Chapter 6

Comprehensive Study on Tool Wear during Machining of Fibre-Reinforced Polymeric Composites

Sikiru Oluwarotimi Ismail[a, *], Shoaib Sarfraz[b], Misbah Niamat[c], Mozammel Mia[d], Munish Kumar Gupta[e], Danil Yu Pimenov[f], Essam Shehab[g]

[a] Centre for Engineering Research, Department of Engineering, School of Engineering and Computer Science, University of Hertfordshire, Hatfield, AL10 9AB, England, UK.

[b] Manufacturing Department, School of Aerospace, Transport and Manufacturing, Cranfield University, Cranfield, Bedfordshire, MK43 0AL, UK.

[c] Mechanical Engineering Department, Muhammad Nawaz Sharif University of Engineering and Technology, Multan 66000, Pakistan.

[d] Department of Mechanical Engineering, Imperial College London, South Kensington, London, UK.

[e] Key Laboratory of High Efficiency and Clean Mechanical Manufacture, School of Mechanical Engineering, Shandong University, PR China.

[f] Department of Automated Mechanical Engineering, South Ural State University, Lenin Prosp. 76, Chelyabinsk, 454080, Russia.

[g] Mechanical and Aerospace Department, School of Engineering and Digital Sciences, Nazarbayev University, Nur-Sultan, Kazakhstan.

Corresponding Author: S. O. Ismail, s.ismail3@herts.ac.uk, +44(0) 1707 28 5213.

Abstract

The use of fibre reinforced polymeric (FRP) composites has increased rapidly, especially in many manufacturing (aerospace, automobile and construction) industries. The machining of composite materials is an important manufacturing process. It has attracted several studies over the last decades. Tool wear is a key factor that contributes to the cost of the machining process annually. It occurs due to sudden geometrical damage, frictional force and temperature rise at the tool-work interaction region. Moreover, tool wear is an inevitable, gradual and complex phenomenon. It often causes machined-induced damage on the workpiece/FRP composite materials. Considering the geometry of drill, tool wear may occur at the flank face, rake face and/or cutting edge. There are several factors affecting the tool wear. These include, but are not limited to, drilling parameters and environments, drill/tool materials and geometries, FRP composite compositions and machining parameters. This chapter focuses on drilling parameters, tool materials and geometries, drilling environments, types of tool wear, mechanisms of tool wear and methods of measurement of wear, effects of wear on machining of composite materials and preventive measures against rapid drill wear. Conclusively, some future perspectives or outlooks concerning the use of drill tools and their associated wears are elucidated, especially with the advancement in science and technology.

Keywords: FRP composites, Machining/drilling, Tool/drill wear, Measurement, Mechanism.

6.0 Introduction

The significance of drilling process has been increased widely both technologically and commercially in recent years (Groover 2007). Tool wear is a main factor contributing to the cost of a machining process. Drill wears are responsible for the roundness of holes, burr formation, surface roughness; hence, they directly affect the quality of machined hole (Abu-Mahfouz 2005).

Wear has been commonly defined as the amount of matter lost by the drill tool (Ertunc et al. 2001; Iliescu et al. 2010). Tool wear occurs in diverse and varied ways being a complex occurrence (Dimla et al. 1997) and gradual process (Astakhov and Davim 2008). There are a number of factors dependently contribute to the wear of cutting tool: cutting speed, depth of cut and feed rate (cutting parameters), machine-tool characteristics, workpiece materials and cutting fluids (Astakhov and Davim 2008). Carbon fibres are highly non-homogeneous, discontinuous, brittle, abrasive, and anisotropic in nature and have limited plastic deformation, as such an excessive abrasive wear is located along the cutting edges of twist drills, especially on the uncoated carbide types (Faraz et al. 2009). Consequently, as it prolongs, roundness and bluntness of the drill occur, as depicted in Fig. 6.1. When the drill has not been used, the maximum wear, VB_{max} is zero (null). Immediately after 560 holes have been drilled, the VB_{max} increased to 235 μm, later rendered the drill ineffective after drilling 610 holes.

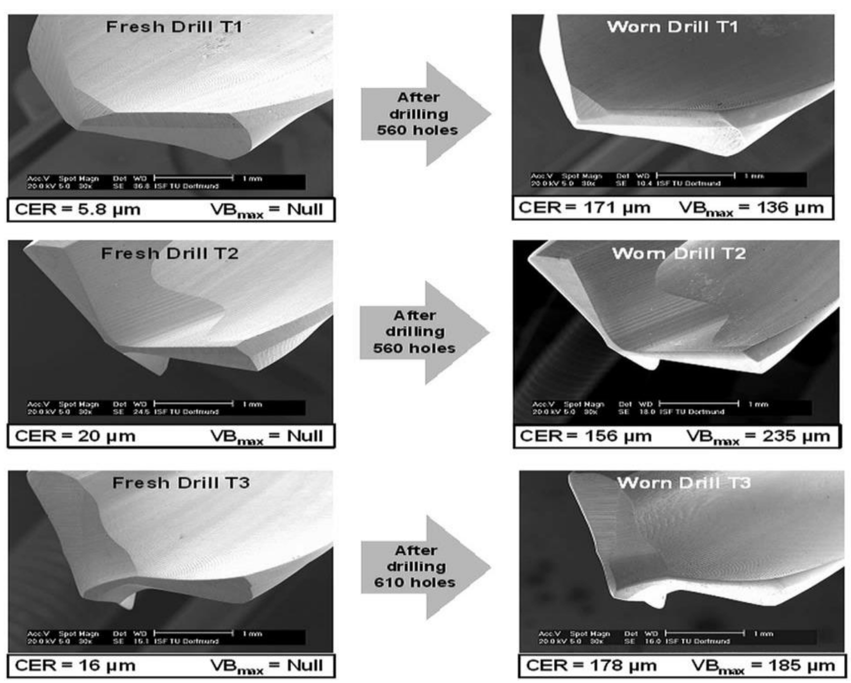
(a)  (b)

Fig. 6.1 Scanning electron microscope (SEM) images of (a) sharp cutting edges and (b) smoothly rounded/worn heads (Faraz et al. 2009).

Moreover, the rise in cutting speed causes an increase in both thrust force and torque (cutting forces). They which adversely increase the tool wear, especially the flank wear during high speed drilling of carbon fibre reinforced polymer (CFRP), irrespective of the tool coatings (Murphy et al. 2002). In addition, chip formation involves a brittle fracture, which is mainly based on the alignment of the composite fibres, with powdery and dust-like chips rampant while stock on the drill causes wear. The thermal conductivity of drill materials strongly determines their wear rate, and it has been reported that wear decreases with higher thermal conductivity of the drill materials (Sakuma et al. 1985).

The resultant effects of tool wear include an increase in drilling forces, degraded surface finish, increase in temperature, drilled hole inaccuracy and tool breakage, poor hole roundness, burr formation and centering issue (Abu-Mahfouz 2005). When drill wear reaches an unacceptable level under certain drilling conditions, it causes production loss, later it damages the work and machine tool, if not properly controlled.

6.1 Drilling Parameters

Selection of drilling parameters and proper setting of these parameters are very important, because input factors, such as drill bit diameter, feed rate and cutting speed affect or determine tool wears. Jayabal and Natarajan (2010) established an optimal scheme of drilling parameters, which offered minimum values of tool wear for drilling process of composites. Genetic algorithm and Nelder-Mead optimisation techniques were employed for analysis and empirical modelling of the parameters and their levels.

6.2 Drilling Tool Materials and Geometries

Drilling tools with better physical and thermal properties ensure better interaction of tool with workpiece/fibre reinforced polymeric (FRP) composites with minimal chances of rapid tool wear. For drilling of various FRP composite, selected tool materials should have the following properties to avoid excess tool wears (Lantrip 2008):

- Good toughness.
- Fair hardness.
- Good wear resistance.
- Chemical non-reactive.
- Good thermal conductivity.

A range of materials are available and they have been commonly used for manufacturing of various drill bits for composite drilling. These include, but are not limited to, carbide, high speed steel, super hard material (diamond, polycrystalline cubic boron nitride or polycrystalline diamond), cobalt and coating materials: titanium nitride (TiN), black oxide and titanium carbonitride cobalt (TiCN), among other substances. Different studies have compared these tool materials for minimum tool wear, as subsequently discussed.

Aluminum titanium nitride (AlTiN) coated drill enhances the hardness of the drills and provides solid lubrication to curb bluntness of the drill bit. Moreover, it can be used at higher temperatures, as AlTiN is a high temperature alloy, as reported by Sriraman et al. (2015). In another study, Park and Kwon (2011) examined drilling of CFRP and titanium stacks with uncoated tungsten carbide (WC) drill and boron aluminum magnesium (BAM) coated WC drill. During this process, tool surface was observed by X-ray energy dispersive spectroscopy (XRD), SEM and confocal laser scanning microscope (CLSM). A lower flank wear was observed for drilling with coated drill, when compared with an uncoated drill. Moreover, after drilling 20 holes, the BAM coat was damaged and tool wear increased after drilling 40 holes. Hence, the coated tools exhibited a longer tool life. Edge roundness is a dominant wear during drilling of CFRP materials. CFRP composites are brittle in nature, stagnation region confronting cutting edge propagates dullness at the cutting edge, as investigated by Wang et al. (2013).

In addition to coated drills, drill bits with special geometrical design are gaining attention. Drill geometry is mainly based on the following different characteristics (Xu et al. 2019):

- Angles (helix angle and point angle).
- Edge preparation (chamfer or round).
- Drill shape (Twist or helical).

These geometrical variables are closely related globally for outstanding performance of special drills, considering better quality of machined surface and minimum tool wear. SenthilKumar et al. (2013) studied tool wear by machining 100 holes separately with two drill point angles of 118º and 130º. Drill with point angle of 130º showed lower tool wear. According to Garrick (2007), the diamond coated drill bits with special K-land design resulted in a longer tool life than other comparative conventional drills.

6.3 Drilling Environments

Application of right types of lubricant or cooling media helps to minimise tool wear during drilling process of composite materials. In drilling, the cutting fluids can reduce friction at tool-chip interface point, minimise heat generation at drilling point and facilitate the removal of chips produced during the process. Moreover, the cutting fluid/coolant mainly performs following functions when drilling composite materials (Xu et al. 2019):

- Elimination of chips sticking on drill bit flute.

- Reduction of force generation on tool-chip interaction point.
- Reduction in heat generation that enhances tool wear.

Many experimental studies have examined and concluded that tool life can be significantly enhanced by using cooling media during drilling of composite materials. For instance, for drilling CFRP composite, Xia et al. (2016) experimentally investigated that cryogenic cooling has a significant effect on reducing the outer corner wear, roundness in the cutting edge of cutting tool and surface quality of machined hole. Uncoated tools were used for the experiments. Moreover, comparison of both drilling environments (cryogenic cooling and dry condition) showed that a lower drill wear due to thermal damage is observed in cryogenic cooling.

The successful application of cutting fluids largely depends on the method of application of the cutting fluids during drilling process. Three commonly known fluid supply methods include flood cooling, wet drilling and mist spraying (Sen et al. 2019).

Moving forward, Tashiro et al. (2011) compared two drilling environments, dry process drilling and water mist cooling. Although, water mist cooling process exhibited a lower thrust force, however, chips produced were harder. Moreover, comparison based upon the number of holes drilled in both environments showed that a longer tool life is possible in dry process when compared with the mist cooling process. A sequence of experiments was conducted for the evaluation of three application methods of cutting fluids: flooding, misting and spraying. Drilling with spray mist method offered better results of tool wear, when compared with other two methods of cutting fluid application (Shyha et al. 2011).

In addition, the use of excessive cutting fluids has damaging effects on environment and health of the people in the working area. To overcome these issues, near dry machining appeared as an emerging technique. Minimum quantity lubrication (MQL), also called near dry machining, has gained attention in composite materials machining. MQL is a sustainable process that considers environmental and economic aspects (Xu et al. 2019). MQL is the application of minimal amount of biodegradable oil droplets along with compressed air at too-chip interaction point to minimise the heat produced (temperature rise) during machining, which consequently prolongs the life span of tools (Rahim and Sasahara 2011). For examples, Krolczyk et al. (2019) and Sen et al. (2019) recently and extensively reviewed the cooling lubrication techniques applied in machining. MQL was suggested as such a method of cooling-lubrication that has a great potential to replace conventional cooling techniques, because MQL did not only reduce the tool wear and surface roughness, but also it is less dangerous to environment and human health. MQL has attract wide industrial applications and become a famous technique worldwide, because of less consumption of lubricant and its better results than those obtained by traditional flood cooling technique in terms of tool/drill wear and quality of surface characteristic of machined part (Brinksmeier et al. 1999). In another study, Brinkmeier and Janssen (2002) performed a number of experiments and reported that tool wear can be minimised using internal supply of MQL during drilling. Similarly, minimum tool wear has been observed when drilling with diamond and WC tool under MQL cooling condition (Park et al. 2012).

Also, experimental investigation into drilling of composite-titanium compound in a MQL environment has been performed. The results indicate lower drill wear and improved surface quality with a MQL drilling. However, when Xu et al. (2019) compared MQL and dry drilling, dry drilling produced lower thrust force and hole cylindricity. Wang et al. (2018) experimentally observed that the application of coolant mist through the outlet located at the lower most position of secondary cutting-edge resulted in great reduction of drill wears. In a comparative experimental study, drilling in MQL produced decrease of 22% (lower) flank wear when compared with dry and flood coolant and decrease of 30%/lower flank wear than in compressed air environment. Besides, MQL in combination with lower oil flow and higher air flow rates offered a maximum tool life (Iskandar et al. 2014). Bhattacharyya and Horrigan (1998) employed a liquid nitrogen as cooling media when drilling Kevlar composite samples. Under the cryogenic cooling, a lower tool wear was observed. Additionally, protruded, fuzzy and uncut fibre defects were completely removed with the application of cryogenic coolant. This facilitated the entry and exit of drill and consequently, reduced the chances of tool wear and hence tool life was increased (Xia 2014).

Kannan et al. (2018) investigated into drilling of CFRP under different environments (conventional flood drilling, dry and compressed air and MQL). Experimental results revealed that the dry cooling offered lower thrust force when compared with other cooling environments, while flood lubrication showed highest thrust force. MQL drilling presented a better machining performance, longer tool life and superior surface quality than dry drilling. MQL and dry drillings offered good 110 and 80 holes with coated WC drill, respectively.

6.4 Types of Drill Wear

There are many types of drill wear based on parts of the drill where such wear occurs, as shown in Fig. 6.1 and 6.2. Drill wears and their causative mechanisms are subsequently elucidated.

6.4.1 Crater Wear

Crater wear arises from erosion of the drill just under the cutting edge, occurring mostly on the tool rake face through diffusion mechanism. Wearing action is accelerated by higher temperatures and stresses induced by tool-chip interaction. It has a parabolic relationship with feed rate and distance along the drill lips and linear relationship with cutting speed (Choudhury and Raju 2000). The wear is usually measured by the depth or area coved by the crater (Groover 2007). Crater wears are attributed to the diffusion process. Application of protective coating on tool surface is an effective way of slowing the diffusion process, hence, minimising crater wear.

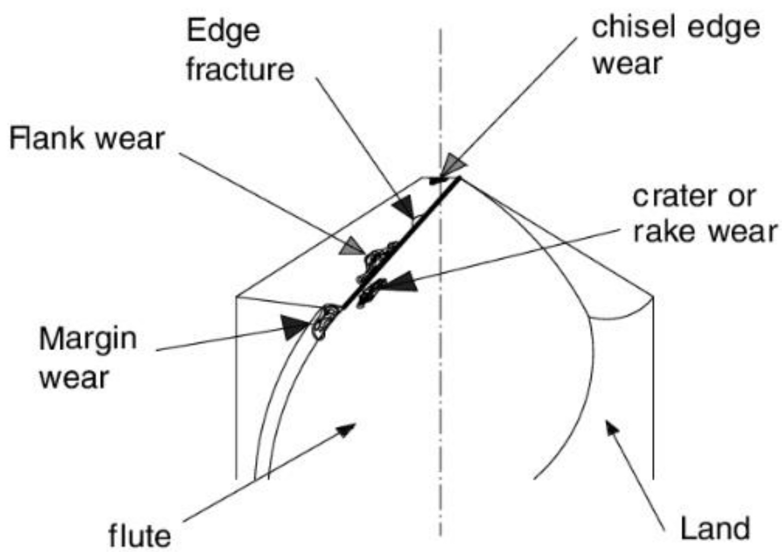


Fig. 6.1 A schematic representation of various types of wear on twist drill (Abu-Mahfouz 2005).

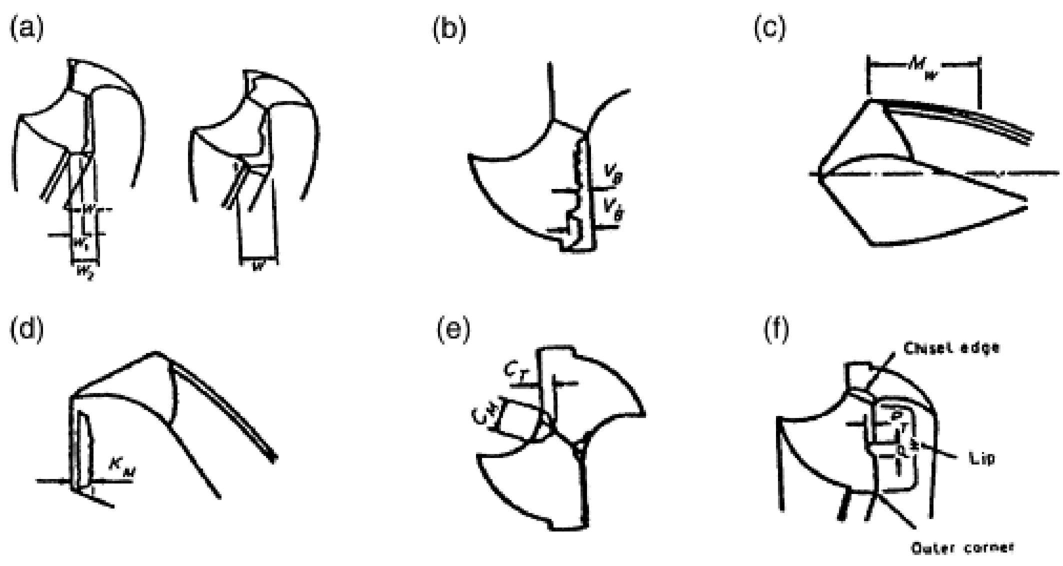


Fig. 6.2 Various types of wear: (a) outer corners wear; (b) flank wear; (c) margin wear; (d) crater wear; (e) chisel edge wear and (f) chipping at lip (Ertunc et al. 2001).

6.4.2 Flank Wear

Flank wear arises on the flank (relief) face of the tool. This wear is a progressive process and a commonly used indication for detecting the degree of condition of drill wear or as basis for tool wear (Abu-Mahfouz 2005). Both elevated temperature and intimate friction contact at drill tool-work interface cause flank wear. It increases with increasing delamination factor (Khashaba et al. 2010) and is predominant at a low speed. The summarised basic causes, mechanisms, types, consequences of flank type of wear are later shown in Fig. 6.4. Basically, tool flank and rake faces are the two important zones where tool wear occurs in a drill (Liu et al. 2000).

6.4.3 Fracture or Cutting-Edge Chipping

An increase in wear leads to an increase in torque and thrust force. Failure to endure the rise in progressive wear causes drill edge chipping or fracture/breakage. Irrespective of the types of drill wear, they are caused by composite-drill high interface temperature and friction, fibre orientations, anisotropic and abrasive nature of CFRP composite materials, drilling variables/parameters, especially high cutting speed. Mostly, friction and temperature wears are considered as abrupt wears and these two wears are undesirable tool failure modes rather than gradual wear which results in a longer tool life.

6.4.4 Other Types of Wear

- *Margin or Corner Wear*: It occurs due to the misalignment of the drill and heat caused by both insufficient coolant and high spindle speed.
- *Chisel Wear*: It is very rampant at chisel point of the cutting tool (drill).
- *Outer Corner Wear*: It occurs on the outer corner of the drill tool lips (Ertunc et al. 2001). The drill corner wear land can be simply analysed, as indicated in Fig. 6.3. Where *W*, *Wa* and *Wb* represent the drill corner wear land, right and left cutting edges, respectively.

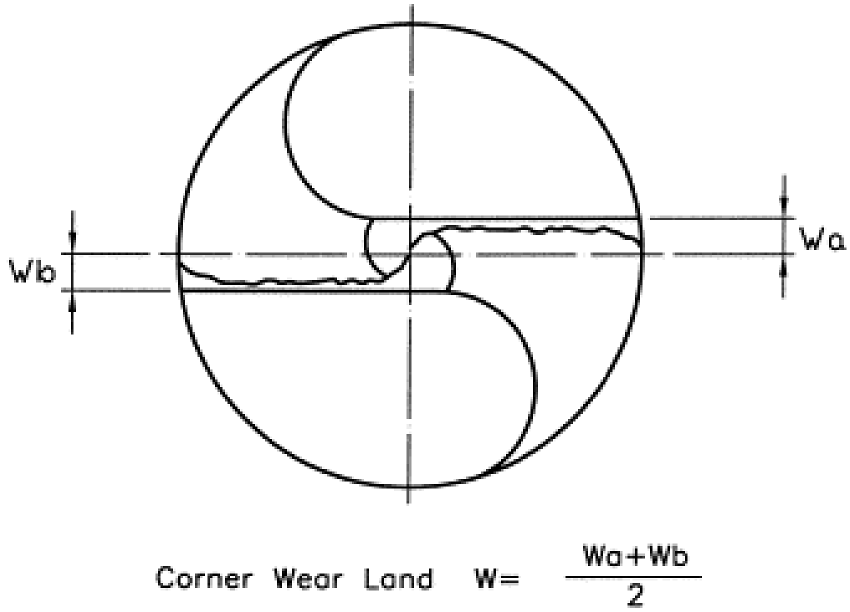


Fig. 6.3 Description of a drill corner wear land, depicting its simple analysis and features (Liu et al. 2000).

6.5 Mechanisms and Determination of Twist Drill Wear during Drilling of Composite Materials

6.5.1 Mechanisms of Wear

Tool wear during conventional composite machining is an unavoidable phenomenon, since production of chips through plastic deformation is required before occurrence of cutting (drilling) operation, under cutting forces (thrust and torque). This occurs after interaction between cutting tool (drill) and workpiece (composite material), leading to a high friction and interface temperature. These two factors caused the atoms of the cutting tool to gain great kinetic energy, resulting to tool wear as the particles of the cutting tool tends to move away.

In other words, wear occurs due to removal of some parts of material from the surface of cutting tools which is due to cutting tool-workpiece physical (mechanical) and chemical interactions

(Ertunc et al. 2001). Classification of wear mechanism according to Astakhov and Davim (2008) are shown in Fig. 6.4 and subsequently explained.

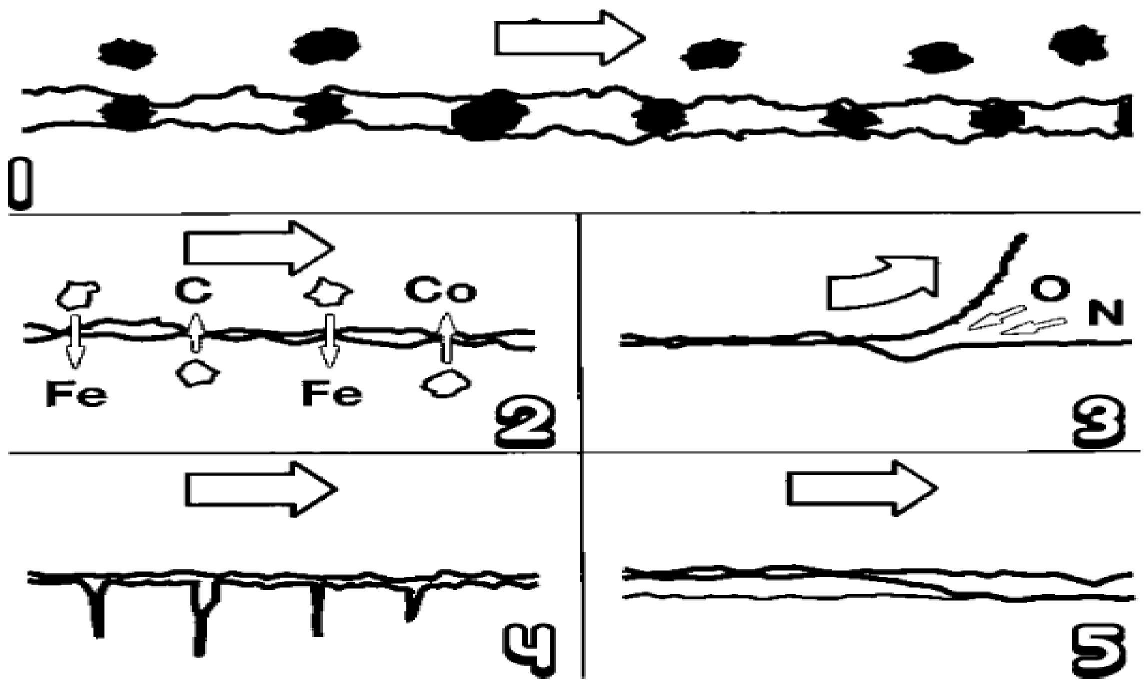


Fig. 6.4 Wear mechanisms, showing (1) abrasion, (2) diffusion, (3) oxidation, (4) fatigue and (5) Adhesion (Astakhov and Davim 2008).

- *Abrasion:* This is a thermo-dynamic wear mechanism, commonly called mechanical wear. Usually, hard abrasive particle present in workpiece/FRP composite causes scratching and eliminating small portions from the tool. Flank wear majorly occurs by the abrasion wear.
- *Adhesion*: It happens due to friction, pressure and high temperature. It occurs at tool rake face and chip interface point. As newly formed chip flows along the tool, it removes a portion of tool surface with it and causes erosion on the surface.
- *Diffusion*: This is a thermo-chemical wear process, commonly called chemical wear, whereby atoms of hard material (drill tool) diffuse into the soft material matrix (workpiece) at high

temperature. It is strongly dependent on temperature. Diffusion is a significant cause of crater wear.

- *Oxidation:* It occurs due to the chemical reaction between the drill tool face and oxygen. It mainly happens on the rake side of the tool. Oxidation layer being weaker layer easily scratches off, revealing new surface for further reactions.
- *Fatigue:* Fatigue occurs at high pressure when two surfaces slide on each other due to friction, tensile and compressive forces causing surface crack. Fatigue mainly results in flank wear.

Furthermore, the most commonly encountered mechanisms are abrasion and adhesive wears, but abrasion and adhesion mechanisms of wear cannot completely describe wear in cutting tools (Ertunc et al. 2001). Tool wear being a convoluted phenomenon depends on many parameters, such as nature of cutting tool and/or workpiece, cutting conditions, contact stress, vibration in machine tool and cutting edge temperature. In addition, the tribological study reveals that wear rate depends on temperature, friction, pressure, speed, nature of workpiece, tool geometry and drill materials. Increase in friction causes an increase in temperature, due to high kinetic energy gained by the drill atoms, resultantly, the wear increases. Excessive wear results into the failure of a drill. In addition, with an increase in the cutting forces, the flank wear, VB increases, as depicted in Fig. 6.5. VB affects the surface roughness. Drill wear passes through several processes before ends in a plastic deformation which causes failure or rupture.

Besides, it is necessary to compare wear rate during machining of synthetic and sustainable natural or plant FRP composite samples. It is evident that the drill wear rate during machine of CFRP composite materials is higher when compared with that of hemp FRP counterpart (Ismail et al. 2016). A null or negligible wear was observed on the high speed steel twist drill diameters of 5 and 10 mm after drilling 32 and 64 holes of hemp FRP composite samples, respectively, compared with a minimum (greater) drill wear that was observed with CFRP counterparts, under same drilling parameters, conditions and environment.

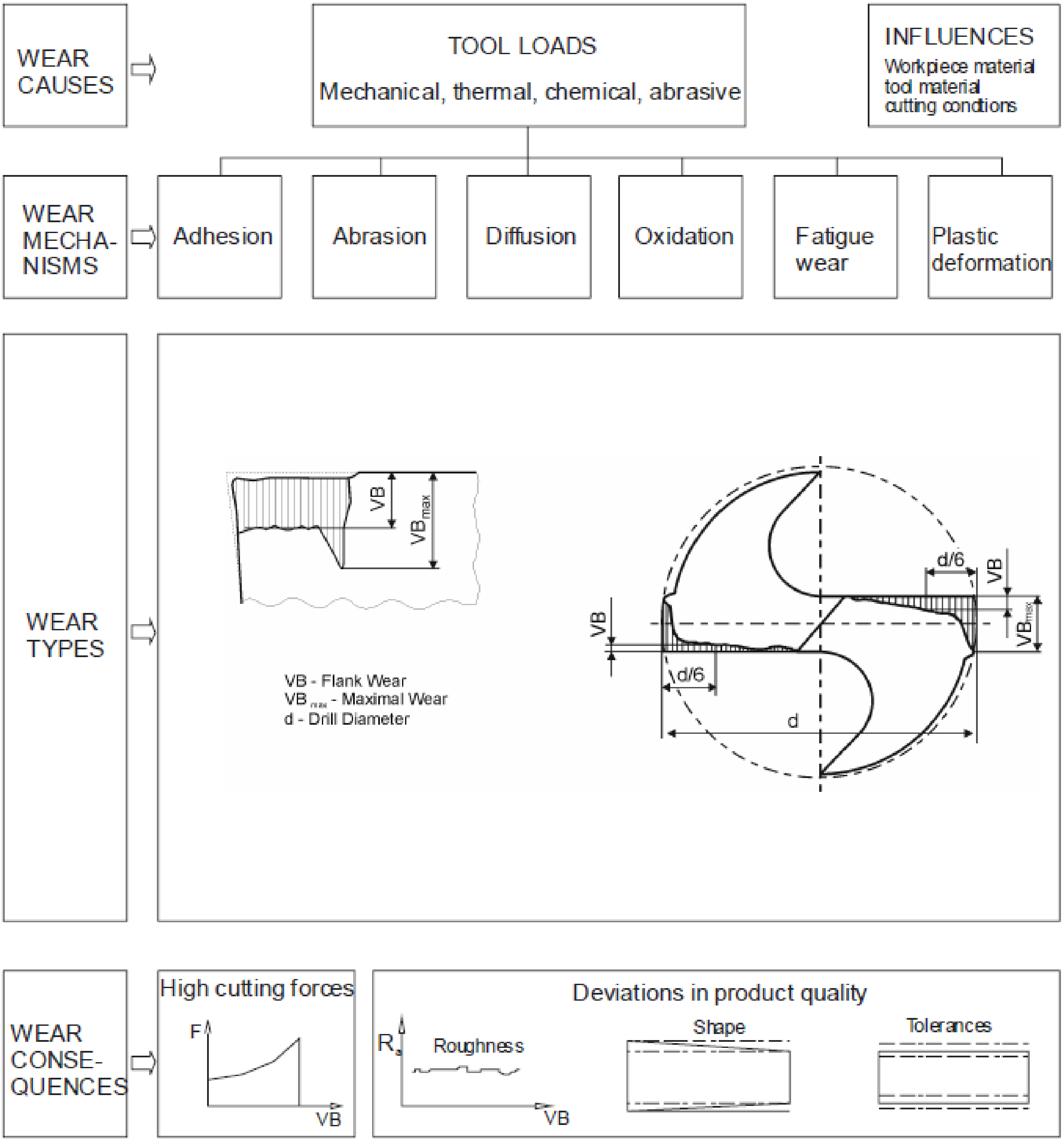


Fig. 6.5 An outline of the causes, mechanisms, types and consequences of tool wear (Dolinšek and Kopač 2006).

More also, tool wear phenomenon is usually a slower and progressive during drilling operation, but catastrophic and abrupt in case of tool failure as well as cutting edge breakage. Considering Fig. 6.6, wear of drill bit starts immediately it is used for operation, known as initial wear, W_o before stable wear region, but with faster rate once it becomes dull. It finally reaches an accelerated failure stage, where it is inefficient in cutting (Ertunc et al. 2001). In stable region, the slope of the wear curve is controlled by the cutting conditions and properties of work materials. With increasing hardness of work materials, drill wear also increases accordingly. Similarly, an increase in cutting speed causes an increase in drill wear ratio.

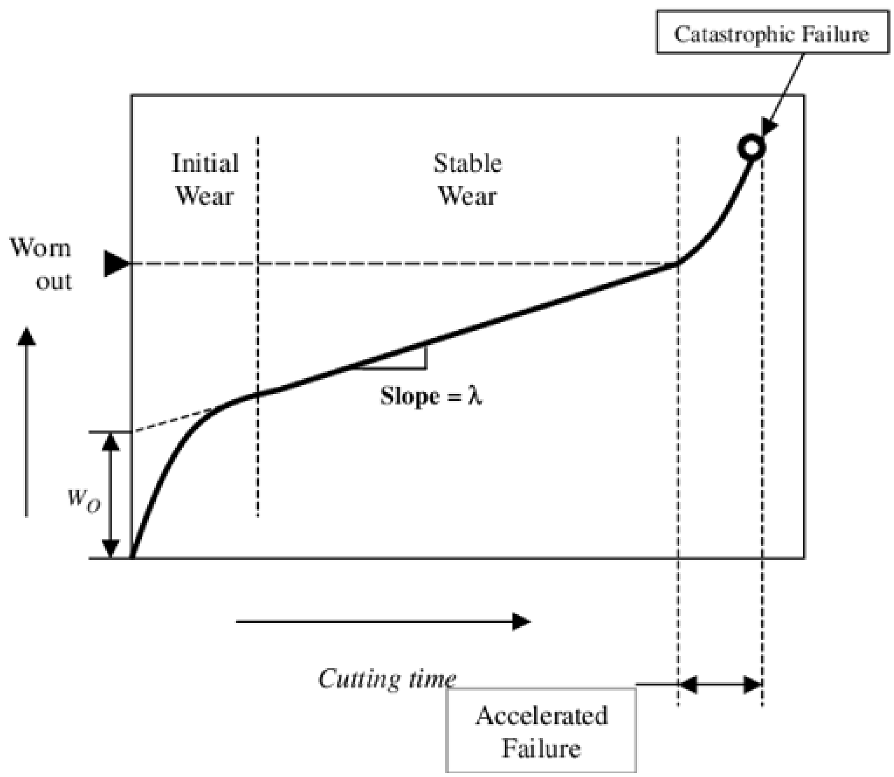


Fig. 6.6 An illustration of drill flank wear evolution and its basic features (Abu-Mahfouz 2005).

6.5.2 Drill Tool Life

Tool life is expressed as a time span for which a drill can be used for machining until its catastrophic wear occurs. In production, using tool till or to a stage of catastrophic failure is usually avoided, as it demands re-sharpening the tool and can impair the quality of the machined surfaces (Groover 2007). Tool life expectancy can also be predicted empirically, using Taylor's equation, as expressed in Eq. (1).

$$V_c T^n = C \quad (1)$$

Where V_c represents the cutting speed (m/min), T denotes the tool life (min) and n stands for exponent, as shown in Table 1 for different cutting tool materials. The exponent depends on drilling parameters, while C designates a constant. Some of these terms can be obtained from past published works or experimental results.

Table 1 The values of exponent for various cutting tool materials (Astakhov and Davim 2008).

Tool material	High Speed Steel	Cemented Carbides	Ceramics
n	0.1-0.2	0.2-0.5	0.5-0.7

Eq. (1) can be represented graphically, as shown in Fig. 6.7.

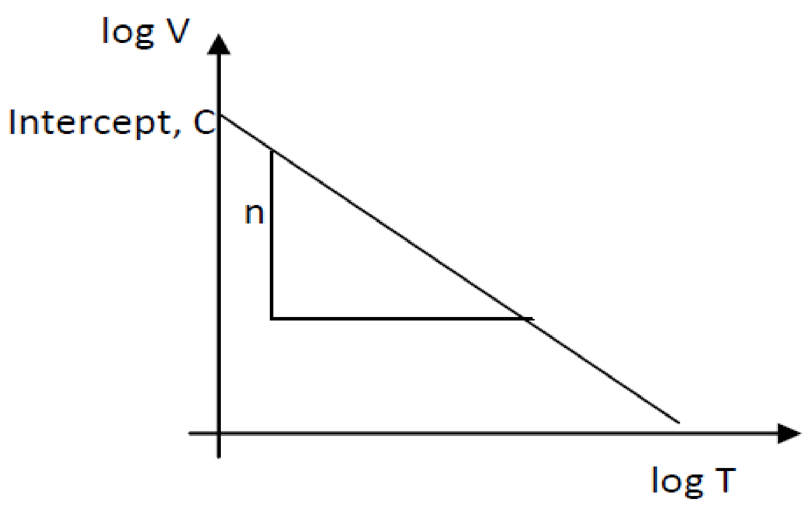


Fig. 6.7 Graph of log V against log T.

For the estimation of the feed rate and depth of cut, Taylor's equation can be generally expressed as Eq. (2).

$$V_c T^n D^x S^y = C \quad (2)$$

Where *D* and *S* stand for the depth of cut and feed rate, respectively. The exponents, *x* and *y*, are obtained experimentally.

Although, tool life prediction can be made based on flank wear, using Taylor's equation. However, in industry, it is difficult and time consuming to estimate the flank wear (Groover 2007). The following are some important measures to predict a particular tool life:

- Visual inspection of tool failure.
- Failure of cutting edge due to fracture failure, temperature failure or gradual failure.
- Scratch test by the operator to check the abnormalities.
- Changes in the typical sound of the operation.
- Stringy chips formation.
- Rougher machined surface.
- Significant increase in power consumption during operation.
- Total drilling time that the drill has been used for drilling.
- The number of holes made by the drill or number of parts machined by the tool.

6.5.3 Wear Determination or Measurement Techniques

During elastic deformation of a material, energy is required in the form of strain energy to control the atomic bonds. The plastic deformation rate is fast for a machining process, such as drilling, at a high strain rate. Almost all the energy used is converted into heat, which causes a rise in temperature, leading to earlier wears and eventually tool failure. The temperature increases with speed when machining materials, such as ferrous and high strength materials include CFRP composites (Choudhury and Raju 2000). Szwajka and Trzepieciński (2016) determined the effect of varying cutting speed on the life span of tool. The results showed that the useful life of tool decreased with an increasing cutting speed, and the wear was more dominant on tool flank. In another study, Lin and Chen (1996) evaluated the effect of cutting speed on drilling of CFRP composite material. It was observed that the tool wear occurred more rapidly at higher speeds rather than at lower speeds. Drilling of CFRP-Ti stack composite material showed that Ti and CFRP cutting promoted WC flank wear and depreciated the drill cutting edge, respectively, as confirmed or observed through SEM and CLSM examinations (Beal et al. 2011).

Moving forward, the maximum flank wear, VB_{max} was carefully measured, using a modern instrument (Mitotoyo tool measuring microscope, type MF workstation) coupled with an integrated desktop computer and a built-in-camera installed with AnalySIS, a commercial digital image processing software (Faraz et al. 2009). Furthermore, the accruing magnitude of cutting edge roundness (CER) was measured with an application of a commercial optical fringe microscope workstation, known as GFM MikroCAD system. The same technique was used by Shyha et al. (2010), but a toolmaker's microscope (WILD M3Z) with attached Nikon EOS 400D digital camera was used and managed by a digital imaging software called Omnimet 8.7.

In addition, failure in drill tool can be monitored by signal processing techniques. Non-linear relationships as well as recognition pattern from noisy complex data of drill wear have been carried out using a multivariate nonlinear analytical tool, called artificial neural network (ANN) algorithms; learning vector quantization (LVQ) and the fuzzy learning vector quantization (FLVQ). FLVQ was found more efficient than LVQ in assessing size of flank wear (Abu-Mahfouz 2005). Also, algorithm for synthesis of polynomial networks (ASPNs) was used by Liu et al (2000) for online prediction of corner wear in drill bits during drilling operations while application of intelligent tool condition monitoring (TCM) systems using ANN was reported by Dimla et al. (1997). Govekar and Grabec (1994) demonstrated a Kohonen type, a self-organising neural network (NN) technique to classify flank wear in drills subject to cutting forces. Tansel et al. (1993), utilised NN, type-ART2 and wavelet transformation techniques to examine the tool wear just at the beginning of failure of tool in micro-drilling operation. The results showed that wavelet monitoring technique was better, especially for automatic monitoring.

Moreover, different measurement techniques can be further applied to measure different types of tool wear. For instance, a universal tool room microscopy can be employed for the estimation of the width of flank wear and analysis of worn surfaces. An investigation through SEM was recommended by Sathish and Raj (2012). Rawat and Attia (2009) experimentally investigated tool wear mechanism and cutting forces affecting the part surface. Chipping and abrasion wears were the dominant mechanisms controlling the drill damage. Li and Tso (1999) estimated the state of drill wear, using values of motor currents for both spindle and feed. It was a new regression technological and fuzzy taxonomy method, involving numbers of cutting parameters: feed rate, diameter of drill and speed. Regression analysis models were established through experimental study to predict when a tool is to be replaced.

Furthermore, the profiles of worn cutting edges of the tool have been observed using the confocal microscope. The detailed wear patterns were studied by superior magnification pictures, which were taken with aid of a SEM (Wang et al. 2013). Periodic recordings of drill weight loss was used by Khashaba et al. (2010) to carry out machinability analysis, effect of drill wear when drilling woven GFR/epoxy composites. Kim et al. (2002) measured the power consumed by spindle motor to accurately estimate the drill wear. The estimated wear error was lower than 0.02 mm, proving the reliability of the real-time error since drill replacement of 0.18 mm is required in flank wear.

6.5.4 Preventive Measures against Rapid Drill Wear

In a quest to have an accurate drilled hole for composite parts, the tool/drill should be in a good condition. Drill wear can be reduced by using optimal setting of drilling parameters, good tool materials and efficient coatings, lubrication or MQL technique as well as suitable coolants or cutting fluids. Coolants could be compressed air (dry type) and mist coolants (wet type). Their various practical applications have been earlier discussed compressively in section 6.3. The Use of wet or liquid coolants are often discouraged during drilling of natural/plant (bast) FRP composites, due to the hydrophobic nature of plant (flax, sisal, palm tree, bamboo, hemp, jute, to mention but a few) fibres. Though, liquid coolants are very effective towards reduction of high drill-composite friction, interface temperature and consequently the tool wear during drilling operation, but the drawbacks of some wet/liquid coolant include high cost, poor application and most importantly an increased moisture absorption (swollen) by the plant FRP biocomposite materials. It further causes a poor/weak fibre-matrix interfacial adhesion, delamination and most importantly, decrease in mechanical properties of biocomposites. Therefore, an application of a compressed air to reduce high tool-workpiece interface temperature and drill wear is advisable when drilling natural/plant FRP biocomposites, as used by Wang et al. (2019). However, wet coolants have a good application during drilling of a selected few synthetic (carbon and glass) FRP composite materials.

6.6 Concluding Remarks and Future Perspectives

6.6.1 Conclusions

Tool wear during conventional composite machining is an inevitable phenomenon. The abrasive, heterogeneous, brittle and anisotropic properties of FRP composite materials/work piece support rapid tool wear rate. Tool wear is a complex occurrence, because its mechanisms involve several branches of science and engineering. Wear of tools differ from one FRP composite to another. Drill wears faster when drilling synthetic (carbon and glass) FRP composite materials than natural/plant FRP counterparts. In addition, tool wear depends on numerous factors, such as types of composites, drilling parameters, tooling materials, tool/drill geometries, to mention but a few. Different types of wear and their mechanisms have been extensively discussed. Both the region where wear occurs and method of occurrence determine the type of wear.

Also, several techniques of determining and analysing wear have been well elucidated within this chapter. Though, wear remains an unavoidable occurrence, but wear rate can be reduced and/or tool life can be maintained by using suitable coolants (either dry or wet/liquid type), coated tools, optimal process parameters, efficient drill design and geometry, among others. The effectiveness of coolant depends on types (compositions) of FRP composites and methods of application.

6.6.2 Future Outlooks

Cutting tools, such as drill bits are very important in manufacturing industries. This is because holes are indispensably required to assemble, join or couple composite components. The widest users of cutting tools during machining of several composites include, but are not limited to, transportation (aerospace, marine and automobile), telecommunication and construction industries. As these sectors grow and develop, the application of cutting tools increases to meet the ever-increasing and insatiable needs of human, using composite parts. Also, in an attempt to maximise productivity and profitability continuously, the pursuit of having an optimal drill with excellent tool life and reduced wear rate remains a continuous exercise.

The effects of tool wear include high power/energy consumption and capital involvement, increased machining-induced damage and high number of part rejects as well as accidents and deaths. These unwanted consequences of tool wear will be either drastically reduced or totally eradicated with advancement in technology/engineering and/or advent of several modern, sophisticated and state-of-the-art machine centres and software packages. These technologies include computer numerical control (CNC), non-conventional machining (abrasive/waterjet, laser, electric discharged, ultrasonically-assisted types, among others), additive manufacturing/3D printing and robot in manufacturing, to mention but a few.

References

Abu-Mahfouz, I. (2005). Drill flank wear estimation using supervised vector quantization neural networks, *Neural Computing and Applications*, 14(3),167–175.

Astakhov, V.P., & Davim, J.P. (2008). Tools (Geometry and Material) and Tool Wear. In: Davim, J.P. (Ed.). Machining, Chapter 2, pp. 29-57, Springer: London.

Beal, A., & Kim, D.D.W., Park, K.H., Kwon, P. (2011). A comparative study of carbide tools in drilling of CFRP and CFRP-Ti stacks. In: *ASME 2011 International Manufacturing Science and Engineering Conference*, Volume 1. ASMEDC, pp. 145–152.

Bhattacharyya, D., & Horrigan, D.P.W. (1998). A study of hole drilling in Kevlar composites, *Composites Science and Technology*, 58, 267–283.

Brinksmeier, E., & Janssen, R. (2002). Drilling of multi-layer composite materials consisting of carbon fibre reinforced plastics (CFRP), titanium and aluminum alloys, *CIRP Ann*, 51, 87-90.

Brinksmeier, E., Walter, A., Janssen, R., & Diersen, P. (1999). Aspects of cooling lubrication reduction in machining advanced materials, *Proceedings of the Institution of Mechanical Engineers, Part B: Journal of Engineering Manufacture*, 213, 769-778.

Choudhury, S., & Raju, G. (2000). Investigation into crater wear in drilling, *International Journal of Machine Tools and Manufacture*, 40, 887-898.

Dimla, D.E., Lister, P.M., & Leighton, N.J. (1997). Neural network solutions to the tool condition monitoring problem in metal cutting-A critical review of methods, *International Journal of Machine Tools and Manufacture*, 37, 1219-1241.

Dolinšek, S., & Kopač, J. (2006). Mechanism and types of tool wear; particularities in advanced cutting materials, *Journal of Achievements iin Materials and Manufacturing Engineering,* 19, 11-18

Ertunc, H.M., Loparo, K.A., & Ocak, H. (2001). Tool wear condition monitoring in drilling operations using hidden Markov models (HMMs), *International Journal of Machine Tools and Manufacture*, 41, 1363-1384.

Faraz, A., Biermann, D., & Weinert, K. (2009). Cutting edge rounding: An innovative tool wear criterion in drilling CFRP composite laminates, *International Journal of Machine Tools and Manufacture*, 49, 1185-1196.

Garrick, R. (2007). Drilling Advanced Aircraft Structures with PCD (Poly-Crystalline Diamond) Drills. In: *Aerospace Technology Conference and Exposition Preoceedings*, SAE Technical Paper Series https://doi.org/10.4271/2007-01-3893

Govekar, E., & Grabec, I. (1994). Self-organizing neural network application to drill wear classification, *Journal of Engineering for Industry,* 116, 233-238.

Groover, M.P. (2007). Fundamentals of modern manufacturing: Materials processes, and systems. John Wiley & Sons: New Jersey.

Iliescu, D., Gehin, D., Gutierrez, M.E., & Girot, F. (2010). Modeling and tool wear in drilling of CFRP, *International Journal of Machine Tools and Manufacture*, 50, 204-213.

Iskandar, Y., Tendolkar, A., Attia, M.H., Hendrick, P., Damir, A., & Diakodimitris, C. (2014). Flow visualization and characterization for optimized MQL machining of composites, *CIRP Annals*, 63 (1), 77-80.

Ismail, S.O., Dhakal, H.N., Popov, I., & Beaugrand, J. (2016). Comprehensive study on machinability of sustainable and conventional fibre reinforced polymer composites, *Engineering Science and Technology, an International Journal*, 19, 2043-2052.

Jayabal, S., & Natarajan, U. (2010.) Optimization of thrust force, torque, and tool wear in drilling of coir fibre-reinforced composites using Nelder–Mead and genetic algorithm methods, *International Journal of Machine Tools and Manufacture*, 51, 371-381.

Kannan, S., Pervaiz, S., & Ghoshal, A. (2018). An Experimental Investigation of Inclined Hole Drilling for CFRP Under Various Lubrication Techniques. *Proceedings of Advanced Manufacturing. American Society of Mechanical Enginers International Mechanical Engineering Congress and Expresition*, November 9-15, 2018, Vol. 2, 1-10, Pittsburgh, Pennsylvania, USA.

Kim, H.Y., Ahn, J.H., Kim, S.H., & Takata, S. (2002). Real-time drill wear estimation based on spindle motor power, *Journal of Materials Processing Technology*, 124, 267-273.

Khashaba, U.A., El-Sonbaty, I.A., Selmy, A.I., & Megahed, A.A. (2010). Machinability analysis in drilling woven GFR/epoxy composites: Part II – Effect of drill wear, *Composites Part A: Applied Science and Manufacturing*, 41, 1130-1137.

Krolczyk, G.M., Maruda, R.W., Krolczyk, J.B., Wojciechowski, S., Mia, M., Nieslony, P., & Budzik, G. (2019). Ecological trends in machining as a key factor in sustainable production – A review, *Journal of Cleaner Production*, 218, 601-615.

Lantrip, J. (2008). New Tools Needed: New cutting tool materials are required for new generation airframes, *Cutting Tool Engineering Magazine,* 72-84.

Li, X., & Tso, S.K. (1999). Drill wear monitoring based on current signals, *Wear*, 231, 172-178.

Lin, S.C., & Chen, I.K. (1996). Drilling carbon fibre-reinforced composite material at high speed, *Wear*, 194, 156-162.

Liu, H., Lee, B., & Tarng, Y. (2000). In-process prediction of corner wear in drilling operations, *Journal of Materials Processing Technology*, 101 (1-3), 152-158.

Murphy, C., Byrne, G., & Gilchrist, M.D. (2002). The performance of coated tungsten carbide drills when machining carbon fibre-reinforced epoxy composite materials, *Proceedings of the Institution of Mechanical Engineers, Part B: Journal of Engineering Manufacture*, 216, 143-152.

Park, K.H., Kwon, P., Kim, D. (2012). Wear characteristic on BAM coated carbide tool in drilling of composite/titanium stack, *International Journal of Precision Engineering and Manufacturing,* 13 (7), 1073-1076.

Rahim, E.A., & Sasahara, H. (2011). Investigation of tool wear and surface integrity on MQL machining of Ti-6AL-4V using biodegradable oil, *Proceedings of the Institution of Mechanical Engineers, Part B: Journal of Engineering Manufacture*, 225 (9), 1505-1511.

Sathish, R.U., & Raj, R.L. (2012). Applying wear maps in the optimisation of machining parameters in drilling of polymer matrix composites–A review, *Research Journal of Recent Sciences,* 1, 75-82.

Rawat, S., & Attia, H. (2009). Wear mechanisms and tool life management of WC–Co drills during dry high speed drilling of woven carbon fibre composites, *Wear*, 267, 1022-1030.

Sakuma, K., Seto, M., Taniguchi, M., & Yokoo, Y. (1985). Tool Wear in Cutting Carbon-fibre-reinforced Plastics : The Effect of Physical Properties of Tool Materials, *Bullet of Japan*

Sciety of Mechanical Engineers, 28, 2781-2788.

Sen, B., Mia, M., Krolczyk, G.M., Mandel, A.K., & Mondal, S.P. (2019). Eco-friendly cutting fluids in minimum quantity lubrication assisted machining: A review on the perception of sustainable manufacturing, *International Journal of Precision Engineering and Manufacturing-Green Technology,* 1-32.

SenthilKumar, M., Prabukarthi, A., & Krishnaraj, V. (2013). Study on tool wear and chip formation during drilling carbon fibre reinforced polymer (CFRP)/titanium alloy (Ti6Al4V) stacks, *Procedia Engineering*, 64, 582-592.

Shyha, I., Soo, S., Aspinwall, D., & Bradley, S. (2010). Effect of laminate configuration and feed rate on cutting performance when drilling holes in carbon fibre reinforced plastic composites, *Journal of Materials Processing Technology,* 210 (8), 1023-1034.

Shyha, I.S., Soo, S.L., Aspinwall, D.K., Bradley, S., Perry, R., Harden, P., & Dawson, S. (2011). Hole quality assessment following drilling of metallic-composite stacks, *International Journal of Machine Tools and Manufacture*, 51 (7-8), 569-578.

Sriraman, P., Prasanna, G., Pradeep, S., & Praveen Raja, D. (2015). A review on experimental optimisation in drilling of cfrp composite, *International Journal of Recent Trends in Engineering and Technology*, 10, 1-4.

Szwajka, K., & Trzepieciński, T. (2016). Effect of tool material on tool wear and delamination during machining of particleboard, *Journal of Wood Science*, 62 (4), 305-315.

Tansel, I.N., Mekdeci, C., Rodriguez, O., & Uragun, B. (1993). Monitoring drill conditions with wavelet based encoding and neural networks, *Journal of Machine Tools and Manufacture*, 33, 559-575.

Tashiro, T., Fujiwara, J., & Inada, K. (2011). Drilling of CFRP/Ti-6Al-4V stacks, *Advanced*

Materials Research, 325, 369-374.

Wang, D., Onawumi, P.Y., Ismail, S.O., Dhakal, H.N., Popov, I., Silberschmidt, V.V., & Roy, A. (2019). Machinability of natural-fibre-reinforced polymer composites: Conventional *vs* ultrasonically-assisted machining, *Composites Part A: Applied Science and Manufacturing,* 119, 188-195.

Wang, F., Qian, B., Jia, Z., Cheng, D., & Fu, R. (2018). Effects of cooling position on tool wear reduction of secondary cutting edge corner of one-shot drill bit in drilling CFRP, *International Journal of Advanced Manufacturing Technology,* 94 (9), 4277-4287.

Wang, X., Kwon, P.Y., Sturtevant, C., Kim, D.D.W., & Lantrip, J. (2013). Tool wear of coated drills in drilling CFRP, *Journal of Manufacturing Processes,* 15 (1), 127-135.

Xia, T. (2014). Investigation of drilling performance in cryogenic drilling on CFRP composite laminates, Master's Dissertation, Deparment of Mechanical Engineering, University of Kentucky: USA.

Xia, T., Kaynak, Y., Arvin, C., & Jawahir, I.S. (2016). Cryogenic cooling-induced process performance and surface integrity in drilling CFRP composite material, *The International Journal of Advanced Manufacturing Technology*, 82:605-616.

Xu, J., Ji, M., Chen, M., & Ren, F. (2019). Investigation of minimum quantity lubrication effects in drilling CFRP/Ti6Al4V stacks, *Materials and Manufacturing Processes,* 34 (12), 1401-1410.