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Study on drilling of CFRP/Ti6Al4V stack with modified twist drills using acoustic emission technique

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Abstract. Carbon Fiber Reinforced Plastic (CFRP) and Titanium Alloy (Ti6Al4V) stack, extensively used in aerospace structural components are assembled by fasteners and the holes are made using drilling process. Drilling of stack in one shot is a complicated process due to dissimilarity in the material properties. It is vital to have optimal machining condition and tool geometry for better hole quality and tool life. In this study the tool wear and hole quality were analysed by experimental analysis using three modified twist drills and online tool condition monitoring using Acoustics Emission (AE) sensor. Helix angle and point angle influence tool performance and cutting force. It was found that a tool geometry (TG1) with high helix angle of 35° with low point angle 130° results in reduction in thrust force of 150-500 N range but the TG2 also perform almost similar to TG1, but when compared with the AErms voltage generated during drilling it was found that progressive rise in voltage in TG1 is less with respect to TG2 which can be attributed to tool life. In process wear monitoring was done using crest factor as monitoring index. AErms voltage were measured and correlated with the performance of the drills.

Keywords: CFRP/Ti6Al4V stack; tool geometry; wear; crest factor; acoustics

1. Introduction

Recent trends in the aerospace industry have been to increase the use of Fiber Reinforce Plastic (FRP) with titanium or aluminium alloy because of the outstanding mechanical properties possessed by them during critical load carrying locations in many military and commercial aircrafts. In recent times CFRP/Ti6Al4V stack have been extensively used for the various components of the airbus. The integration of the various sub-components are made by assembly process which is supported by traditional fastening technique. Drilling is the essential machining process which is used for hole making that support the assembly of the components. Drilling and fastening of the CFRP & metals in one-shot operation reduce manufacturing time in building aircraft structures. The most common problems encountered during drilling of CFRP/metal structures (composite/titanium or composite/aluminium) are damage on the composite material due to the interaction between the continuous metallic chips and the surface of the composite material, the high thrust force induced during drilling can separate CFRP and aluminium plates

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which contribute to the accumulation of aluminium chip and carbon dust at the interface of CFRP/Al and adhesion of the metallic layer on the cutting edge of the tool. (Zitoune *et al*. 2010, 2012 and 2016).

Research papers in the area of drilling of stack composed of CFRP/Ti6Al4V are very less. While drilling the stack heat generated on Ti6Al4V may damage CFRP. Most of the studies were focused on the effect caused by the damage (Brinksmeier and Janssen 2002, Shyha *et al*. 2011, Pecat and Brinksmeier 2014, Kim and Ramulu 2004, 2007). Later on studies highlighted the cause of wear on the cutting tool by the stacked material. Common tool wear mechanisms seen in drilling CFRP and titanium are abrasion, attrition, diffusion-dissolution, mechanical fatigue, and thermal fatigue. When drilling CFRP, common defects observed include and are not limited to: delamination, fiber pullout, fuzzing, and matrix melting In general researchers has studied the modes of the tool flank wear in drilling CFRPs, or in machining FRPs. Effects of flank wear during drilling has greater influence on thrust force and torque. Studies empirically proved that the thrust force increases due to the excessive tool wear, and increases delamination (Marques *et al*. 2009, Tsao *et al*. 2012, Hocheng *et al*. 2014). The wear generated by Ti6Al4V is mostly confined to cutting edge chipping on the drill corners. The distribution of the force along the cutting edge denotes the importance of the chisel geometry for the total cutting forces. Effect of lowering the size of the chisel edge or performing an additional web thinning by grinding in the drill bit will make the cutting in close vicinity of the tool axis more efficient and therefore lower the chances of delamination (Lazar and Xirouchakis 2011, Velayudham and Krishnamurthy 2007).

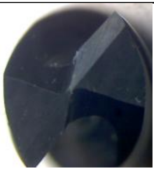
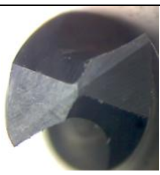
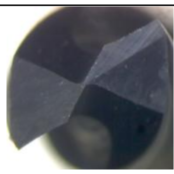
Several studies on process monitoring have been focused on measuring thrust, torque, power and other indicator to detect the tool wear (Park *et al*. 2011, Wang *et al*. 2013, Pecat and Brinksmeier 2014a, Poutord *et al*. 2013, Wang *et al*. 2013, 2014). But among them acoustic emission are considered as one of the effective monitoring methods in the machining environment. AE signals in CFRP and Ti6Al4V are different. In CFRP plate the AE signals are generated by microscopic damage created by the cutting mechanism. Microscopic damages such as micro cracking of matrix, debonding at the fibre/matrix interface, fibre breakage, fibre pullout and localised delamination are induced by the application of thrust force and the impact of the cutting tool with work material during drilling. Monitoring the signal behaviour in machining of Ti6Al4V is not widely reported. In Ti6Al4V the adhesion tendency causes chip build-up at cutting edge, tendency of chip weld to the cutting edge are significant for AE signal. Local deflection of the work material during cutting process is caused by the local deflection of the uncut part of the workpiece.

In this paper, experimental study on drilling of multi-material made of CFRP laminate with titanium alloy (Ti6Al4V) has been carried out. Drilling tests have been conducted using three modified solid twist drill (K20) under various speed, feed and coating thickness. The objective are to identify better tool geometry that can provide better hole quality and AE sensor assisted signals were captured and the signals were decomposed and analyzed to understand behavior of the tool. Wavelet packet transform is used to study the condition of the drill during drilling. (Arul *et al*. 2007, Velayutham *et al*. 2005, Moal 2012].

2. Design and development of modified solid twist drill

Drill geometry plays an important role in drilling of CFRP/Ti stack. Standard drill tool manufactures and innovators form their experience suggested the range of values that gives better

Table 1 Modified drill tool geometry parameters

Parameter	1	2	3
	 TG 1	 TG2	 TG3
Drill point angle	130°	135°	140°
Helix angle	35°	30°	34°
Core diameter (mm)	2.1	1.6	2
Coating thickness(μm)	1.5	2.0	3.5
Web thickness (mm)	0.8	0.9	1

result with respect to various tool geometry parameters. The recommendations are, helix angle should be in the range of 25° and 35° with respect to axis, margin width should be maintained between 5% to 10% of drill diameter, body clearance diameter should be maintained between 92% to 96% of the drill diameter, web thickness should be maintained between 20% to 30% of drill diameter and chisel edge angle should be maintained between 105° and 120°. Developer of drill tool for one shot machining of Ti-Al-CFRP suggested that the helix angle should be in a range of 30° to 35° and point angle be 130° (Sampath and Ni 2008, Capone 2011).

Based on the literature survey and the tool geometry recommendations by the cutting tool manufacturer, five cutting tool parameters point angle, helix angle, core diameter, web thickness and coating thickness have been selected and are presented in Table 1. Torque significantly increases with the web thickness and decreases with the helix angle. Thrust significantly increases with the web thickness and decreases with the point angle and the helix angle. Core diameter has a greater influence on the stability of drilling and coating thickness has a greater influence on the tool life. (Satoshi 2012)

3. Acoustic Emission an assist for signal processing

Monitoring the machining process has gained attention from researchers and designers for more than a decade and new advancements/techniques have taken them to a new level in recent times. As an attempt to monitor the process while drilling of CFRP/Ti stack, Acoustic Emission sensor is predominantly used in signal processing. In this paper, the wavelet transform (WT) have been used as a tool to handle the AE signals and know the behaviour of the tool/work piece interaction. Wavelet toolbox an efficient signal manipulator from Matlab has been used to decompose the signal and extract characteristic features that give useful information about the condition of tool in drilling of CFRP/Ti stack. Wavelets transform a mathematical function as in Eqs. (1)-(3) that multiplies the signal during all its length, with elongated and compressed versions of a mother wavelet. A signal is decomposed into a low frequency component (called approximation) and a high-frequency component (called detail). The approximation in turn is then decomposed into a second level of approximation and detail and this process is repeated. WT can extract signal information in the time domain at different frequency bands and provides flexible time-frequency

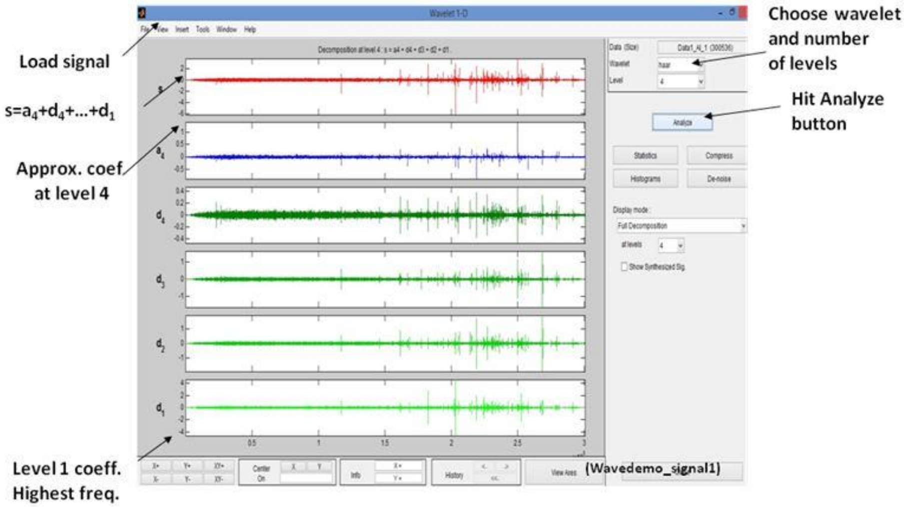


Fig. 1 Signal decomposition

resolution properties.

However, WT has one drawback that the frequency resolution is rather poor in the high-frequency region. Thus, it faces difficulties in discriminating between signals having close high frequency components. To overcome the drawback of wavelet transform, wavelet packet transform is used as one of the most generalized signal decomposition methods. Wavelet packets are alternative wavelet bases formed by taking linear combination of the usual wavelet functions. These bases inherit properties, e.g., orthonormality and time-frequency localization, from their wavelet functions (Wu and Du 1996). In wavelet packet transform, both the approximation and detail parts are decomposed as in Fig. 1. A wavelet packet function is a function with three indices (i, j, k) satisfying Eq. (1)

$$W_{j,k}^{n}(t) = 2^{\frac{j}{2}} W^{n}(2^{j} t - k) \tag{1}$$

where, W^n - Wavelet transform function, t - Represents the time shift or location, i - Packet number, j - Number of level, k - Series of integer.

Wavelet packet functions are defined by

$$W_{2n}(x) = \sqrt{2} \sum_{k} h(k)\, W_n(2x - k) \tag{2}$$

$$W_{2n+1}(x) = \sqrt{2} \sum_{k} g(k)\, W_n(2x - k) \tag{3}$$

where $h(k)$ – low pass filters, $g(k)$ – high pass filters ,$W_1(x) = \psi(x)$, $\psi(x)$ - mother wavelet function, k – Series of integer

Some packets contain important information while others are relatively unimportant. The packets that contain the characteristic features of the signal have higher energy, are called feature packets. In this paper, energy of the wavelet packet is taken as criteria for selection of feature packets (Velayutham *et al*. 2005).

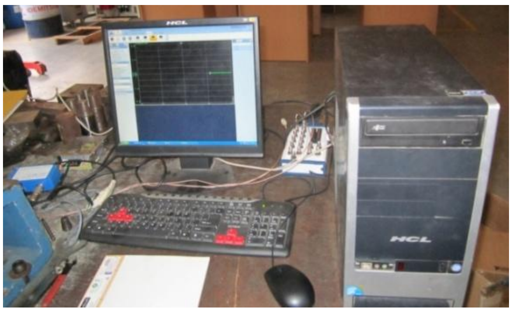
4. Experimental analysis

The CFRP/Ti6Al4V stacks are temporarily fastened together and the experimentation was carried out on Makino SS33 machining centre. Carbon fibre reinforced plastic (CFRP) composite of 4.2 mm thickness (16 layers) was used for conducting the drilling studies. The CFRP composite was made using unidirectional prepregs supplied by Hexcel Composite Company referenced as Hexply T700-M21. The lay-up sequence of the CFRP was [90/-45/0/45/90/-45/0/45]s. so as to get a quasi-isotropic laminate, and the laminate was cured in an autoclave. The nominal fibre volume fraction is 0.58. Ti6Al4V used in the experimental investigation was 3 mm thick .Tool condition monitoring of cutting tool was carried out using Piezotron AE sensor (Model no 8152B111)**.** A miniature impedance converter is built into the Piezotron AE sensor, giving an output low impedance voltage signal. The AE Piezotron Coupler type 5125 B1, is used to supply power to the sensor and for signal processing. AE-Piezotron coupler with built-in RMS converter and Limit Switch has been specially designed for the processing of high frequency sound emission signals. Experimental analysis of drilling trails has been carried out using three type of modified Tungsten carbide (WC) twist drill coated with TiAlN and the detailed setup is shown in Fig. 2.

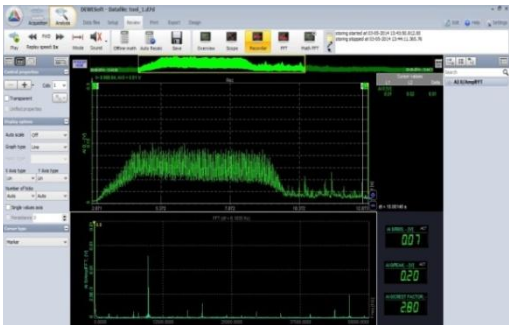
Based on the results obtained in the previous studies on drilling of CFRP/Ti stack, the

(a) Makino SS 33 machining center

(b) CFRP/Ti6Al4V stack with dynamometer



(c) Data acquisition system



(d) Output of acoustic emission sensor signal

Fig. 2 Experimental setup

Table 2 Design of Experiment for drilling CFRP/Ti stack

Levels	1	2	3
Factors	Spindle speed (rpm)	Feed (mm/rev)	Coating thickness (μm)
1	895	0.05	1.5
2	1000	0.1	2
3	1800	0.08	3.5

machining parameters such as spindle speed and feeds were finalized and are presented in Table 2 (Krishnaraj *et al*. 2012b, SenthilKumar *et al*. 2013, Prabukarthi *et al*. 2013, 2011).

As CFRP gives better results in drilling at high spindle speed and low feed while on Ti6Al4V, low spindle speed and high feed are desired. As a result, the combination of high/low speed and high/low feed are made in the design of experiments (DOE). To study the behaviour of the coating on tool wear three coating thickness of 1.5, 2 and 3.5 micro have been used. Experiments were conducted using full factorial design ($3^3 = 27$ tests). In order to measure the axial thrust force and torque Syscon two component strain gauge type drilling tool dynamometer was used. Measurement of delamination was carried out by capturing the image of the CFRP using stereo microscope with camera under 20 X zoom condition and the image were analysed using image J software to measure the delamination factor. Tool wear of cutting tools in metal cutting accounts for a significant portion of the production costs of a component. Tool wear occurs due to the physical and chemical interaction between the cutting tool and workpiece as a result of the removal of small particles of the tool material from the edge of the cutting tool. Heat generation, friction and stress distribution are the main contributors of drill wear. Wear starts at the sharp corners of the cutting edges and distributed along the cutting edges until the chisel and drill margin. Flank wear is considered as one of the criterion to measure the performance of a drill which is done in this study. It occurs due to the friction between the workpiece and the contact area on the clearance surface.

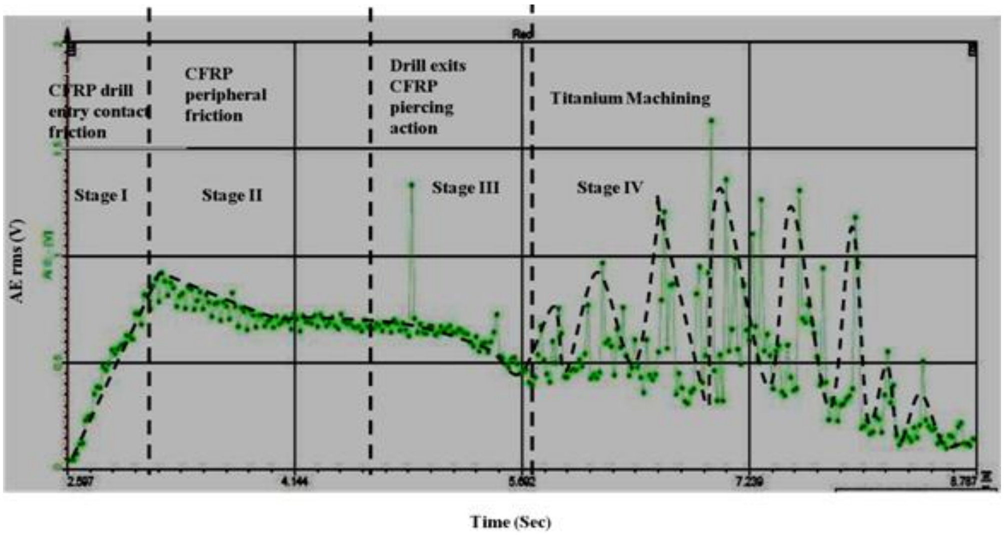


Fig. 3 Stages in drilling of CFRP/Ti6Al4V stack

Tool conditioning monitoring of the drilling process was carried out using AE sensor which is interfaced with data acquisition system. The signal from the AE sensor is directed to the coupler to which has built in RMS converter.

Acoustic emission is the generation of high frequency elastic stress waves in a material due to the release of strain energy during the deformation, fracture and phase changes. These stress waves propagate throughout the material and, therefore, it is not necessary to mount the sensor at the exact location where the waves are emanating. The frequencies emitted generally run between the audible frequency ranges into megahertz range. There are two types of AE signals: burst and continuous. Burst type signals contain pulses over a period of time above a background signal and are significantly separated with limited overlap. Continuous type signals do not have any significant resolutions between individual pulses. Both types can be present in the metal removal process and will be considered during analysis. Several studies on in-process monitoring have been focused on measuring thrust, torque, power and other indicators to detect the tool wear. But among them acoustic emission is considered as one of the accurate monitoring methods in the machining environment. AE based signal monitoring had been widely reported in machining operations.

AE signals from drilling process is stored in the PC for further manipulation and feature extraction. The signal can be sub-divided into regions as stages in drilling as shown in Fig. 3. Contact friction stage as chisel edge touches the work material and creates an indentation, makes a rubbing contact friction (Moal 2012, Sampath and Ni 2008) Micro chipping stage during the period secondary cutting edge gets in contact and drilling forces increases because of cutting of fibre and matrix. In Piercing action stage while the drill reaches the last few lamina of CFRP before exit. This is because the stiffness of the laminate reduces and remaining lamina bends elastically preventing the cutting edges to remove the material. In other words drilling action is not effective at this stage. While the drill touches the Ti alloy there is a steep increase in the AErms value of the signal, because of relatively harder than CFRP. There is a continuous increase in the signal value because the cutting edges constantly hitting the surface for removing the material and the edge chipping caused blunt the tool cutting edges (Ravishankar and Murthy 2000a, b).

5. Results and discussion

5.1 cutting forces in drilling of CFRP/Ti6Al4V stack

Typical thrust force and torque magnitudes when the carbide tool drills through the stack are shown in Fig. 4. The chisel edge of the tool comes in contact first. There is a sharp rise in the thrust force, since the chisel cuts with a negative rake angle. As the tool drills further, the lip region of the tool cuts the workpiece and the rate at which the thrust force increases is comparatively less, since the cutting lip has a positive rake angle. After the entire cutting region is inside the workpiece the thrust force remains almost a constant. It can be seen that the thrust force decreases during the last part of zone. This is because cutting region of the tool slowly comes out of the work-piece. The two regions in the thrust force and torque profiles clearly indicate the CFRP and Ti6Al4V drilling process.

5.2 Effect of Cutting Variables on cutting force

During drilling of CFRP/Ti6Al4V stack, while machining CFRP with three modified tool geometries and analyzed for different spindle speed and feed as presented in Fig. 5. Thrust force is considerably less in tool geometry (TG1 with point angle 130°) when compared to other two modified tool geometries (TG2 with point angle 134°, TG3 with point angle 140°). While drilling CFRP it is advisable to go for high spindle speed and low feed (Shyha *et al*. 2011, Krishnaraj *et al*. (2012)], interestingly the current experiment gives better result with respect thrust force at low spindle speed and low feed the possible reason may be the fresh cutting tool and stability in drilling process provided by the web thinning process. It is clear that the point angle has an influence on thrust force.

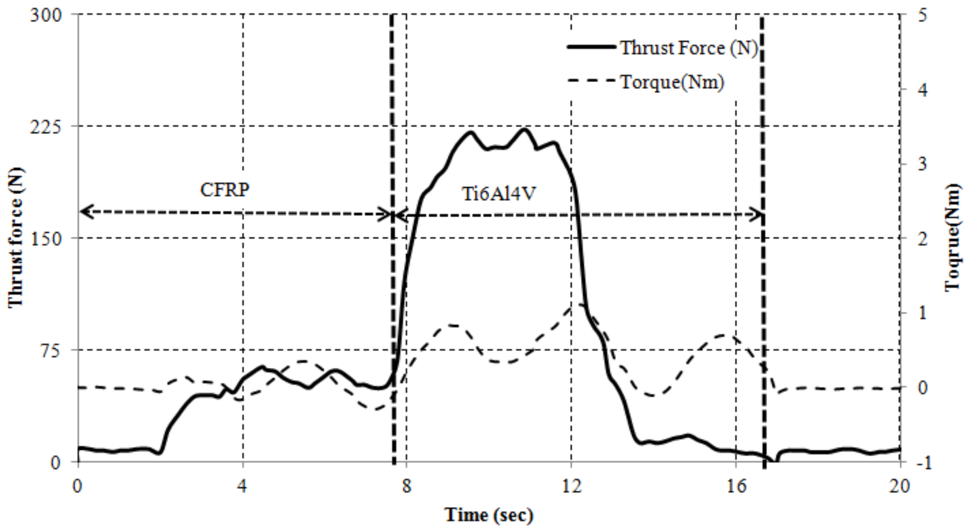


Fig. 4 Thrust force and torque during drilling of CFRP/Ti6Al4V stack

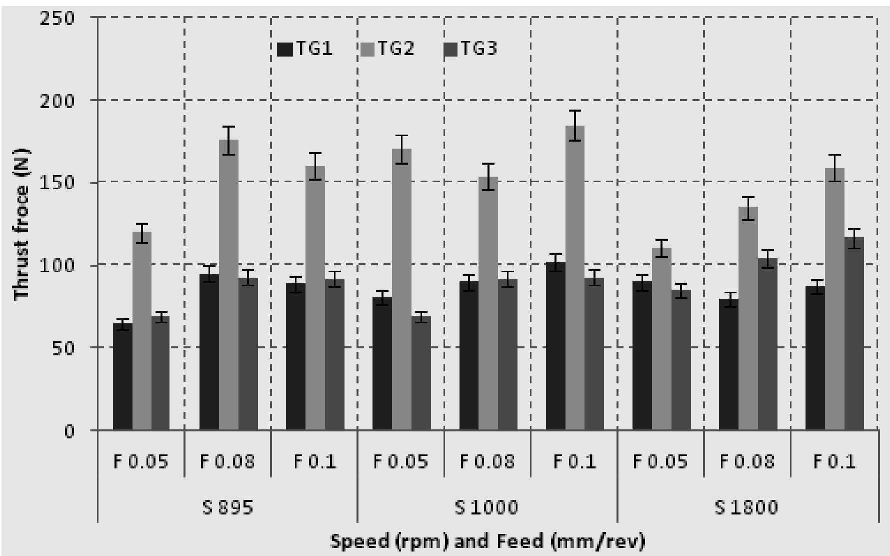


Fig. 5 Thrust force in machining CFRP

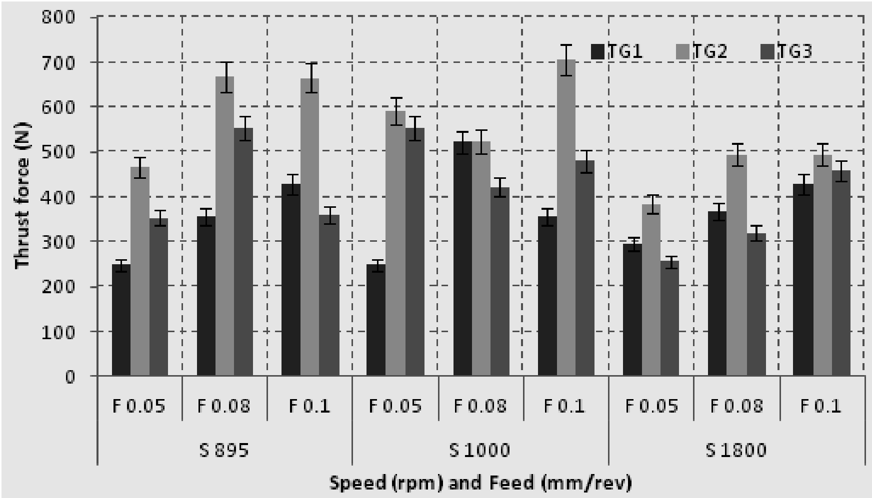


Fig. 6 Thrust force in machining Ti6Al4V

Influence of machining parameter on thrust force during drilling of Ti6Al4V is shown in Fig. 6 in which the overall performance of tool geometry (TG1) is better comparing the other tool geometries. Based on literature review it is understood that, Titanium exhibits better results at low speed and high feeds which reduce exit burr (Ezugwu and Wang 1997, Aurich *et al*. 2009). The thrust force values are three times higher than the CFRP. In case of TG2, the values are four times higher than the CFRP values at 1000 rpm. There might a possibility of high tool wear leads to high thrust force. From experimental results, it found that there is a gradual increase in the thrust force value due to adhesion of chip to the drill surface.

5.4 Influence of cutting variables on tool wear

Various types of wear can be observed when drilling the stack, namely non-uniform flank wear, excessive chipping and micro-cracking. The wear occurs along the drill's cutting edges or the flank faces. An increase in cutting speed led to a proportional increase in the flank wear width. The increase of flank wear rate may encourage adherence of workpiece material and may lead to attrition wear and eventually ended up in severe chipping (Sharif *et al*. 2012). The wear was rapid in all the tools until 10 holes, which are due to the fresh edges, undergo sharp cutting of fiber and matrix. After 10 holes, the wear is in uniform rate and is maintained throughout the end of the study. Progressive flank wear is shown in Fig. 7.

Uneven flank wear is absorbed in TG3 due to higher point angle of 140°. Cutting edge rounding is also absorbed in drilling process, brittle nature of fibers and lower modulus of elasticity of titanium is the reason for the above cause.

5.5 Effect of AErms signals on modified tool geometry

Experimental results of AErms signal, for the different geometries TG1, TG2 and TG3 are shown in Fig. 8. For three different combinations of machining parameters, TG1 and TG3 produce less thrust force than TG2.hp AErms signals intensity is considerably less for the TG1 when

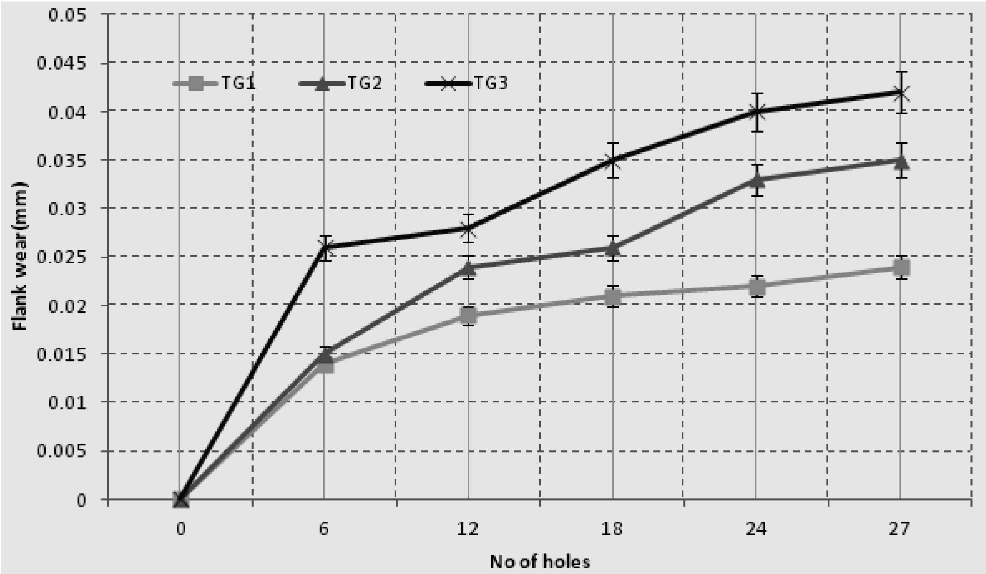
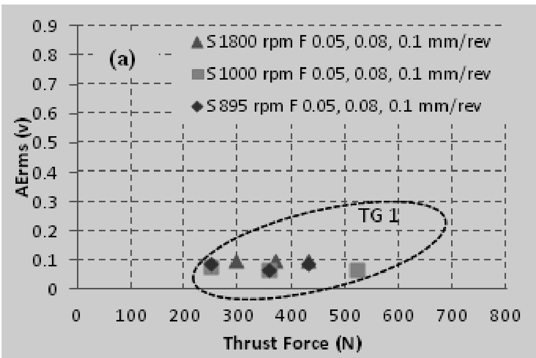
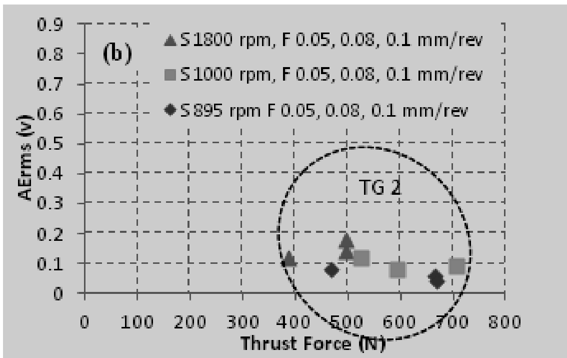


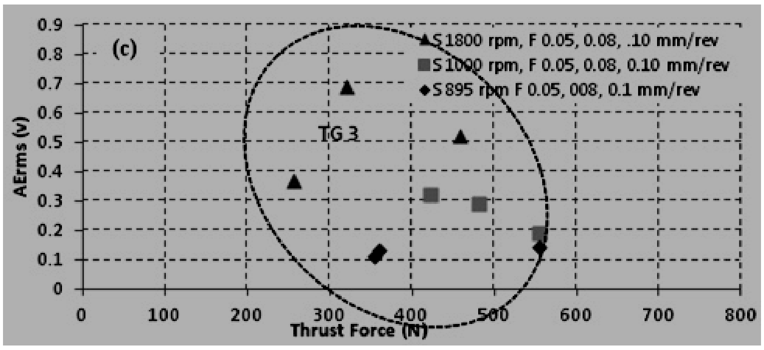
Fig. 7 Tool wear in machining



(a)



(b)



(c)

Fig. 8 Influence of AErms value and machining conditions with respect to modified tool geometry: (a) TG1; (b) TG2; (c) TG3

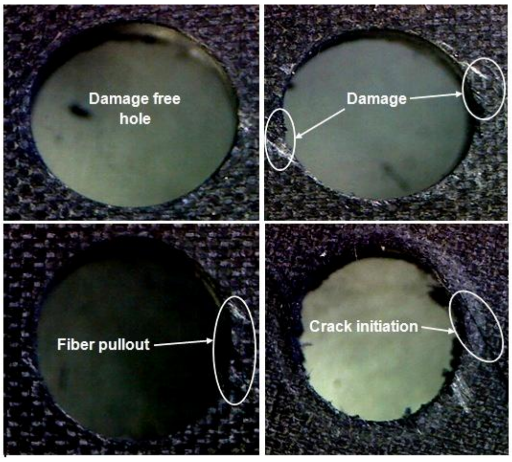


Fig. 9 Delamination in different modes of failure

compared with TG3 which confirm the influence of AE signal with respect to point geometry. Thus increase in AErms voltage and increases thrust force can be a useful in finding the right combination of geometric parameters inorder to improve tool life.

5.6 Effect of cutting variables on delamination

The damage around the holes (entrance and exit) in CFRP was measured using stereo microscope. During the drilling of CFRP composite laminate, delamination occurs at both the entrance and exit. The first phase was concerned with delamination at the entrance (peel up delamination) and the second with the delamination at the exit (push our delamination) during drilling.

Fig. 9 shows various delamination modes of failure. With respect to feed researchers address delamination, here delamination addressed with respect to tool geometries. Peel up delamination was less when compared to push out delamination. Fig. 10 details the peel up delamination with the three tools. All three tool geometry produces an average delamination factor of 1.2. There is a steep increase in delamination after 25^{th} hole while drilling with TG2.

5.7 Effect of cutting variables on drilling energy

Besides thrust force and torque, another variable indicating the effect of drilling condition is the energy required for drilling a hole. Drilling energy (E) can be expressed by considering the relationship between force acting during drilling and machining parameter as shown in Eq. (4) (Li *et al*. 2007).

$$E = \int_0^l F\,dl + \int_0^l \frac{2 * \pi * T}{f}\,dl \tag{4}$$

Where, l – Depth of cutting (m), F – Thrust force (N), T – Torque (Nm), f – Feed per revolution (mm/rev). Energy can be found in correlation with the energy value found in the coefficient of the AE signal as in Fig. 11.

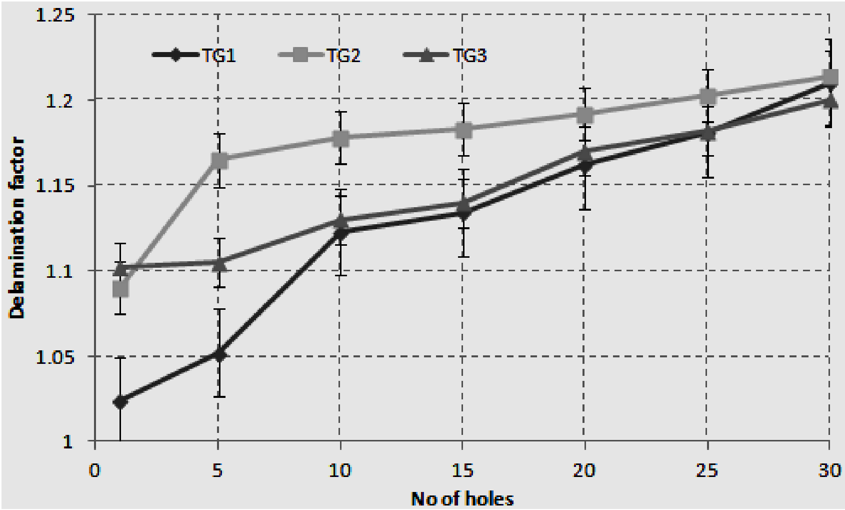


Fig. 10 Peel up delamination in CFRP

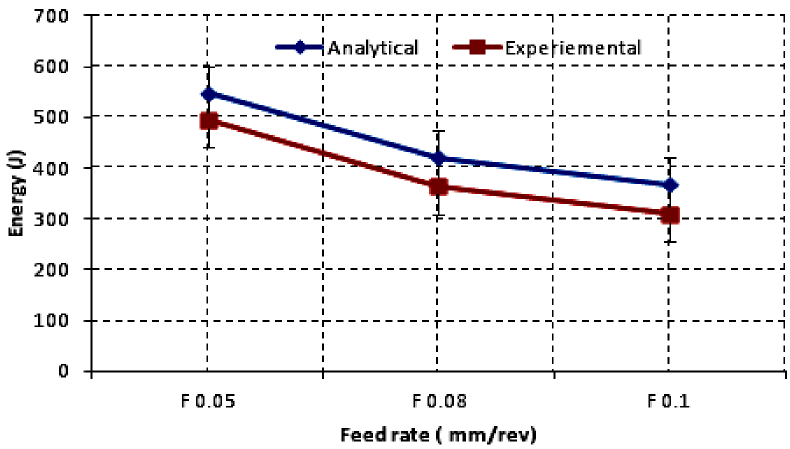


Fig. 11 Comparison of analytical and experimental energy

The analytical formulation gives a clear idea that the feed is the influencing factor in terms of energy. The energy decreases with increase in feed. Energy found from AE sensor is in good agreement with the analytical formulation. However, the small deviation might be due to the distance between sensor and the position of drilled hole.

5.8 Monitoring index

From the nature of AE signals, it can be observed that there is a difference in its characteristics in Ti6Al4V and CFRP. Hence any process monitoring setup must look for developing a monitoring index by taking advantage of this difference. Time domain analysis of the signal was done. Several statistical parameters like standard deviation, kurtosis, skewness and crest factor were applied on the signal. Among these crest factor showed considerable difference between drilling in CFRP and

Ti6Al4V. Crest factor is defined as the ratio of maximum signal amplitude to the root mean square (RMS) of the signal. Formula for crest factor and rms are given in Eqs. (5) and (6).

$$\text{Crest factor} = \frac{\text{Peak}}{\text{RMS}} \tag{5}$$

$$\text{RMS} = \sqrt{\frac{\sum_{i=1}^{N} X_i^2}{N}} \tag{6}$$

Where N = No. of samples in a set, xi = Value of discrete AE signal

The definition of crest factor means that when a signal has high transient peaks, it's crest factor will be high. From the AE signals acquired during CFRP/Ti6Al4V drilling, it can be observed that there are high transient peaks in Ti6Al4V. Hence crest factor value will be high for Ti6Al4V, compared to CFRP. Crest factor for all holes were calculated using MATLAB. In calculating the RMS of a signal, it is important to choose the correct size for N. The value of N must be chosen such that the set contains a transient peak signal in it. Careful analysis of the signal revealed that a transient peak arrived on an average of every 0.05 seconds. It can be seen that the value of the monitoring index shown in Fig. 12 increases rapidly for the first 12 holes due to abrasive wear caused by CFRP on the cutting tool and edge chipping of in the cutting lip because of titanium alloy. Between 12 to 20 holes normal wear is observed. Beyond 24 holes, there is a decrease in crest factor and rapid increase in tool wear, possibly due to rubbing of worn drill flank with workpiece, leading to low energy release (Velayutham *et al*. 2005). In addition, the decrease in monitoring index beyond wear of 20 micron could be due to damping of the AE signals by the thermal influence associated with worn cutting edges in rubbing mode at higher tool wear condition.

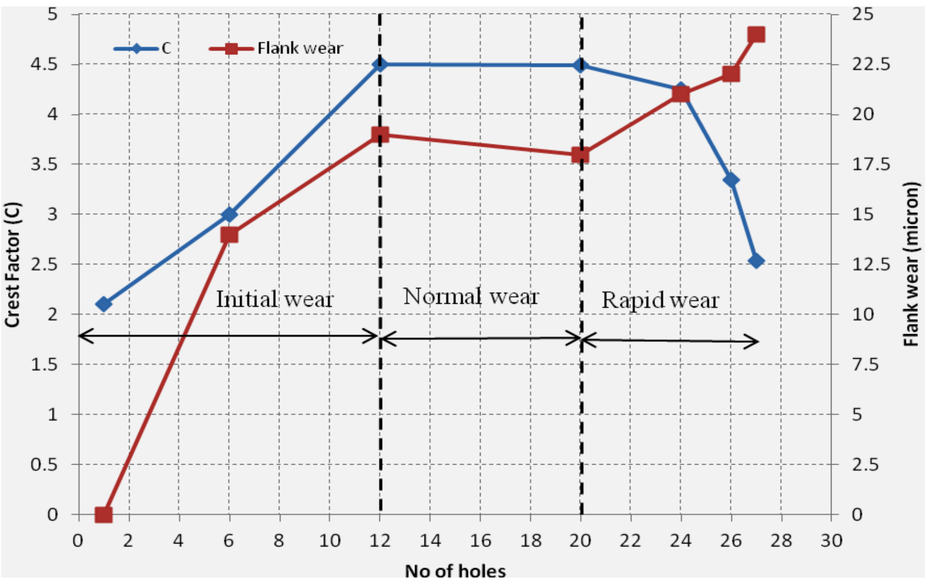


Fig. 12 Monitoring Index

6. Conclusions

Effects of three modified tool geometry under optimized machining conditions were analyzed on thrust force, delamination on CFRP and tool wear and the following conclusion were drawn.

- Influence of point angle on the thrust force can be clearly identified from the experimental result. As the point angle increases the thrust force also increase as witness in TG3 which has a larger point angle of 140°. Tool geometry (TG1) presents lower range of thrust force when compared with the other two tool geometries (TG2, TG3) because as the point angle increases the two components of the horizontal force increase which increase the overall thrust force.
- Helix angle has contained rake and chip evacuation passage which has a greater influence on tool life. Lesser the helix angle greater the tool life. Cutting edge rounding and wear in flank face results in uncut fibers that cause poor hole quality in CFRP. While in titanium, the quality was better because of material nature. Flank wear in drilling of CFRP/Ti stack was less in tool geometry (TG1) as the chip evacuations is better and propagation of tool wear was slow which reduce the wear rate.
- Drills that are coated with 1.5 μm fetch lower thrust force when compared to other coated drills as the thickness increases the cutting edge rounding increases and reduce the sharpness of the cutting lip. Coated drills with thickness higher than 1.5 μm result in peel up of coating after drilling 20 holes.
- Core diameter and web thickness has a greater influence on the tool life. It is confirmed that the dimensions of the TG1 has strong influence on the tool life and may reduce chatter effect.
- Delamination factor for TG1 was less than of TG2 and TG3 because of the smaller point angle the tool cutting lip are sharp and cut the fiber effectively.
- Monitoring index is addressed along with tool wear as a threshold for tool condition monitoring that can predict the tool wear. The be quality of number of holes drilled can be visualized by comparing the monitoring index and tool wear and the intersection point give us the maximum number of hole can be drill with better quality as witness in the current work was 24 hole.

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