Effect of drill geometry and drilling parameters on the formation of adhesion layer in drilling composite-metal stack- up material

*M H Hassan**
J Abdullah
A S Mahmud
School of Mechanical Engineering, Engineering Campus, Universiti Sains Malaysia

A Supran
Advanced Machining Lab, Gandtrack Asia Sdn Bhd, 75350 Batu Berendam, Melaka, Malaysia

**hssn_hfz@yahoo.com*

ABSTRACT

Drilling of two very contrasting materials, composite-metal stack-up in one shot is a necessary and critical process in aircraft structure manufacturing. This drilling process is very complicated because it involves many parameters, and therefore requires systematic study. However no related publication is yet found on this subject. This paper presents a fundamental approach to determine the best combination of geometry and drilling parameters for drilling a stack-up Carbon Fibre Reinforced Plastic and aluminium 7075- T6 materials which lead to longer tool life. The approach is based on a combination of Fractional Factorials (2^{k-3}) techniques where the main effect for each parameter was also identified. The experimental array comprises of four geometry parameters and two drilling parameters, performed in a single shot drilling process. The wear formation at the margin and cutting lips location were observed using scanning electron microscope. In order to quantify the adhesion wear that formed after the drilling process, the percentage of adhesion layer (PAL) was determined and the main effect for each geometry and drilling parameters of twist drill was further analysed. The ideal combination between the tool geometry and drilling parameters that produced a minimum PAL was identified.

Keywords: *Stack materials; Build up layer; Drilling; Wear*.

1. Introduction

Drilling a Carbon Fibre Reinforced Plastic (CFRP) requires different setting than drilling a metal part due to different type of wear mechanism. Abrasive wear is normally observed when drilling a CFRP, whereas adhesion wear is typical for drilling a metal part. Hence, drilling a stack up material with comprise of composite and metal in a single shot drilling process is a challenge due to abrasive and adhesion wear happen simultaneously during the drilling process [1,2]. For example, when drilling a stack up CFRP and aluminium material, the adhesion wear is known as premature wear due to formation of aluminium layer at the cutting lips that deteriorates the quality of drilled hole and reduce the tool life. Tool wear during drilling can lead to costly quality issues, especially in aerospace manufacturing,

ISSN 1823- 5514, eISSN 2550-164X Received for review: 2017-04-21
 Accepted for publication: 2017-05-30
 Published: 2018-01-31

where materials cost is very high coupled with stringent requirements of the industry.

Benezech et al. [3] found the 130° of point angle and 30° of rake angle are optimal geometry for easy chip evacuation and giving a lower tool wear after drilling a multi material. In the other research of multi material drilling, Zitoune et al. [4] studied the effect of drilling diameter to the adhesion wear formation and found that drills with diameter of 6 mm or less are preferred due to reduced chisel edge length. For the coating tools, the adhesion wear happened because of the exfoliation of the coating layer. Subsequently, the chisel edge and flank surface of the tool began to wear [5, 6].

The build-up edge (BUE) and build-up layer (BUL) mostly formed because of high temperature rise during drilling causing metal softening which then stick strongly at the cutting lips and rake face of the cutting tool. When the cutting tool reaches aluminium alloy material, the chips of aluminium alloy will evacuate through the flute and some of the remaining chips will be adhered at the rake face due to the micro weld during the drilling process [7]. Kim & Ramulu [8] reveal that the wear rate of adhesion wear increases with the decrease of feed. This could be due to long contact period between the tool and work piece. This condition encourages build-up layer formation.

Most of the previous research focuses on the drilling parameter and proposed tool geometry from the supplier standard catalogue in order to improve wear resistance of the cutting tools. However, the basic understanding of the tool geometry and drilling parameters need to be researched further. Hence, this paper presents the experiment work to evaluate the effect of tool geometry and drilling parameters on the adhesion wear formation at the margin and cutting lips of the cutting tools when drilling CFRP and aluminium stacks in a single shot drilling process.

2. Experimental condition

2.1 Materials preparation

The CFRP composite specimen consists of 26 unidirectional plies of 0.125 mm thickness each, making the total laminate thickness of 3.25 mm. The 26 unidirectional plies were made of carbon/epoxy prepreg manufactured by Hexcel Composite Company. A thin layer of glass/epoxy woven fabrics 0.08 mm thick were then used at the top and bottom of the CFRP laminate to avoid delamination at the entrance and exit of the hole during drilling. This make the total and final thickness of the whole composite panel, including the paint application becomes 3.587 mm. During the curing process, the CFRP were compacted using a vacuum pump at controlled atmosphere condition and cured in the autoclave until it achieved the nominal fibre volume fraction is 60%. Aluminium sheet used in the stack-up of aluminium-CFRP was Grade 7075-T6 of 3.317 mm thickness.

2.2 Design of experiment

The experimental works were carried out based on a fractional factorial design array with variation of six factors; (1) helix angle, (2) primary clearance angle, (3) point angle, (4) chisel edge angle, (5) spindle speed and (6) feed rate. The array of each factor is tabulated in Table 1. Each cutter was drilled with 100 holes and the final measured value of the cutters were analysed based on the percentage of adhesion layer (PAL). No coolant was used during the drilling since the coolant application would obstruct the carbon panel. OEMs become concerned about contamination in the part, and cleaning is added as a secondary operation to machining. Dry drilling eliminates all this, and eliminates the need to design lubricant channels into the tool.

Table 1: Test array for the parameters study.

Run	Helix angle, β (°)	Primary clearance angle, α (°)	Point angle, ϕ (°)	Chisel edge angle, γ (°)	Spindle speed, N (rev/min)	Feed rate, *f* (mm/rev)
R1	15	6	110	45	2600	0.1
R2	15	8	110	30	2600	0.05
R3	15	6	130	45	1500	0.05
R4	15	8	130	30	1500	0.1
R5	30	6	110	30	1500	0.1
R6	30	8	110	45	1500	0.05
R7	30	6	130	30	2600	0.05
R8	30	8	130	45	2600	0.1

2.3 Cutters fabrication

Tungsten carbide rods with composition 93% WC and 7% Co were ground into eight different geometries by a CNC grinding centre (Walter Helitronic Mini Power) and the diamond wheels (Castle Tech - D64 and D91 grit) attached to the machine. The variation level of helix angle, primary clearance angle, point angle, and chisel edge is according to the recommendations by the cutter manufacturer. The optimum combination of the geometry would be identified to meet the customer’s specification.

2.4 Drilling process

The schematic and actual experimental set-up is shown in Figure 1(a) Figure 2(b) respectively. Drilling experiments were conducted by a computer numerical control (CNC) machine with model Fanuc Robodrill α-T21iFLb. The sequence of drilled hole was illustrated in Figure 1(c) with total 50 holes per panel. Two panels are required to complete the drilling process for each cutter. The stacks-up panels were slot in and clamped inside the fixture during the drilling process.

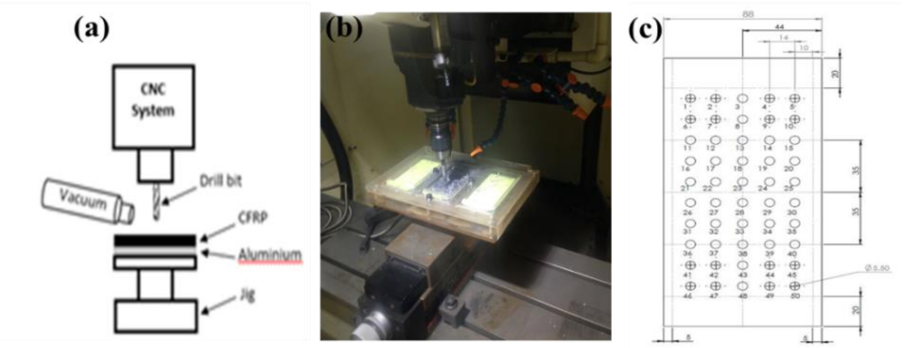


Figure 1 : Drilling set up: (a) schematics diagram (b) actual set up (c) hole location of drilling process per panel.

2.5 Cutting tools analysis

A scanning electron microscope (SEM) was used to provide the high magnification pictures of the adhesion formation and wear identification after the drilling process. The location of observation is at the margin and near to the chisel edge of the cutting tool. An observation or inspection by SEM was done to get more clarification of the adhesion of aluminium at the cutting lips. The fresh drill and worn drill was observed under SEM with the magnification 210X at the margin and 300X at the cutting lips to identify any formation of aluminium build-up edge and build-up layer after the drilling process.

To quantify the amount of adhesion layer formed at the margin and along the cutting lips, the percentage of adhesion layer *(PAL)* was introduced and the values were calculated according to the equation below.

$$PAL, \% = \frac{w_{ad} - w_{ac}}{w_f - w_{ac}} x100 \qquad (1)$$

where, *PAL* is the percentage of adhesion layer, w_{ad} is the weight after drill, w_{ac} is weight after the cleaning and w_f is weight fresh drill. The weight after cleaning process was measured after the tool was cleaned with the wire brush and etching process to remove all the adhesion that formed at the cutting lips.

3. Results and discussions

3.1 SEM observation

Figure 2 and Figure 3 shows the comparison of SEM image of the cutting edge (margin and cutting lips) location between the fresh drill and after drill 100th holes for all trials. These images indicated that the cutting edge was mainly affected by the adhesion wear, whereas the formation of build-up edge (BUE) and build-up layer (BUL) is clearly observed at the cutting edge and rake face respectively. This phenomena is similar with Zitoune et al [5] that showing the presence of a layer aluminium on the cutting edges and the rake face. The formation of BUL is clearly observed at the rake face due to the rough surface known as grinding mark at the cutter flute due to grinding action during the drilling process. Therefore, the small aluminium chips would deposited on the rake face during the high drilling temperature.

Meanwhile, the BUE stuck on the cutting lips and margin then, prevent the tools to perfectly cut the work piece. For R3, R4 and R6 cutters, the formation of aluminium adhesion at the margin and cutting lips is higher from the others cutters because of the lower spindle speed. Drilling at lower spindle speed and feed rate (1500 rev/min and 0.05 mm/rev), shows that the friction between the tool and workpiece, would increase due to the longer contact of time in order to complete the hole penetration. Hence, the cutting temperature will increase and the reaction between aluminium and cobalt occurs to form micro welding on the cutting edge.

In the other hand, some metallic chips that passing through the hole drill flute also contributed to the BUL and BUE at the primary cutting edge. Improper selection of helix angle would interrupt the chip evaucation during the drilling process. Figure 3 show that the drill was designed with 30° of helix angle. Most of the cutters consist of BUL and BUE at the cutting edge expecially at the cutting lips location. This phenomenon occured due to some of the chips was clogged at the flute and melted at the cutting edge.

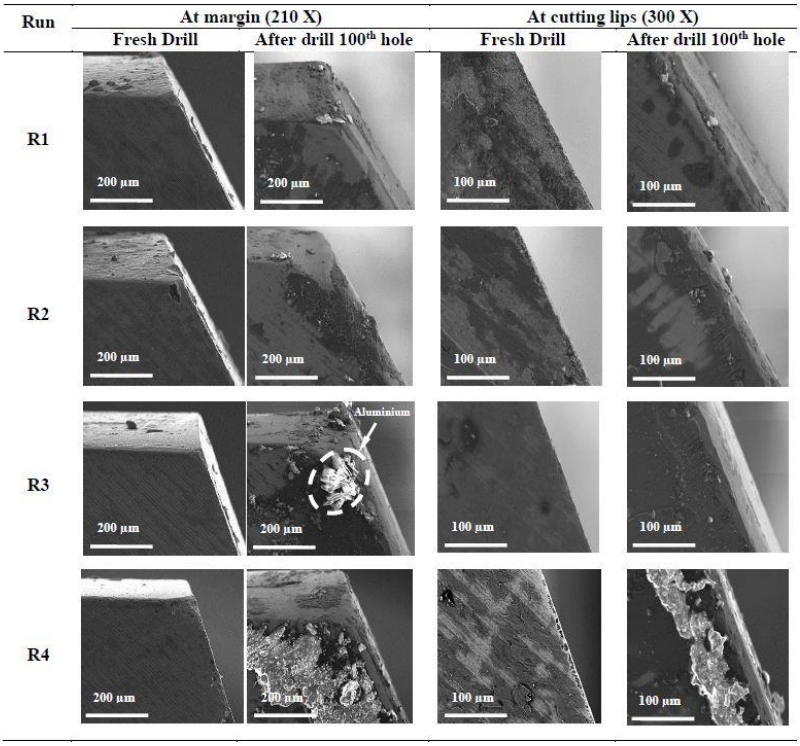


Figure 2 : Example SEM observation for fresh drill and after drilled 100th holes at margin and cutting lips location for 15° of helix angle.

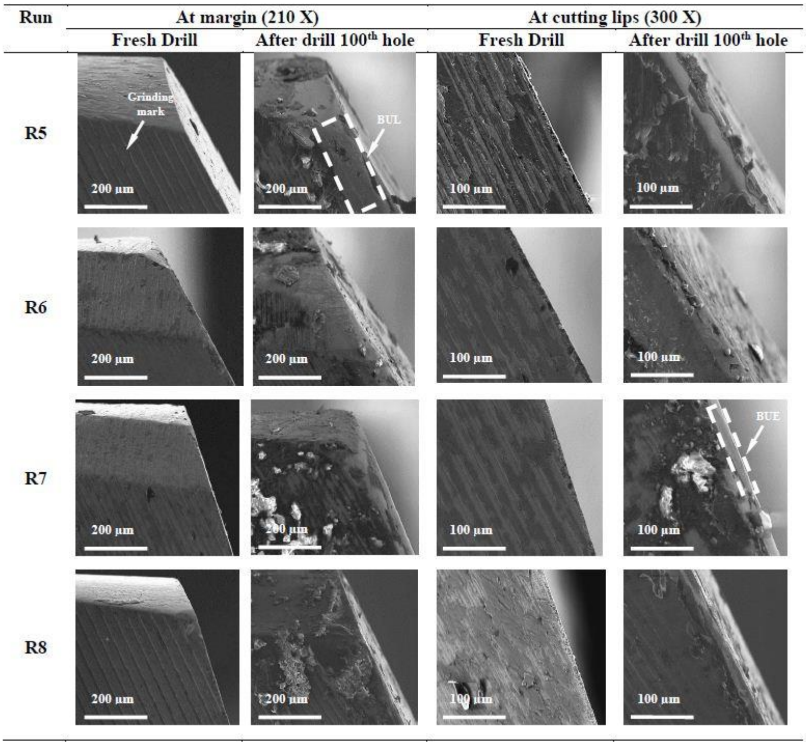


Figure 3 : Example SEM observation for fresh drill and after drilled 100th holes at margin and cutting lips location for 30° of helix angle.

3.2 Percentage of adhesion layer (*PAL*)

In order to observe the abrasion formation at the cutting edge, the tools has been cleaned using etching process. Figure 4 shows the images of the tool margin and cutting lips with comparison between after drilling of the 100th holes and after the cleaning process. After removing the BUE and BUL, the abrasive wear was observed on the cutting tool. This is due to chipping of carbide substrate at the margin location. For R3 and R8 cutter, the cutting edge roundness (CER) was observed at the cutting lips location after the cleaning process. This indicates that the abrasion wear occured during the drilling stack materials arising from the abrasive carbon fiber rubbing against the cutting lips during the drilling process. A higher drilling temperature which is more than 300 °C softened the cobalt binder and removing the carbide grains from their substrate.

Severe chipping with approximate size of 30 micron, was observed at the cutting edge near to the margin side after cleaning process. The adhesion was formed at the chipping location and covered a large part of the flank surface especially at the lower spindle speed. More adhesion of BUE and BUL at minimum spindle speed and feed rate as R3.

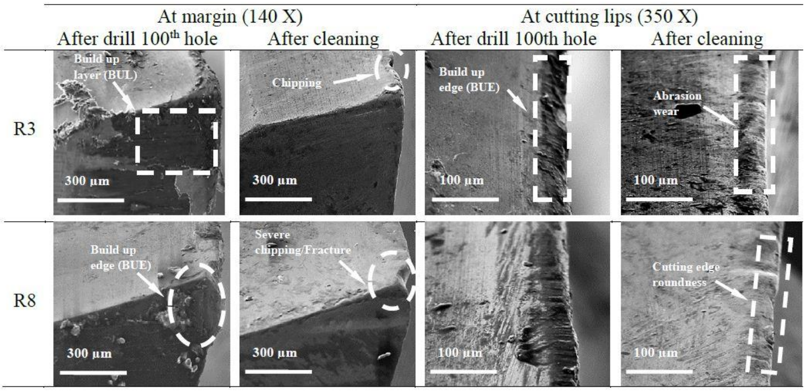


Figure 4: Example SEM pictures of at the margin and cutting lips for percentage of build-up identification.

Figure 5 indicates the PAL value distributed in the range 9.43% - 33.33% for all the cutters. R1 gave the minimum value of PAL due to configuration of cutter geometry. Drilling at the constant drilling parameters (2600 rev/min, 0.1 mm/rev), drill geometry with lower point angle (110˚) give a lower PAL compared to higher point angle (130˚) due to smaller surface contact area between the tool and work. Hence, the drilling temperature is lower and less aluminium adhesion occured at the cutting edge.

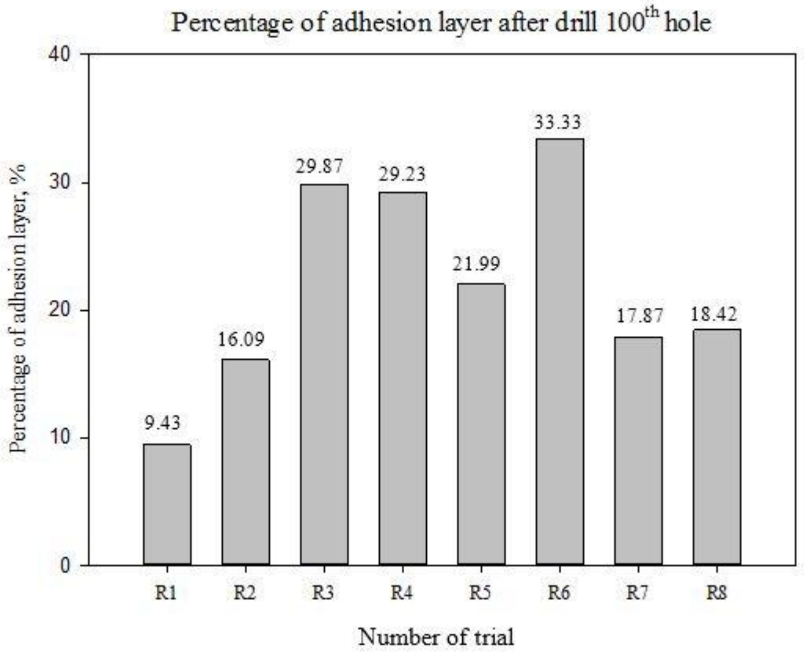


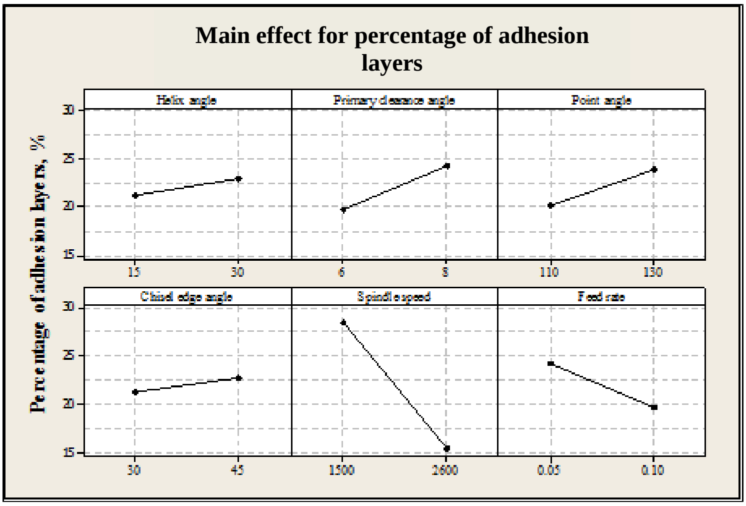
Figure 5: PAL value for each number of run.

3.3 Analysis of variance (ANOVA)

Figure 6(a) and (b) show the main effect plots and associated ANOVA results for PAL. In general, the statistical analysis shows that the main contributing factors for the PAL formation are primary clearance, point angle, spindle speed and feed rate. Spindle speed has the most significant effect with the highest percent contribution (PC) of 74.34% followed by feed rate with PC of 8.79%. An experimental analysis revealed that higher spindle speed reduces amount of aluminium bonding at the cutting edge. When increasing the spindle speed and feed rate, the contact time between the tool and work piece from start until the drill breaks through the bottom part is getting shorter [8].

For the geometry parameters, primary clearance angle and point angle were also significant at the 10 % level although their PC's were small (8.62% and 5.68%, respectively). When the primary angle is increased from 6° to 8°, the formation of PAL at the cutting lips also slightly increase. This is due to the "rubbing action" occurred between the drill tip side and the hole surface that contributed to the higher wear rate since the drill tip is too sharp [7]. Hence, the cutting lips is easy to blunt and aluminium chip is easy to stick at the cutting lips due to high friction during drilling process. For the effect of point angle, drilling at 130° would slightly increase the formation of PAL because the increase in surface contact between the tool and workpiece. For example, at constant feed rate of 0.1 mm/rev, the surface area for 110° of point angle is 0.14 mm^2 and for 130° of point angle, this surface area increases to 0.3 mm^2, hence, higher surface contact will increasing drilling temperature.

(a)



(b)

Percentage of Adhesion Layer

Source	Sum of Squares	df	Mean Square	F Value	p-value Prob > F	PC,%
Model	453.48	4	113.37	28.46	0.0101	
B-primary clearance	40.14	1	40.14	10.08	0.0503	8.62
C-point angle	26.42	1	26.42	6.63	0.0821	5.68
E-speed	346.01	1	346.01	86.86	0.0026	74.34
F-feed rate	40.92	1	40.92	10.27	0.0491	8.79
Residual	11.95	3	3.98			2.57
Cor Total	465.43	7				
Std. Dev.	2		R-Squared	0.9743		
Mean	22.03		Adj R-Squared	0.9401		
C.V. %	9.06		Pred R-Squared	0.8174		
PRESS	84.98		Adeq Precision	14.042		

Figure 6: (a) Main effect of geometry parameters and drilling parameters, (b) Analysis of variance study of geometry and drilling parameters

4. Conclusion

An analysis of percentage of adhesion layer (PAL) was introduced when drilling a stack of CFRP and aluminum material with different twist of drill geometry. The ideal drill geometry and drilling parameter is to achieve a minimum percentage of adhesion layer (PAL) when drilling a stack-up CFRP and aluminum in a single shot drilling process was identified. The results shows that drilling at 15° of helix angle, 6° of primary clearance angle, 110° of point angle, and 30° of chisel edge angle at 2600 rev/min of drill speed and 0.1 mm /rev of feed rate yielded the minimum formation of PAL at the cutting edge. Furthermore, the higher drilling temperature is the other main factor that contributes to the PAL formation when drilling a multi stack materials.

Acknowledgment

This work is supported by the RU-I Grant # 1001/PMEKANIK/814288 of Universiti Sains Malaysia. The authors would like to thank the Gandtrack Asia Sdn Bhd for the use of their facilities for this research project. Equipment and technical support provided by SpiritAero System Subang Sdn Bhd are also acknowledged.

References

[1] I. Shyha, S. L. Soo, D. Aspinwall, S. Bradley, R. Perry, P. Harden, et al., "Hole quality assessment following drilling of metallic-composite stacks," Int. J. Mach. Tools Manuf. vol. 51, pp. 569-578 (2011).

[2] S. A. Ashrafi, S. Sharif, A. A. Farid, and M. Yahya, "Performance evaluation of carbide tools in drilling CFRP-Al stacks," J. Compos. Mater. vol. 48, pp. 2071-2084(2014).

[3] L. Benezech, Y. Landon, and W. Rubio, "Study of manufacturing defects and tool geometry optimisation for multi-material stack drilling," in Adv. Mater. Research pp. 1-11 (2012).

[4] R. Zitoune, V. Krishnaraj, and F. Collombet, "Study of drilling of composite material and aluminium stack," Compos. Struc. vol. 92, pp. 1246-1255(2010).

[5] R. Zitoune, V. Krishnaraj, B. S. Almabouacif, F. Collombet, M. Sima, and A. Jolin, "Influence of machining parameters and new nano-coated tool on drilling performance of CFRP/Aluminium sandwich," Composites Part B. vol. 43, pp. 1480-1488(2012).

[6] L. Zhang, Z. Liu, W. Tian, and W. Liao, "Experimental studies on the performance of different structure tools in drilling CFRP/Al alloy stacks," Int. J. Adv. Manuf. Technol. vol. 81, pp. 241-251(2015).

[7] B. Mubaraki, S. Bandyopadhyay, R. Fowle, P. Mathew, and P. Heath, "Drilling studies of an Al2O3-Al metal matrix composite," J. Mater. Sci. vol. 30, pp. 6273-6280(1995).

[8] D. Kim and M. Ramulu, "Drilling process optimization for graphite/bismaleimide–titanium alloy stacks," Compos. Struc. vol. 63, pp. 101-114 (2004).