rahme, Y. Landon, P. Lagarrigue, F. Lachaud and R. Piquet, Analytical models of composite material drilling, *Int. J. of Advanced Manufacturing Technology*, **52**, 2011, pp. 609-617.

[9] P. Rahme, Y. Landon, F. Lachaud, R. Piquet and P. Lagarrigue, Drilling of thick composite material with a small-diameter twist drill, *International Journal of Advanced Manufacturing Technology*, **76**, 2015, pp. 1543-1553.

[10] P. Rahme, Y. Landon, P. Lagarrigue, F. Lachaud and R. Piquet, Drilling thick composite materials using large diameter drills, *Int. J. of Machining and Machinability of Materials*, **10**, 2011, pp. 202-211.

[11] P. Rahme, Y. Landon, P. Lagarrigue, R. Piquet, F. Lachaud, B. Marguet, J. Bourriquet and C. Leroy, Chisel edge effect on delamination when drilling thick composite materials with a twist drill, *SAE International Journal of Aerospace*, **1**, 2009, pp. 776-781.

[12] P. Rahme, Y. Landon, R. Piquet, F. Lachaud and P. Lagarrigue, Drilling of thick composite structures with pilot hole using a twist drill, *16th European Conference on Composite Materials, Seville, Spain, June, 2014*.

[13] P. Rahme, Y. Landon, R. Piquet, F. Lachaud and P. Lagarrigue, Analytical model for pre-drilled thick composite plates, *Joint Conference on Mechanical, Design Engineering & Advanced Manufacturing, Toulouse, France, June, 2014*.

[14] F. Lachaud, R. Piquet, F. Collombet and L. Surcin, Drilling of composite structures, *Composite Structures*, **52**, 2001, pp. 511-516.

[15] C.C. Tsao and H. Hocheng, Effect of eccentricity of twist drill and candle stick drill on delamination in drilling composite materials, *International Journal of Machine Tools & Manufacture*, **45**, 2005, pp. 125-130.

[16] C.C. Tsao and H. Hocheng, Effects of peripheral drilling moment on delamination using special drill bits, *Journal of Materials Processing Technology*, **201**, 2008, pp. 471-476.

[17] C.C. Tsao, Effect of induced bending moment (IBM) on critical thrust force for delamination in step drilling of composites, *International journal of Machine tools and Manufacture*, **59**, 2012; pp. 1-5.

[18] J. Jinhyuk and K. Feng, A gundrilling force system, *International Journal of Machine Tools and Manufacture*, Vol 47, Issues 7-8, 2007, pp. 1276-1284.

[19] P. Rahme, Y. Landon, P. Lagarrigue, R. Piquet, F. Lachaud, B. Marguet, J. Bourriquet and C. Leroy, Drilling of thick composite structures – State of the art, *Proceedings of SAE International, Toulouse, France, September, 2006.*

[20] J.A. Yang, V. Jaganathan and R. Du, A new dynamic model for drilling and reaming processes, *International Journal of Machine Tools & Manufacture*, **42**, 2002, pp. 299-311.

[21] N. Guibert, H. Paris and J. Rech, A numerical simulator to predict the dynamical behavior of the self-vibratory drilling head, *International Journal of Machine Tools & Manufacture*, **48**, 2008, pp. 644-655.

[22] A. Langella, L. Nele and A. Maio, A torque and thrust prediction model for drilling of composite materials, *Composites: Part A*, **36**, 2005, pp. 83-93.