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An Experimental Study of Influence of Drill Geometry on Drilling of Carbon Fibre Reinforced Plastic Composites

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Abstract*—This paper presents the experimental results of drilling 10mm diameter holes in 20mm thick CFRP composite laminate using HSS, Solid Carbide (K20) and Poly Crystalline Diamond insert drills. The effect of feed rates, cutting speeds and the geometry of drill on delamination, surface roughness, cutting forces and chip formation are studied. The experimental results show that delamination free drilling process may be obtained by the proper selections of drill point geometry and the process parameters. However, at high spindle speed and lower feed rate the heat generation due to friction between cutting edges and the work material facilitate softening of the matrix which resulted in poor surface finish and lower delamination. Carbide drill produced serrated or non homogeneous chips at low speeds.Reduced number of cutting edges resulted in increased force . Hardness of drill material also influences variation in cutting forces.

***Keywords*—Drilling, Tool geometry, CFRP, Delamination.**

I. INTRODUCTION

Carbon Fiber Reinforced Plastic (CFRP) composite materials are widely used in many applications such as automotives, aircraft etc.

The unusual mechanical properties such as high specific strength, stiffness and fatigue limit, enable the structural design more reliable than conventional metals TsaoaC.C and Hocheng.H [1]. They are fabricated by processes such as hand lay-up, filament winding, pultrusion, etc. and then subjected to machining to facilitate the dimensional control for easy assembly. The mechanism of machining composites has been recognized as a process different from that of conventional materials. A suitable selection of cutting conditions is difficult due to the coexistence of hard abrasive fibers and a soft matrix. Due to the presence of two or more dissimilar phases, composite materials pose great challenges during machining Velayudham et al.[2].

Drilling is a frequently practiced machining process in industry owing to the need for component assembly in mechanical structures. Many authors [3-5]reported that the quality of the drilled surfaces depend strongly on the drilling parameters, tool geometry and tool material. An inappropriate choice of these parameters can lead to unacceptable material degradation, such as fiber pull-out, matrix cratering, thermal damage and delamination, Chen.W [5]. Among the defects caused by drilling, delamination appears to be the most critical problem, especially in applications where a high level of reliability and safety is required. In addition to the problems of tool wear, it is difficult to achieve the quality of surface needed for the accurate assembly of components in structures.

Piquet et al. [6] carried out drilling on thin carbon/epoxy laminates with two types of drills, a helical drill and a drill of special geometry, and reported that both drills leads a damage at the entrance in the wall and the exit of the hole, while a special geometry drill shows a significant reduction in the final damage on CFRP.The delamination factor has been widely used to characterize the level of damage on the work material at the entrance and exit of the drill. The delamination factor (Fd) $\mathbf{F_d = Dmax/D}$ may be calculated from the ratio of the maximum diameter (Dmax) of the delamination zone to the drill diameter (D).

Hocheng and Tsao[9], conducted experiments to prove the benefit of using special drills instead of twist drills.Totally four different drill geometries were used. Special drills that were used include, saw drill, candle stick drill and step drill made of high speed steel (10mm in diameter) .They have reported that thrust force varies with drill geometry and with feed rate. The tangential force (moment) decreases with increasing point angle because the tool orthogonal rake angle at each point on the primary cutting edge increases with increase in point angle. Min et al. [10] developed a FE drilling model that showed chip formation at the exit surface. The model simulated the formation of a crown and homogeneous chip as a function of the feed rate and shows that a homogeneous chip is formed at lower feeds and a crown chip is formed at higher feeds. The failure criterion was based on the equivalent plastic strain in the discrete elements. When the plastic strain reached a certain limit in an element, it was removed from the simulation space. Klocke et al.[11] used a plastic failure criterion to model chip separation..

Palani kumar et al. [13] reported that delamination decreases as spindle speed increases and a combination of high speed, low feed and point angle of the tool could reduce delamination to a greater extent.Gaitonde et al.[14] studied the delamination tendency with respect to cutting speed, feed rate and point angle. Influential parameters on delamination were analyzed through 3D response surface plots it is reported high-speed cutting plays a major role in reducing damage at the hole entrance.Abroa et al. [15] presented a survey on drilling of carbon and glass fibre composites results reveal that the phenomena associated to shearing of polymeric composite materials require additional studies in order to have a better understanding of these materials.

Davim et al. [16] reported a technique to measure the adjusted delamination factor using digital analysis results indicated that the use of digital analysis is suitable to estimate the damages produced during drilling. Rubio et al. [17] reported the comparison between conventional and adjusted delamination factor. The latter provided realistic results for assessment of drilling induced damage.Abroa et al. [18] reported the effect of tool geometry and material on the thrust force and delamination during the drilling of GFRP composite.It was found that the effect of cutting speed on the thrust force was negligible and abrasion led to elevation of thrust force.

The aim of this paper is to reveal the parametric influence of drill material and its geometry on the quality of machined surface of CFRP.The experiments were conducted as per an L_{27} orthogonal array. The parameters considered in this work are spindle speed, feed rate and type of drill. The tool materials were chosen as High Speed Steel (HSS), Carbide and Poly Crystalline Diamond (PCD).The HSS and cemented carbide (K20) have four flute with Helix angle 59˚, Radius of Ball Nose 5mm and point angle 10˚.The PCD tool has two flute with helix angle 30˚, Radius of Ball 5mm and a point angle 8˚. Finally the effects of drill point geometry, drill material and process parameters on the thrust force, delamination, surface roughness and chip formation are presented and discussed. Though there are a lot of works on CFRP drilling the present work focuses on the effect of extremely rare drill geometry on the same work material at different operating conditions and developing a consensus between the nature of chip formation and the tool wear.

II. EXPERIMENTAL

A. Materials and Methods

The CFRP laminates are fabricated using the hand lay-up technique. Carbon fibre (Zoltek, PANEX® 35)was used as a reinforcement in the Epoxy matrix(Huntsman, Warm curing epoxy system based on Araldite® LY 1564 SP/Hardener XB3486formulated amine hardener) and was cured at 220°C for 90 minutes. This composite laminate was produced with a fiber orientation of 0/90 degrees with 20 layers of the fabric and resin used successively. The properties of the fibre are listed in Table1.The different types of drill used in this study are shown in Fig.1.

Table1. Properties Carbon Fibre

TYPE OF FIBRE	TENSILE STRENGT H (MPa)	TENSILE MODULU S E (GPa)	ELECTRICA L RESISTIVIT Y Ω-cm	%CARBO N CONTENT	DENSIT Y ρ (g/cc)	FIBRE DIAMETE R d (m)
Stitch Bonded Unidirectiona l	3800	228	0.00155	95	1.81	7.2

Fig.1.Drills used in the study a) HSS Ball Nose,b) Carbide Ball Nose,c) PCD Ball Nose

B. Experimental Procedure:

The experimental setup is shown in Fig.2.Arix VMC 100 CNC drilling machining centre was used for making drills in the CFRP composites using different drill bits such as HSS, Solid Carbide and PCD.The experiments were conducted as per the L_{27} orthogonal array. The drilled holes were analyzed using a optical technique with 1 μm resolution and 30x magnification to measure the delamination damage at the entrance and exit of the holes. The spindle speed used were 2500, 3000, 3500 rpm and the feed rate employed were 50, 75 and 100 mm/min.

The computer controlled data acquisition system was used to collect and record the data during experiments. The Kistler dynamometer was used to record the cutting forces.

Fig2.Experiment setup with dynamometer arrangement

III. RESULTS AND DISCUSSION

A. Influence of Drilling parameters on the Cutting forces

The cutting forces were measured for the different cutting conditions. It is noted that the cutting force and torque were initially high during the entry of drill into the composite and further increases as the cutting edge penetrates into the laminate. Fig.3 shows the measured thrust force during drilling of CFRP laminate at different speed and feed conditions with different drills.

It can be seen that effect of cutting speed on the cutting forces differs with various tool geometry and material. As expected, feed rate has a greater influence on thrust force as higher feed rates correspond to higher values of thrust force. It is also observed that thrust force is high as feed rate increases due to the change in the shear area. There is tremendous increase in thrust force values for PCD because the amount of margin left after providing the flute is more. Greater the margin less is the cutting edge. So the energy required to pierce through the laminate is manifested in the form of high thrust force values. This reveals that drill geometry has significant effect on the thrust force. The thrust force generally increases as the speed increases but decreases further in the case of Carbide and PCD tool this is because the energy required to intiate drilling is higher than to remove the material thereafter. On contrary to carbide, the cutting force observed during drilling using PCD is quite different due to reduced number of cutting edges than HSS and Carbide there is increased margin area which resulted in phenomenal rise of forces. The value of cutting force is high as compared with the carbide.

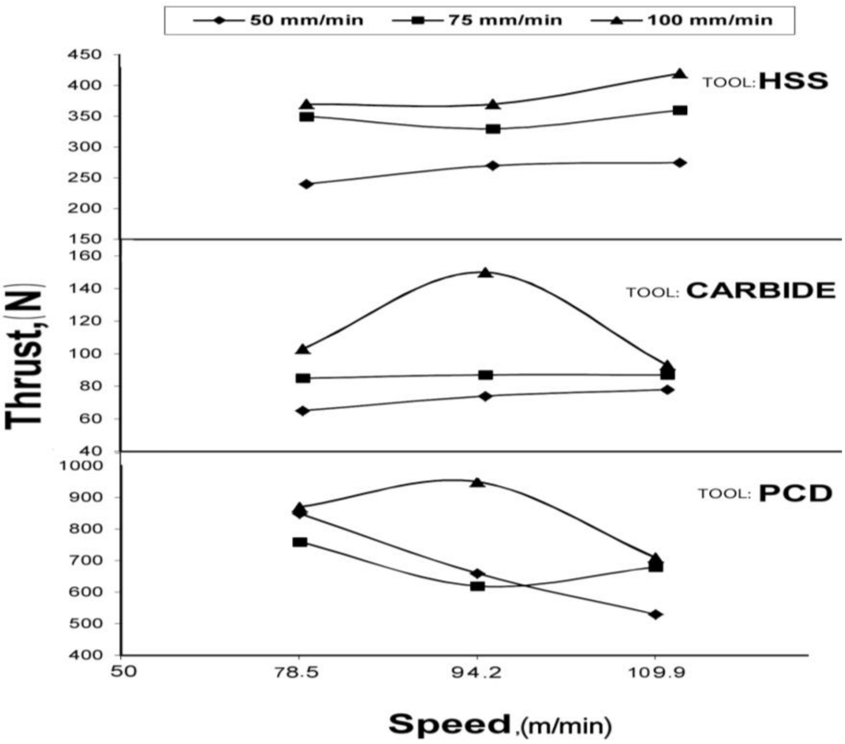

Fig.3.The m**e**asured thrust force at different Speed

Fig.4 shows the measured moment during drilling of CFRP laminate at different speed and feed conditions with different drills. On the contrary, to this work done by Hocheng and Tsao, the thrust force increases with increase in point angle. In order to decrease the thrust force, tool with a smaller point angle is preferred,due to reduced cutting edges and unusual nose profile reduced point angle has resulted in increased force in the case of PCD drill despite having excellent hardness . Since the hardness of HSS drill is less compared to the other drills it has very poor indentation effect so the energy to pierce through is manifested in the form of higher values of force as compared to Carbide drill.

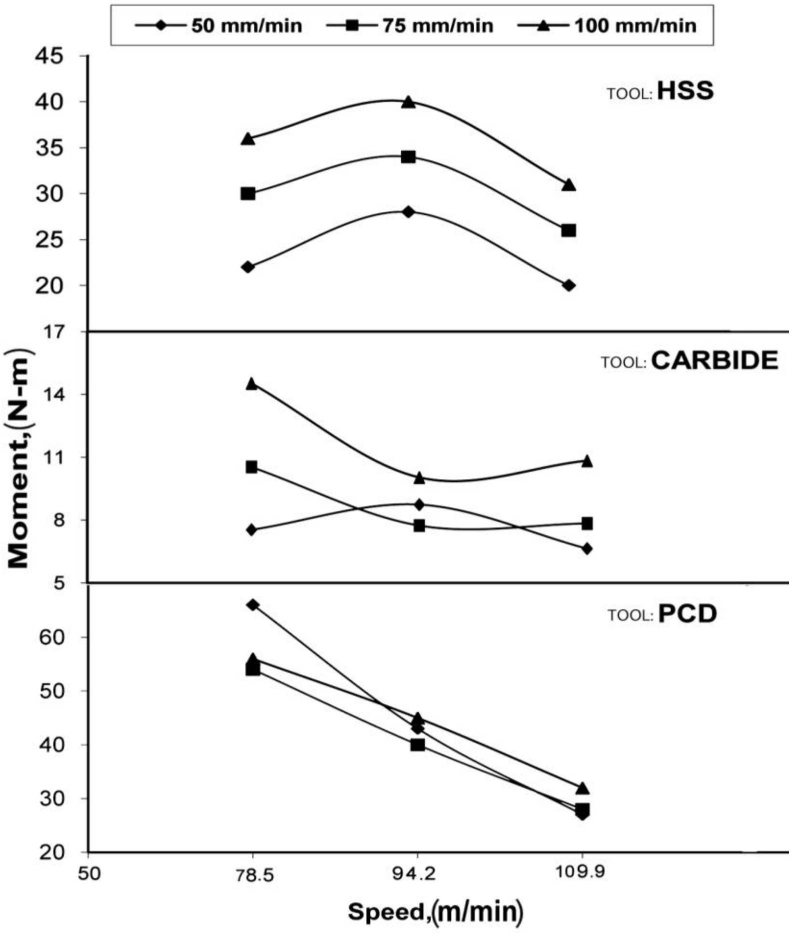

Fig4.The measured Torque at different Speed

The Carbide drill has larger helix angle (59 ˚degree) so the thrust and torque developed is smaller. This is because the tool orthogonal rake angles at each point on the primary cutting edge are increased with increasing helix angle; hence it reduces the thrust and torque. Since the profile of PCD drill used is of different geometry, there is a higher variation in the cutting forces. The number of flute is less compared to the other two so the margin is wider hence the frictional area becomes more so the chance of cutting forces to elevate is as expected. It is found that thrust force varies with drill geometry and with feed rate this enables for the use of higher feed rates if adequate drill geometry is selected. Also to note that PCD has the maximum hardness than HSS or Carbide as result of which wear is high which is evident from the thrust force plot.

Based on these results, it is possible to say that low feed rates reduce maximum thrust force during drilling. This outcome is further compared with delamination results subsequently.

B. Delamination

Delamination is often regarded as the biggest defect found in the drilling of carbon composites.Delamination usually occurs on the top and bottom layer of the laminate. At the entrance, this phenomenon is called peel-up and occurs as the drill bit enters the material and the upper most layer of laminate gets separated from the rest of the body. The delamination of the bottom layer of the sample occurs on the tip of the drill bit which pushes the bottom layers of the laminate. Table.2. Indicates that the increase in cutting speed reduces the delamination for HSS drills, whereas the increase in feed rate increases the delamination in the case of Carbide drills.

Drill point geometry has significant effect on the delamination along with cutting speed and the feed rate.Hardness of drill material has contributed towards material removal and delamination in spite of same drill geometry and process parameters in the case of HSS and Carbide drills. For Carbide drill at cutting speeds of 94.2m/min and feed rate of 75mm/min delamination is found to be at its maximum value. However, for the highest cutting speed (109.9m/min), an increase in feed rate does not result in appreciable elevation of the damage. This is because at lower cutting speeds lower heat generation takes place and delamination occurs as result of stress produced by shearing action. Evaluation of damage around the hole shows that delamination onset was always observed, independently of feed rate or drill geometry Fig.5 shows micrograph of delamination.

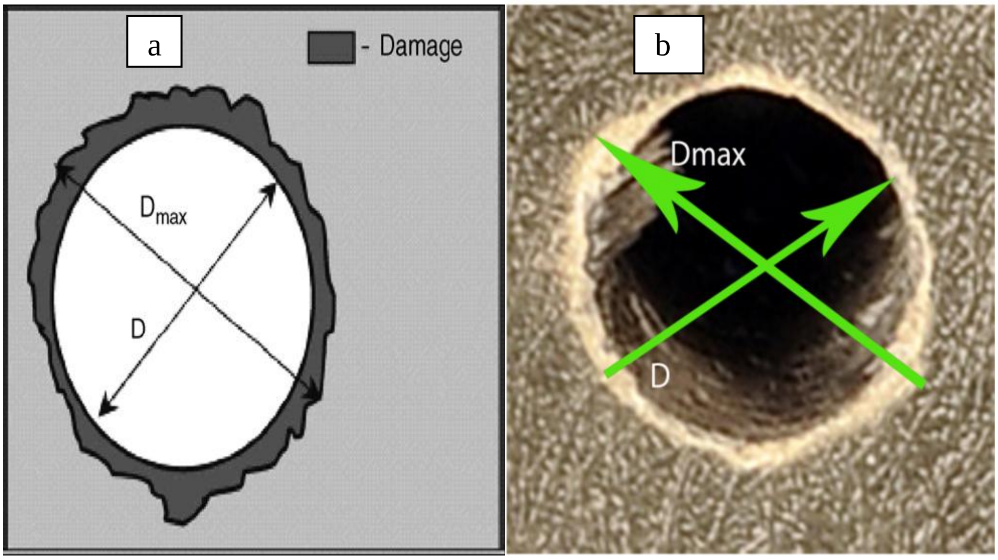

Fig.5 a)Representation of Delamination,b)Micrograph showing Delamination

Table 2.**Effect of Process variables on Delamination**

Tool	Speed(m/min)	Feed(mm/min)	Delamination Factor(Dmax/D)
HSS	78.5	50	1.31
HSS	78.5	75	1.27
HSS	78.5	100	0.99
HSS	94.2	50	1.31
HSS	94.2	75	1.12
HSS	94.2	100	1.22
HSS	109.9	50	1.04
HSS	109.9	75	1.03
HSS	109.9	100	1.01
CARBIDE	78.5	50	1.01
CARBIDE	78.5	75	1.04
CARBIDE	78.5	100	1.03
CARBIDE	94.2	50	1.1
CARBIDE	94.2	75	1.4
CARBIDE	94.2	100	1.2
CARBIDE	109.9	50	1.01
CARBIDE	109.9	75	1.04
CARBIDE	109.9	100	1.02
PCD	78.5	50	1.00
PCD	78.5	75	1.01
PCD	78.5	100	1.2
PCD	94.2	50	1.02
PCD	94.2	75	1.02
PCD	94.2	100	1.01
PCD	109.9	50	1.19
PCD	109.9	75	1.10
PCD	109.9	100	1.00

Chisel edge should be as reduced as possible to reduce Delamination when operating at lower feeds. Peel-up delamination is a consequence of the cutting force pushing the abraded and cut materials to the flute surface. Prior to complete the machining, the material spirals up the flute. It is found that the delamination is lower at the lower feed rates for all drills. Push-out delamination occurs in interlaminar regions, so it depends on fibre nature and the orientation of laminate. This is because of the compressive thrust force that the drill tip always exerts on the uncut laminate plies. At this point loading exceeds the interlaminar bond strength. The increase of feed rate, with the consequences already discussed in previous section and does not cause a predominant increase in delamination factor. One can conclude that PCD drills are more reactive to feed rate changes, when delamination is to be considered. Table.2.shows the effect of process variables on delamination and surface roughness.

C. Hole Surface Roughness

The surface roughness decreases as the feed rate increases but decrease with increasing chisel edge, such as might arise due to tool wear. The surface roughness was measured along the drilling direction using a Mitutoyo 301 Surface roughness tester. It can be seen that hard carbide tools produce a better surface finish compared to that achieved when using HSS drills. There is slight overall increase in the roughness values at 78.5m/min and there is a decrease in the surface roughness for those tests conducted at 94.2m/min.This is possibly due to the influence of primary relief angle and the flute at this speed, which gives rise to to a rounding of the cutting edge leading to a slight reduction in roughness.Fig.6 shows the variation of surface roughness at different speeds. Feed rate clearly affects the surface roughness; speed is only of minor influence. In general the values recorded for surface finish were better than the expected for this type of drilling operation. This is because of the burnishing effect produced by the rubbing action of the drill on the sides of the drilled hole. There was evidence of burnished surfaces at various locations within each drilled hole. These results can also be influenced by the number and orientation of fibers that are within the stylus evaluation length.

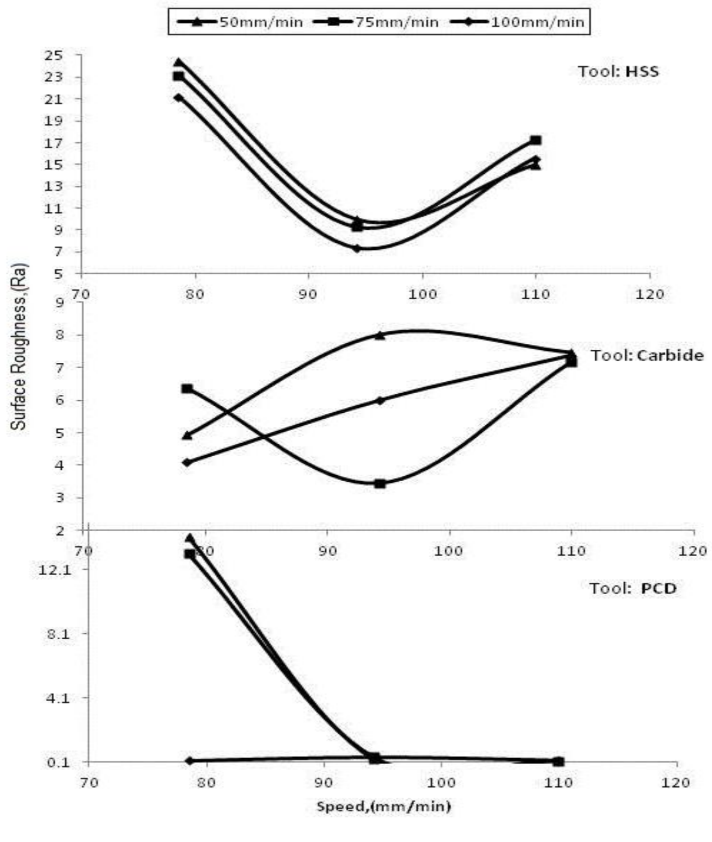

Fig.6 Measured surface roughness at different speeds

Smoother surfaces were produced with PCD drills, followed by Carbide drill at medium speeds. In spite of the good appearance of the holes produced by Carbide drills, roughness was high which is because of different fibre cut mechanism.

D. Chip formation

Chip formation is influenced by the fiber orientation and occurs through a series of consecutive ruptures**.** Furthermore, crater wear occurs to a major extent. Discontinuous chip formation is the main cause for crater wear. Large clearance angle should be provided to improve the tool life. However, this causes flagging of the tool that may prop up cutting edge chipping. The chip reduction coefficient is calculated for all the experimental runs as follows.

The degree of thickening of the chip is expressed by

$\zeta = a2/a1 > 1.00$ (since $a_2 > a_1$) *(1)*

where, ζ = chip reduction coefficient
a2=thickness of chip after cut(mm)
a1= thickness of chip before cut (mm)
a1= (s/2) sinØ *(2)*
a2=Cos (βn-γn)/Sinβn *(3)*
s-drill feed (mm/rev)
Ø-1/2 point angle
βn-normal shear angle (degrees)
γn-normal rake angle (degrees)

It is found that as feed increases the chip reduction coefficient decreases for all the cases. On the contrary the chip reduction coefficient increases with increase in speed initially and thereafter decreases with increase in speed.So the value of chip reduction coefficient, ζ (and hence cutting ratio) depends mainly upon tool rake angle and chip-tool interaction. The force exerted by the tool on the laminate arises out as thrust force. As a result of compression, shear stress is developed within the compressed region, in different magnitude and direction. Wherever the value of shear stress exceeds the shear strength of the laminate in the deformation region, slip takes place resulting shear deformation. As a result the slip stops propagating before separation takes place. In the mean time the succeeding portion of the chip undergoes compression followed by yielding and shear. This phenomenon repeats rapidly resulting in formation and removal of chips in thin layer by layer which can be witnessed in the case of Carbide drill.

Due to intensive rubbing of the laminate with the tool at high feed and temperature the lower surface becomes smooth due to further plastic deformation. The pattern of shear deformation by lamellar sliding can also be seen in actual chips.Thus, an optimum clearance angle has to be determined for every tool. Fig.7.shows the nature of chip formation and their corresponding chip reduction coefficient values.

Fig.7. Chip formation at different drilling conditions

Continuos ribbons like chips were produced when drilling was done with carbide drill. In the case of PCD, finer (powder) chips were formed when machining at high speed and feed rates. On the contrary very rough and coarse chips were produced when HSS was used. This phenomenon existed at all conditions of drilling. Serrated chips were produced at low speeds in the case of carbide drills. Mechanism of material removal was quite different in the case of PCD drills which may be due to reduced number of flutes.

IV. CONCLUSIONS

The following are the conclusions drawn from the experimental work

Low feed rates appear appropriate for laminate drilling, as it reduces the thrust force. However, this option can result in thermal degradation of the matrix and may not be suitable for industrial processes where productivity is of paramount importance. Large helix angle in the Carbide drill significantly reduces the thrust and torque.Delamination observed is minimum in the case of high cutting speed and feed for PCD tool.Delamination is also vey minimum for Carbide and HSS tool at high speeds.Delamination factor increases with increase in cutting speed and feed but at high speed and feed it decreases due to greater work done which facilitates easy drilling of composites without much distortion. Hardness of drill material significantly contributes for variation in forces and finish

Carbide drills produced continuous ribbon like chips due to lamellar sliding. Shear deformation takes place because of tool-material slip which resulted in discontinuous particle like chips in the case of HSS and PCD drills.Discontinuos chips formed accounts for the crater wear, as these chips act as free abrading material which creates a micro-ploughing action on the tool surface.PCD provides good surface finish at high cutting speed and feed rate, because the work done is more due to lower helix angle which facilitates the initial penetration.

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