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Drilling of Composite Laminates- A Review

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***Abstract:** The emerging trends of material technology strived the development of composite materials. This enhanced properties of composite materials promoted their applications in automotive and aerospace industry. Laminated composites found wide spread applications in contrast to others due to their ease of manufacture. Machining of laminated composites is essential to have functional upshots; out of which drilling is the key operation needed for fabrication. In this paper a critical review on mechanical drilling of composite laminates is presented. It is aimed to cover drilling operations, drill bit geometry and materials, delamination in drilling and its remedies, thrust force and tool wear. The readers should acquire the knowledge of mechanical drilling of composite laminates and its hurdles, so that one can take necessary precautions to have effective and efficient operation.*

1. INTRODUCTION

Composites are proved to be the effective constructive materials for present day industry due to their excellent properties. The superior advantages (such as high strength-to-weight and stiffness-to-weight ratios) of composite materials led them to replace convention metallic materials in a wide range of industries including aerospace, aircraft and defense [1-3].

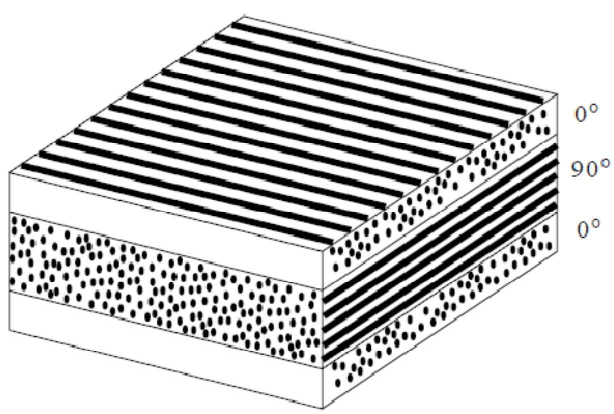

Figure 1. Composite laminate

A widely used geometry for continuous fiber composites is the laminate. Laminates are made of plies, in which all fibers often have the same direction. The fibers are usually much stronger and stiffer than the matrix so a ply is stiffer and stronger in the fiber direction - it is anisotropic. A laminate, such as the one shown in Figure 1, usually contains plies with different fiber directions even if the load is primarily in one direction. The reason is that a laminate with fibers in only one direction would be very weak in the direction transverse to the fibers, and small transverse loads due to uneven lateral contraction, for example, could trigger fracture of such a laminate. Laminate geometry is described by the direction of the fibers in its plies. The laminate in Figure 1 would, for example be labeled [0/90/0].

Drilling operations on composite laminates is essential for fastening with other materials to have useful outcomes [4]. The fastening efficiency and excellence is relied on the quality of drilled hole. Producing error free précised holes is desired to ensure high joint strength during assembling of materials by riveting or bolting. However, the peculiarity (non-homogeneous, anisotropic and highly abrasive and hard reinforced fibers) of composite laminate constituents poses hurdles during machining [5, 6]. Several undesirable damages (such as delamination and fiber pull-out) induced by drilling drastically reduce strength against fatigue, thus degrading the long-term performance of composite laminates [7]. The peel up and push out damages are shown in Figure 2.

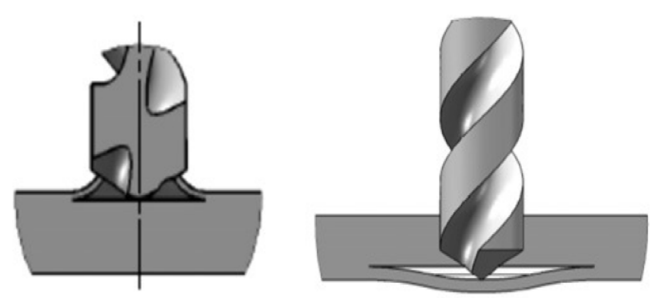

Figure 2. Peel up Damage Push out Damage

Among the various forms of material damage, delamination due to drilling is one of the major concerns in machining a composite laminate. It was reported that, in aircraft industry, the rejection of parts consist of composite laminates due to drilling-induced delamination damages during final assembly was as high as 60% [8]. The thrust force has been cited as the primary cause of the delamination [9]. The delamination may arise at the entry or exit of the drill bit during process and is shown in Figure 3 [10].

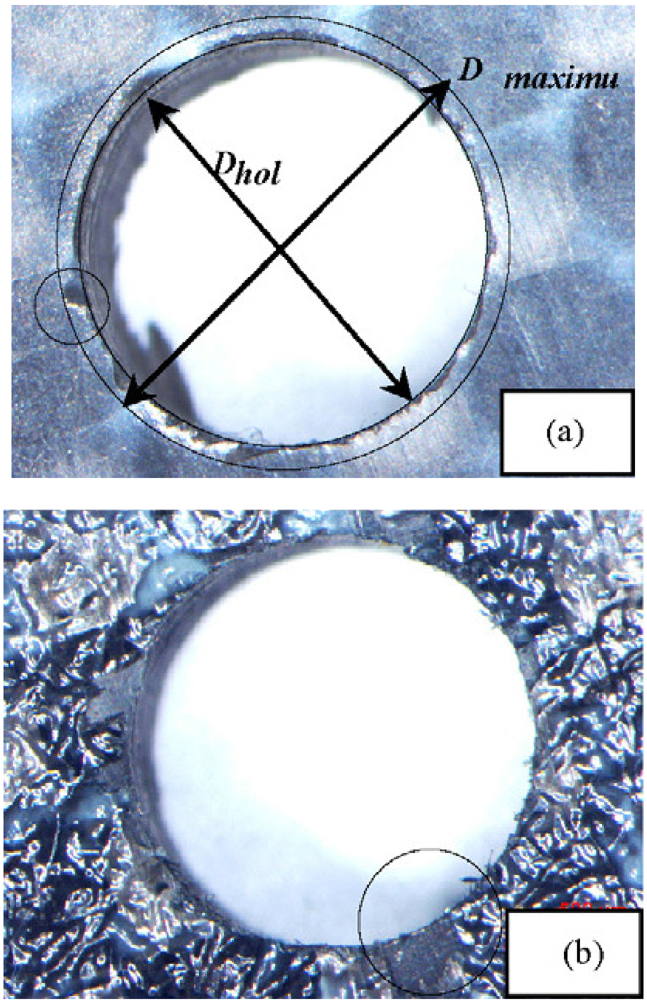

Figure 3. Delamination (a) Entry Delamination (b) Exit Delamination [10]

The present work is aimed to provide a comprehensive review on mechanical drilling of composite laminates. Several critical aspects of drilling of laminates for various types of composites are presented and discussed.

2. DRILLING OF COMPOSITES

S. Jain et al [8] studied drilling on composite laminates. It has been demonstrated that the critical thrusts and feed rates obtained for unidirectional laminates can be conservatively used for multi-directional laminates. With regard to the tool geometry, the chisel edge width appears to be the single most important factor contributing to the thrust force and hence delamination. Application of diamond-impregnated tubular drill tool was resulted much smaller thrust and much better hole quality as compared with the standard twist drills. I.singh et al[11] aimed to correlate drilling-induced damage with drilling parameters. Tool point geometry is considered a major factor that influences drilling-induced damage. The results established that the cutting speed to feed ratio as an important variable that influences drilling-induced damage. E M.A. Azmir et al[12] analyzed the feed rate, spindle speed and type of tool materials on thrust force and delamination. It was observed that the increase in federate and spindle speed promotes thrust force and subsequently delamination occur. The split point fibre (SPF) drill gave the lowest values of thrust force and delamination.

T. N. Valarmathi et al [13] studied the influence of cutting parameters in a systematic approach on delamination in drilling of prelaminated Medium Density Fiberboard wood panels with High Speed Steel (HSS) twist drills of different diameters. The results revealed that the most dominant factor which influences the delamination is feed rate followed by the drill diameter. The drilled hole with minimum delamination was obtained at high spindle speed, low feed rate and small drill diameter combinations.

H. Ho-Cheng et al [14] analysed delamination failure for a composite laminate using a fracture mechanics approach in which the opening-mode delamination fracture toughness. The analysis predicted that an optimal thrust force (defined as the minimum force above which delamination is initiated) exists which is a function of drilled hole depth. In addition, the optimal thrust force for delamination free drilling can be used to control the machine. P. Y. Andoh et al [15] used acoustic emission signal technique for determining the initiation of delamination. L. M. P. Durao et al [16] presented a comparative study on different drill point geometries and feed rate for composite laminates drilling is presented. For this goal, thrust force monitoring during drilling, hole wall roughness measurement and delamination extension assessment after drilling is conducted. Delamination was evaluated using enhanced radiography combined with a dedicated computational platform that integrates algorithms of image processing and analysis. An experimental procedure was planned and consequences were evaluated. Results show that a cautious combination of the factors involved, like drill tip geometry or feed rate, can promote the reduction of delamination damage.

Mathew J. et al. [17] studied that thrust is a major factor responsible for delamination and it mainly depends on tool geometry and feed rate. Trepanning tools, which were used in this study, were found to give reduced thrust while making holes on thin laminated composites. In this work the peculiarities of trepanning over drilling of unidirectional composites were emphasized. The models for prediction of critical thrust and critical feed rate at the onset of delamination during trepanning of unidirectional composites based on fracture mechanics and plate theory were also presented. Mathematical models correlating thrust and torque with tool diameter and feed rate were developed through statistically designed experiments. It was observed that sub-laminate thickness is the most decisive parameter from the viewpoint of critical feed rates.

3. DRILLING OF GFRP COMPOSITE LAMINATES

Khashaba et al. [18] investigated the effect of drill pre-wear and machining conditions (feed and speed) on the machinability parameters (thrust force, torque, peel-up and push-out delaminations and surface roughness) in drilling GFRE composites. It is observed that the influence of cutting speed on thrust force in drilling woven-ply GFRP composite laminates varied with tool wear, but the influence suppresses for fresh drill bits. At high cutting speed and feed the drill pre-wear promotes the effect of peel-up and push-out delaminations and also leads to destruction of the matrix and micro-cracking at the ply interfaces, which deteriorates the surface finish.

Abrao et al [19] studied the effect of the cutting tool geometry and material on the thrust force and delamination during drilling of a glass fiber reinforced epoxy composite laminate with four drills with distinct geometries and composition by varying the cutting parameters. The results demonstrated that the drill responsible for the highest thrust force was also responsible for the second smallest delaminated area. Within the cutting range tested the damaged area increased considerably with feed rate and moderately with cutting speed.

Khashaba UA et al [20] Performed experimental analysis varying machining variables for thrust force and machinability parameters (delamination size, surface roughness, and bearing strength) evaluation during drilling of woven GFRE composites. The results revealed that the delamination size was proportional to feed and drill diameter due to the increasing of thrust force. Surface roughness increases with increasing the cutting feed.

J.Ramkumar et al [21] studied the effect of workpiece vibration on drilling of glass/epoxy (UD-GFRP) laminates using three types of drill, e.g. tipped WC, 2-flute solid carbide and 3-flute solid carbide. The drilling tests were performed at optimum cutting conditions for which thrust, power and tool wear are minimum. It was observed due to the vibration of the workpiece during drilling the parameters namely Thrust, tool wear, temperature, power and AE (RMS value) are very much reduced.

P.Mehbudi et al [22] conducted ultrasonic assisted drilling tests on GFRP laminates to reduce thrust force and delamination by the application of vibrations and rotation to drill bits. The results show that applying ultrasonic vibration reduces the thrust force and therefore the drilling induced delamination dramatically up to 50 per cent. It was concluded that increasing vibration amplitude leads to significant reduction in thrust force and delamination damage.

A.Sadek et al [23] conducted Vibration-assisted drilling (VAD) on CFRP laminates to reduce thermal and mechanical defects. the effect of the process parameters (speed, feed, frequency, and amplitude) in the low frequency–high amplitude regime (<200 Hz, <0.6 mm) on the hole quality attributes were predicted using machinability maps. The yielded optimized VAD conditions reduced the cutting temperature by 50% and the axial force by 40% and delamination-free holes were produced without affecting productivity.

Capello E, Tagliaferri V [24] studied the effect of the drilling on the residual mechanical behavior of glass fiber reinforced plastic (GFRP) laminates when the hole is subjected to bearing load. Moreover, the effects of drilling with or without a support beneath the specimens are analyzed and discussed. Feed rate is the major factor which had stringent effect on Push-down delamination in the presence of support beneath the specimen

Capello, E., et al [25] investigated the effect of drilling conditions on the residual mechanical behavior of GFRP laminates subjected to a bearing load under static and cyclic dynamic conditions. The Results characterized that the main cause for the mechanical failure is the micro damage generated at the inner part of the hole surface, while the delamination failure is nominal.

R. Piquet et al [26] proposed a specific cutting tool to suppress or avoid several defects and damages (entrance damage, roundness and diameter defects and plate exit damage) usually encountered in twist drilled holes on carbon/epoxy composite laminates. High Speed machining carried out for drilling GFRP ensures low damage levels [27].

V. Krishnaraj et al [28] analysed the influence of drilling parameters (spindle speed and feed) on the strength of the GFR woven fabric laminates and further studied the residual stress distribution around the hole after drilling. Feed rate and spindle speed were found to be the significant factors which influence Degree of damage. Experimental results indicated that failure strength and stress concentration are related to the drilling parameters.

Velayudham et al [29] studied the dynamics of drilling of high volume fraction glass fiber reinforced composite. At high fiber volume, fibers do not show much relaxation and normal hole shrinkage associated with polymeric composites was not observed during drilling. It is concluded that the higher cutting speeds and feed yields marginal variation in thrust and wear with smoother drilling.

Vikas Dhawan et al[30] investigated the effect of spindle speed and feed rate on thrust force generated in drilling glass fiber-reinforced plastics with natural fillers namely coconut coir, rice husk, and wheat husk as fillers along with synthetic glass fibers. The drilling experiments have been extensively conducted at six different levels of feed rate and spindle speed using carbide twist drills of 4 mm. Predictive model has been developed using Levenberg–Marquardt algorithm to predict the thrust force with material, spindle speed, and feed rate being the input parameters and thrust force being the output parameter.

4. DRILLING OF CFRP COMPOSITES

R. Zitoune et al [31] conducted the experimental analysis of the orthogonal cutting applied to unidirectional laminates in carbon/epoxy for various angles between the direction of fibers and the tool cutting direction (cutting speed). The numerical modeling of the orthogonal cutting in statics for the simple case of fibers orientated at 0^0 with respect to the tool's cutting direction is presented. The great influence of the angle between the fiber orientation and the direction of cutting speed of the tool is observed on the chip formation as well as the rupture modes. Numerical computation is based on the fracture process and more particularly on the computation of the energy release rate by the method Virtual Crack Extension (using the software, SAMCEF).

U.A. Khashaba et al [32] studied the effects of the drilling parameters, speed and feed on the cutting forces, torques and delamination in drilling chopped composites with different fiber volume fractions. At elevated feeds the thrust and torque reduces with increase in cutting speed. No clear effect of the cutting speed on the delamination size is observed, while the delamination size decreases with decreasing the feed.

Nagaraja et al [33] aimed to minimize the drilling induced delamination in bi-directional carbon fiber reinforced epoxy composite (BCFREC) laminate by using high speed steel drill at different feed rate and spindle speed. Thrust force has been cited as the main cause of delamination. The results revealed that the delamination tendency, thrust force and torque increase with the increase in feed rate and spindle speed. Furthermore, the study indicated that the effect of spindle speed on thrust force and torque is not significant and lower feed rate has to be used for higher spindle speed in HSS drill in order to reduce the delamination damage

L.M.P Durao et al [34] proposed that the source for the delamination occurrence is the indentation caused by the drill chisel edge. It was observed that the Low feed rates were found to be suitable for suppressing the axial thrust force and consequently delamination in composite laminate drilling. Moreover, low feeds minimize the loss of mechanical strength of the drilled part.

It was concluded that delamination could be avoided with proper selection of combination of the factors involved, like tool material, drill geometry or cutting parameters

Vaibhav A et al [35] simulated drilling CFRP laminated composite using three dimensional finite element analysis. It was observed that the thrust force, torque and delamination damage increased abruptly with an increase in the feed rate, but reduced gradually with increasing cutting speeds. Numerical studies indicated that low feed rates and high cutting speeds are ideal for drilling carbon/epoxy laminates.

Jean François Chatelain et al [36] studied the effect of using a configurable setup to support parts on the resulting quality of drilled holes of CFRP laminates. The results demonstrated that the damage is due to the combination of two main factors: the spring-back of the thin part and the thrust force. When the distance between supports is increased, it is observed that the spring-back increases but the thrust force decreases. Using high cutting speeds and a low feed, it was possible to completely eliminate the observable damage.

Luís Miguel P. Durão[37] drilled quasi-isotropic hybrid laminates with 25% of carbon fiber reinforced plies of 4 mm thickness. Three different drill geometries are compared. From the results it is observed that drill geometry had significant influence on delamination.

Wen chou-chen [38] investigated the variations of cutting forces with or without onset of delamination during drilling operations on CFRP composite material varying the tool geometry and drilling parameters. The experimental results demonstrated that the proper selection of tool geometry and operating parameters produce delamination-free drilling process. Experimental results indicated that the flank surface temperatures increase with increasing cutting speed but decreasing feed rate which influences Delamination.

5. CONCLUSIONS

An overview of mechanical drilling on composite laminates is presented. Drilling of composite laminates differs significantly in many aspects from drilling of conventional metal and their alloys. Delamination is observed to be the serious damage arising during drilling of composite laminates. Both thrust force and torque are responsible for delamination during drilling of composites still there is no comprehensive mathematical model consisting of these parameters. There are some empirical models of delamination and thrust force for drilling of composite laminates, but they would not be sufficient to emphasize the physical meaning of drilling of composite laminates. Generally, the use of low feed rate and high cutting speed favor the minimum drilling-induced delamination and extend tool life. The hole quality can be improved by using special drill bits, support plate, pre-drilled pilot hole, vibration-assisted twist drilling and high speed drilling.

REFERENCES

[1] Soutis C., “Fibre reinforced composite in aircraft construction”, *Progress in Aerospace Science,* 41, 2005, pp.143–51.

[2] Davim JP, Reis P, Antonio CC., “Experimental study of drilling glass fiber reinforced plastics (GFRP) manufactured by hand lay-up”, *Composites Science Technology,* 64, 2004, pp.289–97.

[3] Sinmazçelik T, Avcu E, Bora MÖ, Çoban O., “A review: fiber metal laminates, background, bonding types and applied test methods”, *Materials and Design,* 32, 2011, pp.3671–85.

[4] Hufenbach W, Dobrzan´ ski LA, Gude M, Konieczny J, Czulak A., “Optimisation of rivet joints of CFRP composite material and aluminium alloy”, *Journal of Archieves Materials and Manufacturing Engineering,* 20 2007, pp.119–22.

[5] Teti R., “Machining of composite materials”, *CIRP Annals – Manufacturing Technology,* 51, 2002, pp.611–34.

[6] Abrao AM, Faria PE, Campos Rubio JC, Reis P, Davim JP., “Drilling of fiber reinforced plastics: a review”, *Journal of Materials Processing Technology,* 186, 2007, pp.1–7.

[7] Mishra R, Malik J, Singh I, Davim JP., “Neural network approach for estimate the residual tensile strength after drilling in uni-directional glass fiber reinforced plastic laminates”, *Materials Design,* 31 2010, pp.2790–5.

[8] S.Jain and D.C.H Yang., “Delamination-Free Drilling of Composite Laminates” *Journal of Manufacturing Science and Engineering,* 116(4), Nov 01, 1994, pp. 475-481.

[9] L-B zhang, L-J Wang, X-Y Liu., “A mechanical model for predicting critical thrust forces in drilling composite laminates”, *Proceedings of the Institution of Mechanical Engineers, Part B: Journal of Engineering Manufacture*, February 1, 2001 vol. 215 no.2 135-146.

[10] Rawat S, Attia H., “Wear mechanisms and tool life management of WC-Co drill during dry high speed drilling of woven carbon fibre composites” *Wear,* 2009;261, pp.1022–30.

[11] I.singh, N.Bhatnagar., “Drilling of uni-directional glass fiber reinforced plastic (UD-GFRP) composite laminates”, *The International Journal of Advanced Manufacturing Technology*, February 2006, Volume 27, Issue 9-10, pp.870-876.

[12] E M.A. Azmir, Praveena Nair Sivasankaran, Z. Hamedon., “Experimental Study on Drilling Process of CFRP Composite Laminate”, *Materials Science Forum,* Volumes 638 – 642, pp.927-932.

[13] T. N. Valarmathi, K. Palanikumar and S. Sekar., “Parametric Analysis on Delamination in Drilling of Wood Composite Panels”, *Indian Journal of Science and Technology,* Vol 6 (4), April 2013.

[14] H. Ho-Cheng and C.K.H Dharan., “Delamination during Drilling in Composite Laminates”, Journal *of Manufacturing Science and Engineering,* 112(3), Aug01, 1990, pp.236-239.

[15] P. Y. Andoh, F. Davis, J. Antonio., “Prediction of a delamination area during drilling of carbon composite laminates structures”, *Journal of Science and Technology*, Vol. 31, No.2, 2011, pp 120-134 120.

[16] Luis Miguel P. Durao, Daniel J.S. Gonçalves, Joao Manuel R.S. Tavares, Victor Hugo C. de Albuquerque, A. Aguiar Vieira, A. Torres Marques., “Drilling tool geometry evaluation for reinforced composite laminates”, *Journal of composite structures*, 2009, 10, 35.

[17] Mathew J., Ramakrishnan N., Naik N.K., “Investigations into the effect of geometry of a trepanning tool on thrust and torque during drilling of GFRP composites”, *Journal of Materials Processing Technology*, Vol. 91, No.1, 1999, pp. 1-11.

[18] Khashaba UA, EI-Sobaty IA, Selmy AI, Megahed AA., “Machinability analysis in drilling woven GFR/epoxy composites”, part II – effect of drill wear. *Composites:* 41, *Part A,* 2010;pp.1130–7.

[19] Abrao AM, Campos Rubio J, Faria PE, Davim JP., “The Effect of cutting tool geometry on thrust force and delamination when drilling glass fibre reinforced plastic composite”, 29, *Materials and Design,* 2008, pp.508–13.

[20] Khashaba UA, EI-Sobaty IA, Selmy AI, Megahed AA., “Machinability analysis in drilling woven GFR/epoxy composites: Part I – effect of machining parameters”, *Composites Part A: Applied Science and Manufacturing*, 2010, pp. 391–400.

[21] Ramkumar J, Malhotra SK, Krishamurthy R., “Effect of workpiece vibration on drilling of GFRP laminates”, *Journal of Materials Processing Technology,* 152, 2004, pp.329–32.

[22] P. Mehbudia, V. Baghlania, J. Akbaria, b, A.R. Bushro, N.A. Mardib., “Applying ultrasonic vibration to decrease drilling-induced delamination in GFRP laminates”, *Procedia CIRP 6* (2013), pp.577 – 582.

[23] A. Sadek, M.H. Attia, M. Meshreki, B. Shi., “Characterization and optimization of vibration-assisted drilling of fiber reinforced epoxy laminates”, *CIRP Annals - Manufacturing Technology,* 62 (2013) 91–94

[24] Capello, E., Tagliaferri, V., “Drilling damage of GFRP and residual mechanical behavior – Part I: drilling damage generation”, *Journal of Composites Technology and Research* 23(2), 2001, pp. 122- 130.

[25] Capello, E., Tagliaferri, V., “Drilling damage of GFRP and residual mechanical behavior – Part II: static and cyclic bearing loads”, *Journal of Composites Technology and Research* 23(2), 2001, pp. 131- 137.

[26] Piquet, R., Ferret, B., Lachaud, F. and Swider., P., “Experimental Analysis of Drilling Damage in Thin Carbon/Epoxy Plate using Special Drills”, *Composites Part A: Applied Science and Manufacturing*, 31(10):2000, pp.1107-1115.

[27] Rubio, J.C., A.M. Abrao, P.E. Faria, A.E. Correia and J.P. Davim., “Effects of high speed in the drilling of glass fibre reinforced plastic: Evaluation of the delamination factor”, *International Journal of Machine Tools Manufacture,* 48, 2008, pp.715-720.

[28] Krishnaraj V, Vijayarangan S and Rameshkumar A., “Effect of drilling parameters on Mechanical Strength in drilling GFRP, *International Journal of Computer applications in technology*, Special issue on “Advanced Manufacturing Tooling” Vol 28(1), 2007, pp 87-93.

[29] Velayudham A., Krishnamurthy R., Soundarapandian T., “Evaluation of drilling characteristics of high volume fraction fibre glass reinforced polymeric composite”, *International Journal of Machine Tools and Manufacture,* 45 (2005), pp.399–406.

[30] Vikas Dhawan, Kishore Debnath, Inderdeep Singh, Sehijpal Singh., "Drilling of Glass Fiber-Reinforced Epoxy Laminates with Natural Fillers: Thrust Force Analysis" Proceedings of the *International Conference on Research and Innovations in Mechanical Engineering* Lecture Notes in Mechanical Engineering, 2014, pp.105-115.

[31] R. Zitoune, F. Collombet, F. Lachaud, R. Piquet, P. Pasquet., **"**Experiment–calculation comparison of the cutting conditions representative of the long fiber composite drilling phase", *Journal of Composites Science and Technology*, 65, 2005, pp. 455–466.

[32] Khashaba, U.A**.,** Seif, M.A., and Elhamid**,** M.A., "Drilling Analysis of Chopped Composites", *Composites: Part A*, Vol. 38, pp.61-70, 2007.

[33] Nagaraja, Mervin A Herbert, Divakara Shetty, Raviraj Shetty and B Shivamurthy., "Effect of Process Parameters on Delamination, Thrust force and Torque in Drilling of Carbon Fiber Epoxy Composite", *Research Journal of Recent Sciences*, Vol. 2(8), 47-51, August 2013.

[34] L. M. P. Durão, D. J. S. Gonçalves, J. M. R. S. Tavares, V. H. C. de Albuquerque, A. Torres Marques., "Drilling process of composite laminates – a tool based analysis", *14th European conference on composite materials,* 7-10 June 2010, Budapest, Hungary.

[35] Vaibhav A. Phadnis, Farrukh Makhdum, Anish Roy, Vadim V. Silberschmidt., "Drilling in carbon/epoxy composites: experimental investigations and finite element implementation", Composites *Part A: Applied Science and Manufacturing*, 2012, 1-32.

[36] Jean François Chatelain, Imed Zaghbani, Gilbert Lebrun, Kaml Hasni., "Effect of Support Distance on Damage of Drilled Thin CFRP Laminates", *International Journal of Mechanical, Aerospace, Industrial and Mechatronics Engineering,* Vol:7 No:9, 2013.

[37] Luís Miguel P. Durão, A.G. Magalhães, António Torres Marques, A.M. Baptista, M. Figueiredo., "Drilling of Fibre Reinforced Plastic Laminates", *Materials Science Forum* Volumes 587 - 588, pp.706-710.

[38] Wen chou-chen., "Some experimental investigations in the drilling of carbon fiber-reinforced plastic (CFRP) composite laminates", *International Journal of Machine Tools and Manufacture*, Volume 37, issue 8, August 1997, pp. 1097–1108.