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Study on Tool Wear and Chip Formation during Drilling Carbon Fiber Reinforced Polymer (CFRP)/ Titanium Alloy (Ti6Al4V) Stacks

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Abstract

Composites are used in conjunction with another material to form a multi-material stack-up, which results in greater strength to weight ratios. In a wide range of aerospace applications dissimilar material stack-ups of composites and aluminium and/or titanium are used. Drilling is probably the most common machining operation applied to composites since components made out of composite materials are usually near net shaped and require only holes for assembly integration. In this investigation, experiments were conducted by varying the drilling parameters and determining the optimum cutting conditions for drilling of CFRP/Ti stacks using Genetic Algorithm (GA) optimization technique. Tool wear study was performed by drilling 100 holes each with 118° and 130° point angle drills. Less progressive tool wear and better chip evacuation was achievable in 130° point angle drills when compared with 118°point angle drills.

Keywords: Drilling, Tool wear , Carbon fiber reinforced plasitc (CFRP), Titanium alloy (Ti6Al4V), Point Angle (PA), Genetic Algorithm (GA)

1. INTRODUCTION

Light weight materials are being used extensively in present aircraft industry to reduce fuel consumption. Especially composite materials are replacing metal parts in aircrafts. In that case metals are stacked with composites to supplement their properties. These hybrid structures result in better strength to weight ratio. Recent trend in aircraft industry has been using CFRP/Ti stacks in many parts including fuselage and tail. In spite of the advantages, the hybrid stacks are difficult to

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machine. The excessive abrasive nature of CFRP causes chipping in tool. The low thermal conductivity of titanium alloy causes built up edge (BUE), thus reducing tool life significantly. Large amount of research has been done on tool wear in machining CFRP and Ti alloy separately. Tool wear study in machining of CFRP/Ti alloy stacks is limited. Low feed and low spindle speed are desirable for machining CFRP. Machining of Ti alloy is efficient at low spindle speed. **Lin and Chen** carried out a study on drilling carbon/epoxy material at high speed and concluded that an increase of the cutting velocity leads to an increasing drill wear that in turn provokes it an increase in the thrust force [1].**Ramulu et al** made a study on the drilling of composite and titanium stacks and found that fewer holes were produced when high spindle speeds and slow feed were used. It is found that carbide drills outperformed all other tools in terms of tool life, minimal surface damage and heat induced damage on both workpiece materials [2].

Krystian k et al studied drilling of CFRP/Ti stacks with two flute and three flute drills and also varying helix angle of 20° and 40°. Drills with higher helix angle suffered from chipping of primary cutting edges when used at higher feed rate. But drill with lower helix angle has stronger cutting edge and is less prone to chipping however resulting in higher cutting forces and temperatures. **[**3] D.A**. Stephenson et al** examined the chip formation mechanisms of spiral chips and string chips. In this study, the interactions from drill flute and work piece on chip forming and evacuation were analyzed. Also, this study proposed chip length models for both spiral chips and string chips based on the difference between the natural chip exit angle and the actual chip exit angle. Based on these models the chip forming smoothness can be revealed and the average chip length can be predicted qualitatively[4].**Prabukarthi et al** stated that the attaining of lower thrust force at higher feed rates is due to the fact that the modulus of elasticity of the material decreases when drilling at high speeds. Likewise higher thrust force will be obtained at lower feed rates **[5]Krishnaraj** et al oprimized the machining paramtere for high speed drilling of CFRP and mentioned that 12,000 rpm spindle spped and 0.137 mm/rev feed was the optimized machining condtion with lees tool wear [6]**. Prabukarthi et al** optimized the machining parameter on drilling of Ti6Al4V alloy and stated that spindle speed of 1000 rpm and feed rate of 0.13mm/rev produce acceptable hole diameter deviation [7].Unlike metals; CFRP cutting involves not only tool edge chipping but also excessive abrasive wear due to the hard carbon fibers. The dominant wear mechanism on the WC drill for the higher drilling speeds are edge micro-chipping and abrasive wear by the hard fractured graphite fibers and carbide grains. Furthermore, the carbon fibers can attack the cobalt binder, which is relatively soft, causing a lowered binding force with the carbide grains, which can accelerate tool wear and crack propagation. The flank wear on the WC drill, when drilling CFRP, was significantly affected by cutting speed [8].Drilling CFRP-metal stacks poses several challenges due to the different machining properties of two or more distinct materials. The ideal tooling solution for metal is not the most efficient or cost effective for CFRP and vice versa. This leads to a compromise in tool geometry and cutting parameters which often leads to severe tool wear, in turn causing increased drilling forces, poor hole quality and large metallic burrs in CFRP-metal stack drilling. Excessive heating caused by Ti machining induces a many of hole quality problems in CFRP [9]. Cutting tool life is one of the most important economic considerations in metal cutting. In roughing operations the various tool angles, cutting speeds, and feed rates are chosen to give an economical tool life. Conditions giving a very short life are uneconomical because tool-grinding and tool replacement costs are very high. On the other hand, the use of very low speeds and feeds to give long tool life is uneconomical because of the low production rate. Clearly, any tool or work material improvements that increase tool life will be beneficial. Considerable efforts have been made over the years to develop new and improved materials with better tool life. To form a basis for such improvements much effort has been made to understand the nature of tool wear and other forms of tool failure. To address these issues an experimental analysis of tool wear were studied by drilling 100 holes each with 118°lip angle and 130° lip angle drill bit. Comparisons were done with respect to flank wear, chisel edge wear, delamination, burr height, tolerance and the respective parameters which influenced them the most were found out. Chip morphology was also analyzed and the effect of tool geometry was studied.

1.1. Experimental Analysis and formulation of Design of Experiments

Experimental studies were carried out in Deckel Maho 835 Vertical machining Centre. A Syscon two – component tube type strain gauge drilling dynamometer (model: SI-674) shown in Fig.1 was used to measure the axial thrust force and torque. The imbalance of the wheatstone bridge circuit can be related to the thrust force and the torque values, the imbalance produce a proportional voltage equal to the applied force and torque. The proportional charge output from the dynamometer was fed to a Syscon charge amplifier (model: SI-223D), thus producing a scaled voltage output signal proportional to the applied load in the digital form. Digital storage oscilloscope (Tektronix TDS210) was used to measure and store the thrust and torque variations during drilling.

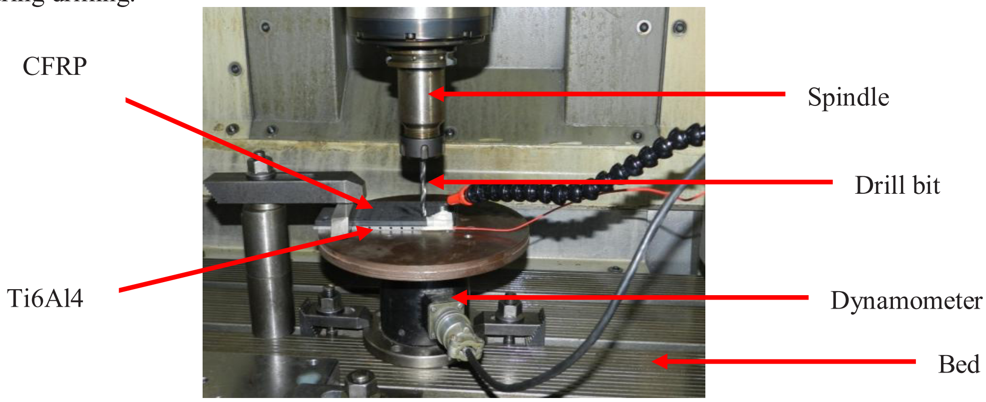


Fig.1. Experimental Setup

Two drill tool of varying geometry were taken for tool wear study. They were used to drill 100 holes in CFRP/Ti alloy stacks. The tool wear was measured after drilling 10 holes. The flank wear and chisel edge wear was measured using Mitutoyo tool makers microscope (TM-500 Series). Periodic recording of tool wear where done using Mitutoyo make stereo microscope. The Taguchi method involves reducing the variation in a process through robust design of experiments. The overall objective of the method is to produce high quality product at low cost to the manufacturer. Taguchi developed a method for designing experiments to investigate how different parameters affect the mean and variance of a process performance characteristic that defines how well the process is functioning. The experimental design proposed by Taguchi involved using orthogonal arrays to organize the parameters affecting the process and the levels at which they should be varied. Instead of having to test all possible combinations like the factorial design, the Taguchi method tested pairs of combinations. This allowed for the collection of the necessary data to determine which factors affected product quality the most with a minimum amount of experimentation, thus saving time and resources. The Taguchi arrays can be derived or looked up. Small arrays can be drawn out manually and large arrays can be derived from deterministic algorithms. The arrays are selected by the number of parameters (variables) and the number of levels (states). Two levels of three factors namely spindle speed; feed rate and coating were taken. The factors and their corresponding levels are level I spindle speed 612 rpm and feed 0.05mm/rev and level II spindle speed 1826 rpm and feed 0.05 mm/rev.

1.2. Regression Analysis

Regression analysis is a statistical tool for the investigation of relationships between variables. Usually, the investigator seeks to ascertain the causal effect of one variable upon another. To explore such issues, the investigator assembles data on the underlying variables of interest and employs regression to estimate the quantitative effect of the causal variables upon the variable that they influence. The investigator also typically assesses the statistical significance of the estimated relationships, that is, the degree of confidence that the true relationship is close to the estimated relationship. The data obtained from the experiments conducted were fed to Minitab software. The regression equations obtained are as follows

$$\text{Thrust in CFRP} = 96.67 - (0.0163 X N) + (567 \times F) \quad (1)$$

$$\text{Thrust in Ti} = 412 - (0.057 \times N) + (2834 \times F) \quad (2)$$

Where N – Speed in rpm F – Feed in rev/mm

The correlation coefficient (R^2) of the "Eq. (1&2)" are 80.1% & 65.95% respectively. The correlation coefficient for the thrust force on Ti alloy was less than 80% because of practice difficulty in exactly getting the force value when the drill moves from CFRP to Ti alloy. The genetic algorithm (GA) is a population-based search optimization technique. In general, the fittest individuals of any population tend to reproduce and survive to the next generation, thus improving successive generations. However, inferior individuals can, by chance, survive and also reproduce. Genetic algorithms have been shown to solve linear and nonlinear problems by exploring all regions of the state space and exponentially exploiting promising areas through mutation, crossover and selection operations applied to individuals in the population. The use of a genetic algorithm requires the determination of six fundamental issues, chromosome representation, selection function, the genetic operators making up the reproduction function, the creation of the initial population, termination criteria and the evaluation function [10].The genetic algorithm uses three main types of rules at each step to create the next generation from the current population by means of selection rules select the individuals called parents that contribute to the population at the next generation, crossover rules combine two parents to form children for the next generation and mutation rules apply random changes to individual parents to form children. In computing terms genetic algorithm map strings of numbers to each potential solutions. Each solution becomes an individual in the population and each string becomes a representation of an individual. There should be a way to derive each individual from its search for improved solution. The algorithm operates through a simple cycle by mean of creation of population of strings (initial population),evaluation of each string, selection of best strings and genetic manipulation to create a new population of strings (new generations). The cycle is repeated until the level of fitness is attained. For the objective function formed as in equations (1 & 2), the genetic algorithm tool in MATLAB was executed by varying the population size while retaining selection rules, crossover rules and mutation rules as the same to obtain the optimized operating condition. The convergence of computed values from continuous iterations was obtained at a population size of 800. The Optimized values of spindle speed and feed are 859 rpm and 0.0581 mm/rev.

2. Tool Wear Mechanism Study

Wear is the removal of the material from the surface of a solid body as a result of mechanical action of the counter body. Wear may combine effects of various physical and chemical processes proceeding during the friction between two counteracting materials such as micro-cutting, micro-ploughing, plastic deformation, cracking, fracture, and welding, melting and chemical interaction. Various forms of tool wear on the drill tools are flank wear, crater wear, chisel edge wear and chipping. Wear on the flank of a cutting tool is caused by friction between the newly machined workpiece surface and the contact area on the tool flank. The width of the wear land is usually taken as a measure of the amount of wear and can be readily determined by means of a toolmaker's microscope. The flank wear also increase the cutting forces and also heat between tool and work piece. The wear patter is irregular along the edge of the tool. Often, chipping wear leads to a catastrophic failure early in the life of the tool which masks the failure mode. Mechanical issues such as machine spindle or part fixture vibration will contribute to chipping wear. A tool holder with a large cantilever condition will cause harmonic vibrations to be amplified at the cutting edge. Excessive loads on the tool will cause chipping. [11, 12].In this current research flank wear and chisel edge wear were studied for two types of twist drills of the following specification given in Table 1.

Table 1. Specifications of Tool with TiAlN coating

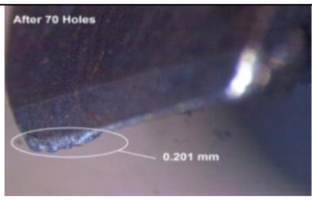
	SGS (SOLID WC-118°)	SGS (SOLID WC-130°)
Point angle	118°	130°
Helix angle	20°	30°
Chisel edge thickness	1.215 mm	0.450 mm

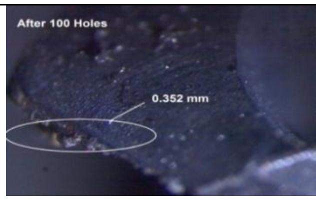
2.1. Tool Wear analysis for 118° Point angle drill

The 118° drill had a higher flank wear and chisel edge wear rate which is shown in Table 2. This can be attributed to higher thrust force because of larger chisel (1.215 mm) acting on the tool flank resulting in localized plastic deformation. The plastic deformation results in increased contact area and hence higher friction between drill and workpiece. This increases the temperature of both tool and workpiece at the cutting zone. As a result the ductility of tool flank increases causing a higher flank wear rate after 80 holes.

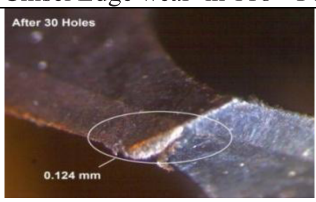
Table 2. Flank and Chisel Edge wear for 118° Point Angle drill

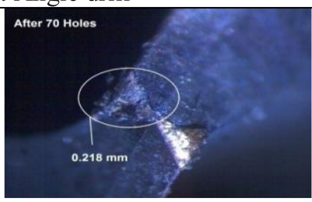
Flank wear in 118° Point Angle drill

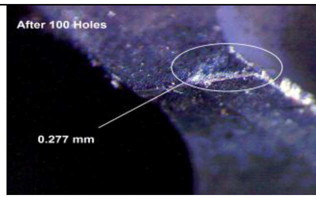




Chisel Edge wear in 118° Point Angle drill







2.2. Tool Wear analysis for 130° Point angle drill

The flank wear in 130° drill occurred at a lower rate when compared to 118°. In contrast to the 118° drill tool, the 130° tool produced a very low thrust force. The chisel edge thickness of 0.45 mm is the main reason for low thrust and hence a lower flank wear rate. There was no sudden increase on flank wear rate like 118° drill. The progressive chisel edge and flank wear were presented in Table 3.

Table 3. Flank and Chisel Edge wear for 130° Point Angle drill

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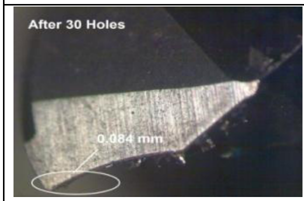
<td>
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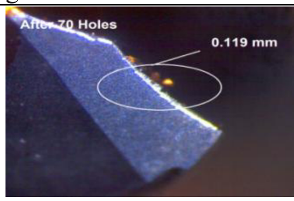
<td>
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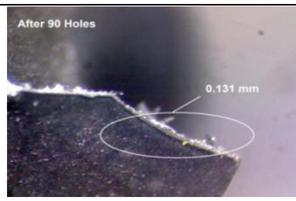
<td>
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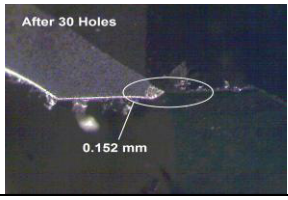
<td>
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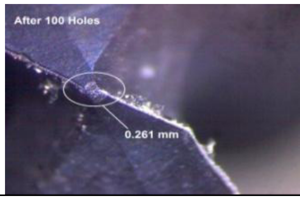
<td>
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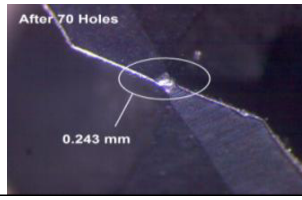
<td>
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3. Chip profile study

Chip shape is the most important factor for the smoothness of a drilling process. The drilling process will be smooth if chips are well broken. While drilling CFRP/Ti stacks, CFRP chip are broken into smaller dust particles because of high abrasive characteristic. While the drill passes from CFRP to Ti alloy a continuous Ti chip was formed which was analyzed in detail during the cores of the study. However, most ductile materials do not break during drilling, and instead, form continuous chips. Based on the chip forming mechanisms, continuous chips can be categorized to spiral chips and string chips. When chips are initially generated, because the inner cutting edge moves slower than the outer cutting edge, the inner chip is inherently shorter than the outer chip. This difference in length within the chip forces it flow to the drill center instead of perpendicular to the cutting edge. Spiral chip which is show in fig 2 are structurally determined to rotate on their own axis while moving upwards. This motion is only free when the drilled hole is shallow. The chip natural flow angle θ can be obtained from eq (3 & 4).

$$\theta = (\rho_p/2) - \eta \quad (3)$$

$$\eta = \sin^{-1}((D_b - W_b)/ D_b)*\sin(\rho_p/2)) \quad (4)$$

Point angle- ρ_P D_b- Diameter of the drill W_b- Drill web thickness

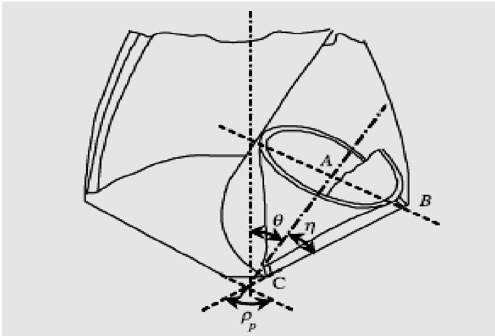

Fig 2 Chip Flow

3.*1 Chip profile analysis during drilling using 118° point angle drill*

Chip shape for first the 40 holes was spiral cone chip which is easier to be ejected, so the length of spiral cone chip can be considered as a scale to evaluate the difficulty for chip evacuation in drilling. Therefore short chips are preferred and also tight helix chips provide better surface finish. As the wear progress after 40 holes up to70 holes the length of the spiral cone decreases and the bending effect comes into picture where ribbon chips of large lengths are formed. This is due to the chips not able to rotate around its own axis. After 70 holes the wear becomes severe due to which thrust force increases rapidly. This makes the chip to reduce its thickness and the pitch starts increasing. Since the helix angle is 20˚ in this drill, chip instead of flowing through the flute freely it gets bent heavily with large lengths. Long ribbon chips are not ideal in terms of both chip evacuation and surface finish of the machined hole. A detailed chip shape transformation is shown in Table 4.

Table 4. Chip shape during drilling of Ti6Al4V using 118˚ point angle drill

Chip Shape (1 to 40 Holes)		
		
Chip Shape (40 to 70Holes*)*		
		
Chip Shape (70 to 100 Holes)		
		

3.2 Chip profile analysis during drilling using 130° point angle drill

Chip formation for 1 to 40 holes is ideal which is short spiral one. Once the number of holes in increases from 41 to 70 spiral chip length is less and the remaining is ribbon shaped. During the drilling of 70 to 100 holes chisel edge is totally worn out and this again increases the thrust force which pushes the chip to unwound. The unwound chip changes its pitch and when it equals the pitch of the drill the transition from spiral to string chip takes place. This highly creates the chip evacuation problem which even leads to breakage of tool when proper chip breaking is not provided. A detailed chip shape transformation from 1 to 100th hole is given in Table 5.

Table 5. Chip shape during drilling of Ti6Al4V using 130˚ point angle drill

Chip Shape (1 to 40 Holes)		
		
Chip Shape (40 to 70Holes)		
		
Chip Shape (70 to 100 Holes)		
		

4. Results and Discussion

4.1 Effect of point angle on flank wear

Abrasion is the major mechanism for flank wear. Generally flank wear is independent of spindle speed. The complex hard phase within Ti abrades the flank surface after shearing the 3D microstructure. Due to the rapidly evolving flank wear with number of holes, the thrust force increased more rapidly at the higher spindle speed over the lower spindle speed. When drilling Ti the cutting temperature became high enough to activate high adhesive affinity and to soften the WC drill. Softening of the WC drill is due to the softening of the cobalt (Co) binder that holds the carbide grains together. The flank wear is therefore extended by the mechanism of carbide grains pulled out of the Co binder as the Ti adhesion is removed while drilling through the CFRP in the next hole, in addition to the abrasion by the hard phase in the Ti alloy. In metal drilling, the cutting edges can be partially protected due to the BUE of the cutting edges maintaining the edges more consistently. This is why Ti drilling had a greater effect on flank wear. A detailed comparison between flank wear and number of holes is presented in fig 3.

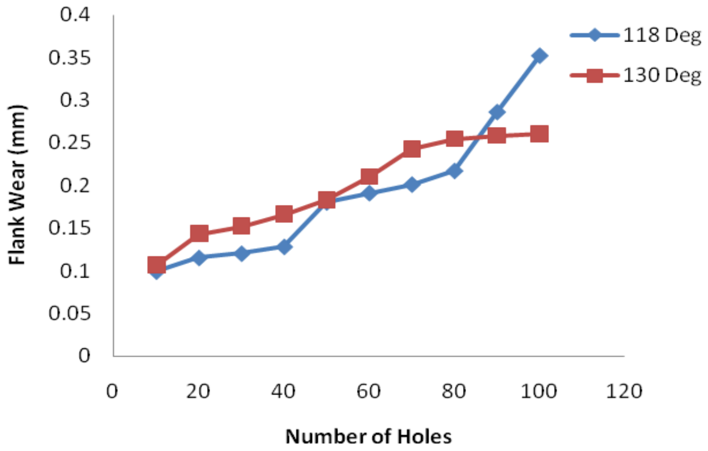

Fig.3. Effect of Flank Wear on point angle

4.2 Effect of point angle on chisel edge wear

The chisel edge wear depends on the feed rate and relief angle. The wear increases with increase in feed rate. Smaller relief angles are not recommended because their contribution to chisel edge wear is high. Furthermore Ti alloy adhesion causes built up edge (BUE) on the chisel edge. When these BUE break up, the rate of chisel edge wear is increased substantially. Chisel edge wear causes an increase in thrust force due to increased bluntness of tool. Given that the stacking sequence of the stacks is CFRP on top of the Ti, Ti adhesion is observed on all the drills after drilling a set of 20 holes. Adhesion is a well-known characteristic in Ti drilling due to the high chemical affinity to most of the tool materials [13].The adhesion leads to build-up edge (BUE) formation, which is an accumulation of work material on the cutting edges. The BUE deteriorates the hole quality and leads to the tool chipping or fracture when the BUE breaks off from the cutting edges. The adhesion was formed as soon as Ti drilling started, and covered a large part of the flank surface especially at the higher spindle speed. The amount of Ti adhesion is directly related to the chemical reactivity of Ti, which increases with temperature. A detailed relationship between chisel edge wear and number of holes is presented in fig 4.

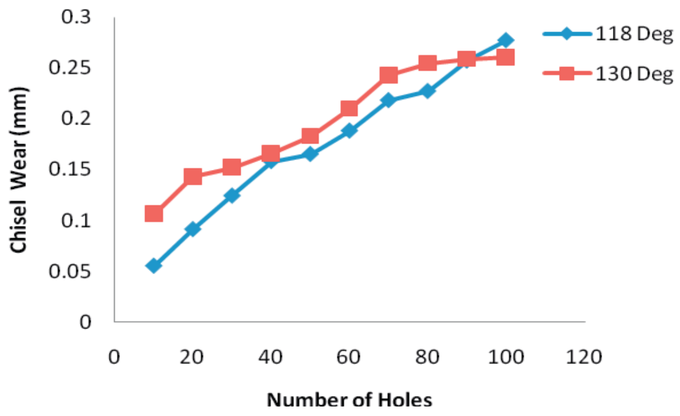

Fig.4. Effect on chisel Edge wear on point angle

5. Conclusion

The machining parameters (cutting speed and feed rate) are optimized using Genetic Algorithm and the result on the effect of tool wear over the optimized machining conditions were presented below

In 118˚ point angle drill there was a rapid increase in flank wear increases rapidly after 80^{th} hole wear reaches to the maximum value of 0.352 mm at 100^{th} hole. While compared with the 130˚ point angle the flank wear was 0.138 mm by the end of 100^{th} hole. Chisel edge wear was greatly influenced by thrust force for both 118˚ and 130˚ point angle drills. Chip formation has a significant influence on the thrust force and tool performance. Tool fails when the chip produced has a long ribbon shape. The overall performance of 130˚ point angle drill is better than 118˚ point angle drill because of smaller chisel edge thickness and increased point angle. In general as number of holes increases the chip shape varies from spiral cone to ribbon chip and after the 68^{th} hole the string chip transformation take place and very long continuous string chips are formed and chip clogging take place. Due to this the drill may eventually fail id proper chip braking method is not used.

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