



Bilal Mughal

STACK DRILLING OF CFRP/TI USING COATED AND UNCOATED
TOOLS

SCHOOL OF AEROSPACE, TRANSPORT AND MANUFACTURING
Ultra-precision Engineering (Manufacturing)

MRes
Academic Year: 2017 - 2018

Supervisors: Prof J. Endrino
Dr S. Goel
August 2018

CRANFIELD UNIVERSITY

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This thesis is submitted in partial fulfilment of the requirements for the
degree of MRes

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ABSTRACT

The aerospace industry is increasingly utilising composite-metal stacks due to their superior mechanical properties and variable physical functions. Energy saving and increased strength/weight ratio are the two main factors why manufacturers are replacing separate composites and metal alloys with the hybrid stacks. These stacks are drilled and joined together with mechanical fasteners such as rivets. Single-shot drilling is a relatively new method and allows for time and cost reduction. But, because of the disparate nature of materials, drilling them at the same time poses great manufacturing challenges. Tool wear, increased temperature and poor machining quality are some of the issues encountered.

This study investigated the performance of tools coated with diamond-like carbon (DLC) and boron-aluminium-magnesium (BAM) coatings which were deposited using physical vapour deposition (PVD) method.

Drilling experiments were carried out on CFRP/Ti stacks and tool wear and hole quality were assessed. Tool wear results showed that DLC 1 tool had the best performance, showing the least wear. For BAM coatings, higher thickness caused the tools to fail earlier than DLC and BAM 1 tools. Uncoated tool failed after 25 holes. Overall coated tools DLC 1 and BAM 1 showed best performance.

Keywords:

Drilling, physical vapour deposition, diamond like carbon, boron-aluminium-magnesium.

Acknowledgements

I would like to express thanks to some individuals for their support during the course of this project.

Firstly, I want to sincerely thank my supervisors Professor Jose Endrino and Dr Saurav Goel for their supervision. Especially Dr Goel for his enthusiastic approach and making the whole MRes an amazing experience.

I would like to thank the technicians, Mr John Hedge and Mr Alan Heaume, for their support in lab. It was an enjoyable experience to work under John on the Kern machine.

I am thankful to Tomasz Brzezinka (PhD student) for the PVD training and help during the coating deposition.

I would also like to thank the other technicians who assisted me during SEM, nano-indentation, material cutting and CMM training.

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List of abbreviations

BAM	Boron-aluminium-magnesium
CFRP	Composite fibre reinforced polymer
DLC	Diamond-like carbon
EDS	Energy dispersive spectrometer
HiPIMS	High power impulse magnetron sputtering
PVD	Physical vapour deposition
RPM	Revolutions per minutes
SEM	Scanning electron microscope
Ti	Titanium
WC	Tungsten carbide

1 Introduction

1.1 Background and motivation

The aerospace industry is increasingly implementing new materials in order to develop airplanes with reduced weight to save fuel costs and extend cycle life. Fibre reinforced polymers (FRPs) have seen increased popularity in aerospace applications due to their exceptional properties. FRPs have the following properties: low density, reduced weight, high young's modulus and high strength to weight ratio. One of ways they achieve weight reduction is by using composite/metal stacks due to their high strength to weight ratio [1]–[5]. Usually FRP is stacked with alloys to increase the strength. A common stack sequence being used is that of carbon fibre reinforced polymer (CFRP) with titanium (Ti).

CFRP have become gradually common due to their distinctive and custom-made properties. Their properties include light weight, high strength-to-weight ratio, extremely high modulus of elasticity (relative to steel), low density, good corrosion resistant, low impact resistance, very low coefficient of thermal expansion, and high electric conductivity [6]. In aerospace assembly for skin segments, fuselage and wing segments, CFRP's are supported by metallic plates of aluminium (Al) and/or titanium (Ti).

The skin segments, fuselage and wing segments of an aircraft are currently being manufactured from CFRP-metal stacked layers. In particular, CFRP-Ti stacks have a high strength-to-weight ratio—with yield strength as high as 830 MPa and a density of roughly 4 g/cm³. It also provides excellent corrosion and heat resistance [9].

For example, the structural weight of the Boeing 787 and the F-22 contains 14% and 39% titanium content, respectively. In terms of composites, the Boeing 787 has a 51% structural weight content while the F-22 has a 36% structural weight content. Structural components made from composites are generally attached to titanium rather than aluminium due to galvanic corrosion that occurs between composite/aluminium stacks [7].

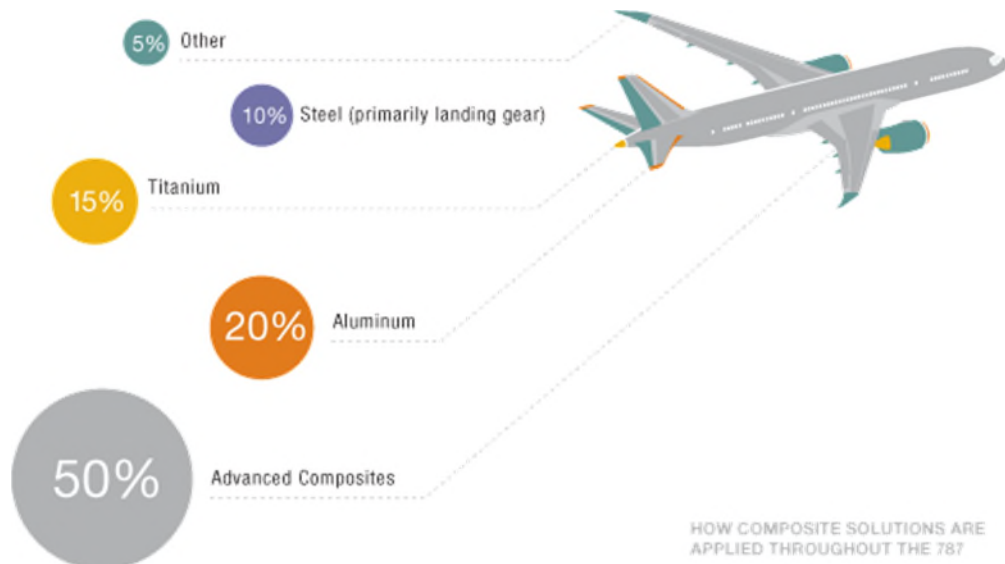


Figure 1. Material composition in Boeing 787 aircraft [1-5]

Despite the advantages of stacked materials, there are manufacturing challenges in the assembly of the different materials. Assembling of components includes many heavy-labour operations involving numerous steps, resulting in high costs. It is common practice in aerospace industry to join the composite/metal components using fasteners such as bolts and/or rivets. This allows for easy assembly/disassembly of components in case of replacements, however, holes need to be created to facilitate this [2]. For fastening the CFRP with metallic plates, the process of hole-making by drilling is employed accounting for 40–60% of material removal in assembly of aircraft [8] and such operation not only determines the total machining time but also strongly affects the reliability of an aircraft. Military aircraft require between 200,000-300,000 fasteners, whereas the number in commercial aircraft can range from 1,500,000-3,000,000 depending on the size.

To ensure the materials are aligned properly during joining, the hole quality is of critical importance. Normally, the materials are drilled separately and assembled temporarily to carry out finishing processes on holes [2]. Another method used is to drill pilot holes and use temporary fasteners to check the alignment of the materials. These holes are drilled to the required size once the alignment has been made. These methods are slow and less productive. One of the ways manufacturers are trying to solve the problem is by drilling the materials simultaneously using a process called single-shot drilling.

Drilling both CFRP and Ti materials in one shot is favourable to obtain tight control on tolerances for fastening. However, the disparate thermal and mechanical properties of the stacked materials and the heterogeneous interface makes it difficult for a cutting tool to last longer. Main issues of drilling CFRP-Ti stacks consist of rapid tool wear, delamination of CFRP and compromised quality of hole [9], [10]. CFRP contains highly abrasive carbon fibres, which produces severe abrasive tool wear and tool edge chipping whilst Ti possesses low thermal conductivity and strong chemical affinity to tool materials, which accelerates chemical wear. Furthermore, high temperature in the cutting zone, may lead to formation of dynamic hard particles as a consequence of micro-welding of the small built-up cutting edges thereby accelerating the chipping of tool edge [11], [12]. Furthermore, some of the problems encountered regarding the drilled hole quality characteristics of CFRP-Ti stacks include heat induced damage, geometric errors, deviations from the true shape and burr formations [9], [10] requiring additional post-drilling treatments.

1.2.1 Newer trends of increasing use of CFRP in aircrafts

By definition, a composite is a mixture of at least two materials or components. This can be broadly referred to even metal alloys wherein mixtures of metals are used to draw upon favourable characteristics such as strength, elasticity or conductivity. Originally, composite materials were developed by the aerospace industry in the early 1940s, however, since their initial production they are now found widespread among a plethora of industries from automotive to defence goods, composites such as fibreglass, or Kevlar are now commonly found worldwide. Composite materials are generally used to enhance such characteristics, and in the case of CFRP, they are found in a polymer structure. The advantages of using polymers includes:

- Stress transfer among fibres
- High resistance to corrosion
- Higher durability resulting in long lifespan of material
- Ease of repair
- High ratio of strength-to-weight

There are also many disadvantages associated with composites which include:

- Difficulty in detecting defection such as delamination
- Can be highly costly
- Can often harbour toxic and harmful products

- Possess lack of standard methodology for repair

However, as composites are becoming more and more widespread, the advantages are steadily outweighing the costs of their use as better and safer procedures are put into place for their efficient use [13].

Carbon fiber reinforced polymers (CFRPs) are carbon composites which are extremely durable and lightweight plastics which are reinforced by carbon fibers. Similar to Titanium, they are highly abrasive and require extremely durable tools and instruments which are resistant to abrasion [14].

The function of fibres in composite materials is to provide reinforcement and the majority of strength to the material. There are three types of fibre reinforcements:

- Particles - A square material.
- Whiskers - A material which is greater in length than in width, they are usually crystalline.
- Fibres - Width is fractional in comparison to length, and can be composed of any form of material. They are the most common form of reinforcement and the most common types are carbon, aramid and glass.

CFRPs are widespread among the aerospace industry, especially due to their favourable properties of stiffness and strength in relation to their density. The use of composite materials stems from the fact that by combining materials, often they retain the majority, if not all, of their advantages and yield next to no disadvantages which would be portrayed by the use of the materials individually. The main form of composite used by the industry are fibrous composites, these differ from conventional composites as they are anisotropic. That is to say that the properties associated with the material differs based on the direction of load exerted in relation to the fibre orientation. A key example of the use of CFRPs within the industry is its initial uses within the Airbus A310. The material has since been successfully implemented for the production of spoilers, fuselage components, and flaps fairings in man more models of aircraft.



Figure 2. Use of CFRP in A380 [1-5]

Since then, the industry has looked toward the possibility of implementing self-healing CFRPs with the ability of autonomous repair into the production of aircraft components such as those aforementioned as self-healing materials have implications of lower costs in place of replacement and repairs for damaged components.

1.2.2 Historical use of titanium alloys in aircrafts

Materials used to construct aircraft need to be both strong enough to hold against the immense pressure of high-altitude flights and also be durable enough to survive the harsh elements that they are constantly exposed to. It was traditional for aircraft to be constructed with steel, however, instead of using steel, a lighter, stronger alternative is now used to increase energy efficiency of aircraft and also increase their durability [15].

Titanium, identified by the elemental symbol of Ti, is a transition metal element of the D-block elements in the periodic table. It was discovered by William Gregor, 1791, and was named aptly after the mythic Greek Titans due to its properties in strength and durability. It has an atomic number of 22, and an atomic weight of 47.867. Titanium has the same strength of steel, whilst being 45% lighter than it, and it also has the highest “weight-to-strength” ratio of any metallic element. This makes it an ideal candidate as an alternative to steel in the aerospace industry. Furthermore, it is highly resistant to corrosion which makes it even more ideal for its use in the outer-assembly of aircraft. Titanium can form many metal alloys with other metallic elements the likes of Vanadium, Aluminium, and Iron. Titanium is said to be the ninth most abundant

metal on Earth and can be found naturally bonded to other elements, hence to obtain it, several extraction and purification processes must be undergone [16].

Pure titanium was first distilled by M. A. Hunter in 1906, and led to study of the element, in turn this led to the industrial mass extraction of the metal in 1932 by William J Krol [16]. Since, Titanium has spread globally across many industries, including the aerospace industry wherein it is used for construction and repair for a myriad of aircraft features such as the fuselage, engine and fittings and other components which may be exposed to high temperatures. 60% of all Titanium is said used in the aerospace industry [17]. Titanium is also used in turbine engine components for compressor blades, disks, and turbine housing.

1.2.3 Mechanical and corrosion properties of Ti alloys

Titanium's properties seem to lie in between those of aluminium and stainless steel in terms of density, elasticity, and strength at high temperatures. With a melting point of 1668°C, low thermal conductivity and expansion coefficient, Titanium is a strong metal, yet light, and highly resistant to corrosion [18]. However, its properties at elevated temperatures are not as adequate, evidently above 450°C Titanium becomes weaker and far more brittle after temperatures of 800°C due to the fact that it starts absorbing oxygen from its surroundings. Even so, its high melting point allows for temporary exposure to high temperatures which is a requirement for the construction of aircraft [15].

Some allows of the metal are rigid and hard, and only recently have the industry been able to create a heat treated alloy, comparable to that of a stainless steel alloy. Before this method was developed, Titanium had to be formed through constant and repetitive heated rolling. Another technique to create the alloy is to use traditional techniques and the heat-treat it. Like Gold, purer Titanium is generally softer than its alloys. Titanium is also not magnetic, and has similar electrical resistance to that of steel.

There are three main forms of titanium alloys; alpha, beta and C alloys. There are two types of crystalline structures, and phases, of Titanium and its alloys: Alpha and Beta. Alpha crystalline Titanium is characterised by its stability at temperatures up to 882°C also known as the beta 'transus', and for its closed hexagonal shaped lattice. Whereas Beta crystalline Titanium becomes stable after the beta 'transus' up until it reaches its melting point at 1668°C, and possesses a cubic-shaped lattice [19]. The additions of

metals for alloying stabilises the beta phase. This is as it lowers temperatures of the change from alpha to beta phase. Such metals include chromium, copper, and iron. Other metals such as tin act as neutrals and instead of having an effect on temperature, enhance the strength of the alpha phase. Titanium alloys are distinguished as A (containing less than 5 percent of beta phase), B (containing more than 20 percent beta phase), or C (containing between 5 and 20 percent beta phase). Alpha types are characterised by being durable in both cold and warm conditions, having ease of welding, and being resistant to being oxidised. Beta types retain strength in cold and hot conditions, possess high bendability, but are prone to being oxidised. Type Cs have a balance of the properties of alphas, as well as betas for compromising properties in the form of retaining strength in cold and warm conditions (but not hot), having good bendability and being excellent for forging [20].

Commercially, Titanium can be acquired as either in a pure form, or as an alloy. Type A-55 for instance is an example of pure Titanium, possessing strength measured between 400 to 555 MPa, whereas a common Titanium alloy is type C-110M which has yield strength onwards of 760 MPa. It contains a small percentage of manganese. Type A-110AT is an alloy with 5 and 2.5 percent aluminium and tin respectively which is similar to type C-119M, except it has the ease of welding characteristic as is evident in alpha types [21].

Titanium's properties include a high resistance to corrosion and oxidation as a result of oxygen absorption (or the reaction with an oxidising agent) on the surface of the metal resulting in a protective coating. The little corrosion which does occur is generally uniform and localisation of corrosion does not occur, for example galvanic, stress, and inter-granular corrosion do not occur.

1.2.4 Joining methods of CFRP and Ti alloys and need for investigating stack drilling

Joining two different materials is a challenge due to their dissimilar physical-chemical properties. According to [22-24], the main methods of joining polymers, composites and polymer-metal hybrids are using mechanical fasteners, adhesive bonding and welding. This study is concerned with joining CFRP and Ti, which is a composite-metal compound. Previously, the two materials were drilled separately prior to aligning them and joining them together using rivets. This resulted in misalignment and increased cost of using different tools for drilling. Recently manufacturers are looking to single-

shot drilling to improve alignment and reduce costs. In this process, the two materials are drilled at the same time using a single tool, leading to time and cost reduction.

A different method of joining the CFRP/Ti is using adhesive bonding. However, this process requires Ti surface pre-treatment to enhance adhesion and curing time can be long, as well as reduced strength due to the adhesive material.

A new method of joining composites to metal alloys is using laser joining. There are successful studies conducted on joining CFRP to aluminium using laser joining [24]–[27]. Despite the method being effective for joining CFRP to Al, it has not been investigated for joining CFRP/Ti stack. Thus, the common method of joining CFRP/Ti stacks is via mechanical fasteners. However, there are many issues involved during drilling which are discussed in the literature review.

2 Literature review

2.1 Overview of mechanical drilling and drilling forces

Drilling is one the most common machining methods which has been used for hole-making. There are countless literature on drilling techniques for various materials. For this study, drilling is the fundamental operation for the application of CFRP/Ti stack in the aerospace industry. The challenge thus arises from the disparate nature of the constituents having different properties and difficulty in machining that affect the hole quality. The assembly of the CFRP/Ti stack is greatly dependent on the hole quality; any defects can lead to reduced strength and failure of the stack, which could be catastrophic in the aircraft. Tool wear and hole defects are a couple of the issues faced during stack drilling. Therefore, it is vital to explore the behaviour and improve the drilling process of hybrid stacks.

One of characteristics triggered during the drilling of FRP/Ti drilling is the generated force as it indicates the mechanical energy consumed by the tool-workpiece interfaces during the removal of chips. The force during drilling can be divided into two parameters: thrust force and torque. The thrust force represents the tool-chip interface, whilst the torque represents the interface between the tool and the machined surface.

Stark variations occur in thrust and torque forces when drilling stack comprising FRP/Ti. The main reasons for the differences are the result of following: due to the orientation of fibres during FRP drilling, due to change in manner of chip separation during the interface and due to saw-like chip formations during Ti drilling. The crucial feature that greatly affects the force during the drilling is the varying removed chip formation methods taking place

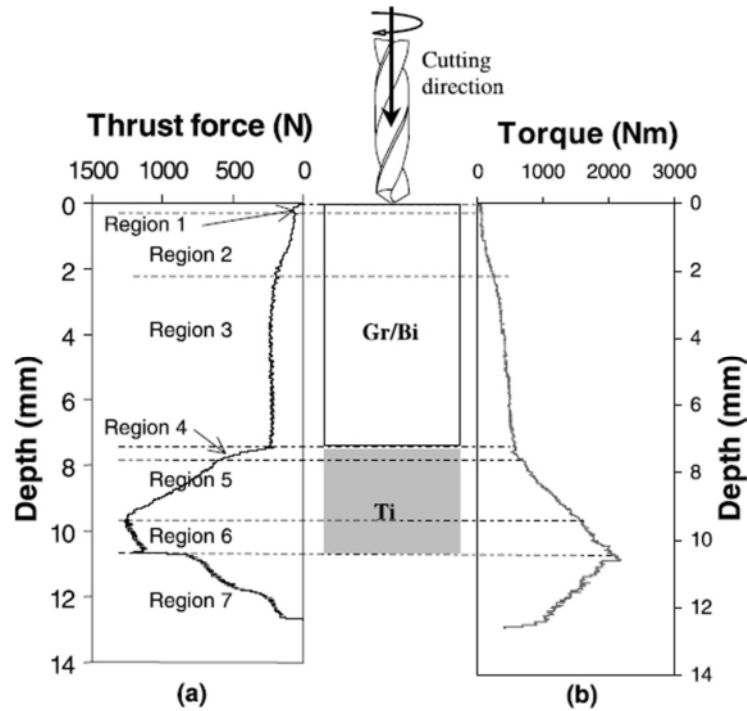


Figure 3. Drilling force signals versus cutting depth when drilling hybrid FRP/Ti

Ramulu et al. [10] studied the influence of drilling parameters on the force generation when drilling FRP (Gr/Bi)/Ti stacks. Results presented in Figure 3(a) and Figure 3(b) indicated that the feed rate had significant effects on the thrust force magnitudes in such manner that a slight increase of feed rate gave rise to the dramatically elevated thrust force, irrespective of the used tool materials. As mentioned above force generated in drilling CFRP is less than compared to drilling titanium. Almost every study on stacked drilling involves the measurement of forces. The thrust force and torque are affected by the following parameters:

- Number of holes drilled
- Speed
- Feed rate
- Tool- i.e. coated or uncoated

As the number of drilled holes increases, the rates of thrust force and torque also increase. This can be attributed to the tool wearing down after subsequent drilling. Li et al. [28] studied the tool wear of coated and uncoated drills during Ti/CFRP stack drilling using helical milling. The forces for both CFRP (Figure 4) and Ti (Figure 5) increased with the number of holes. It should also be noted that the cutting forces for

titanium are much higher. The increase in thrust and force can be confirmed by the following studies (1, 3, and 4).

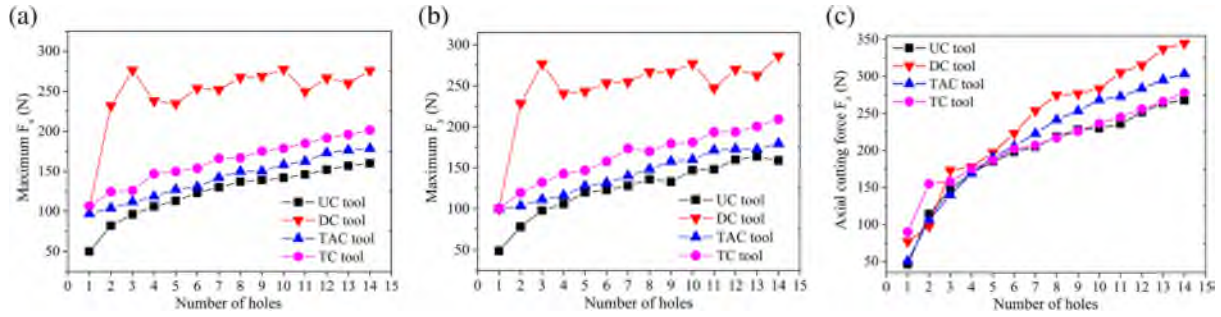


Figure 4. Cutting forces of different tools in helical milling of titanium alloy [2]

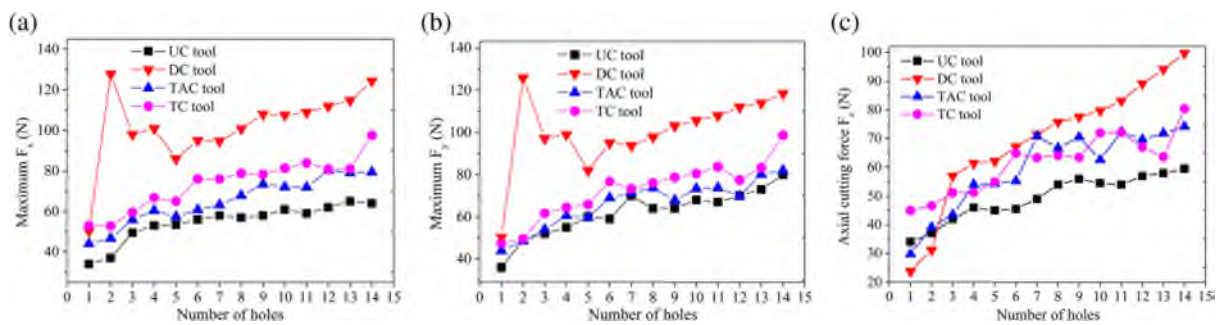


Figure 5. Cutting forces measured for different tools in helical milling of CFRP [2]

Park et al. [1] studied the tool wear of carbide tools in CFRP/Ti stack drilling. They found that the speed (of drilling) affects the thrust force. Figure 6 shows the results of maximum thrust force and torque with increasing hole numbers at high speed (CFRP-6000 rpm, Ti-800 rpm) and low speed (CFRP-2000 rpm, Ti-400 rpm). As shown in Fig. 3, the thrust force increased to 420N at the high speed set up between holes 1 and 100, and 330N for the low speed setup when drilling CFRP, whereas the thrust force increased to 1650N for the high speed condition and 1460N for the low speed condition between holes 21 and 80 when drilling Ti in the stack. Torque values, on the other hand, are similar for both high and low speeds for CFRP drilling. When drilling Ti, drilling at the high speed condition causes a higher torque force on the sample.

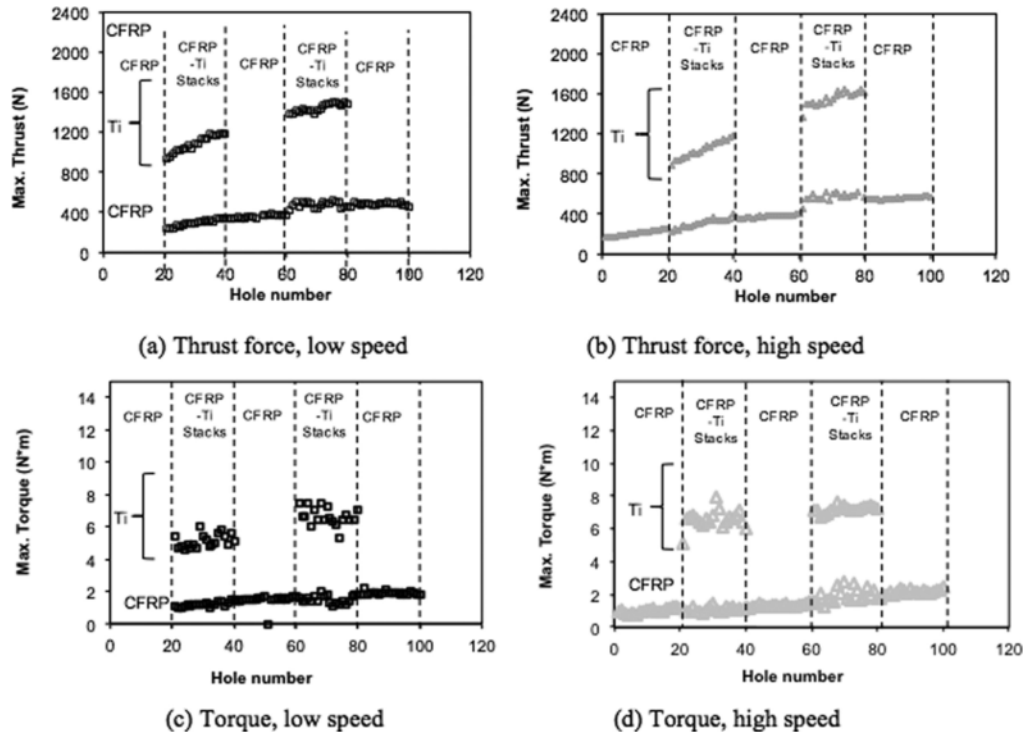


Figure 6. Maximum thrust force and torque with increasing hole number at high and low speeds [1]

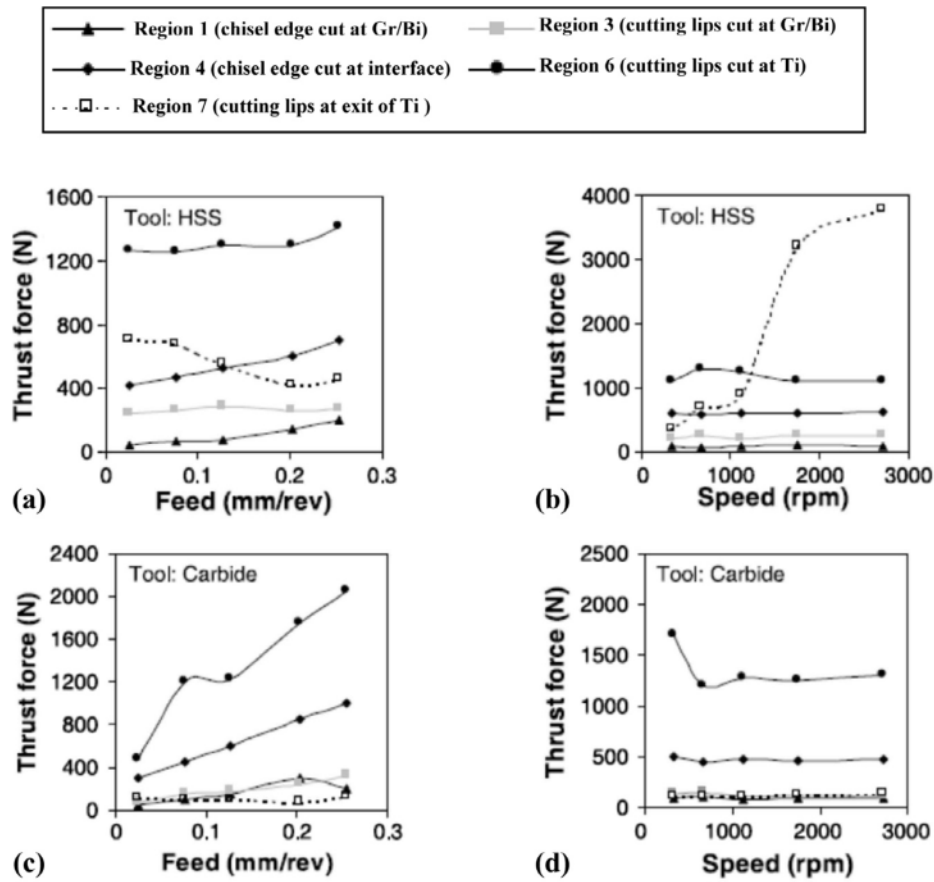


Figure 7. Thrust force at different feeds and speeds [1]

2.2 Cutting mechanisms during CFRP/Ti drilling

The drilling of CFRP/Ti stack shows different behaviour compared to drilling CFRP and Ti separately because of the multi tool work interface areas. The dissimilar properties of each material allow for the mode of chip formations to be more combined and unified controlling the bi-material drilling. This process of combined material removal is a major mechanism that affects the drilling process and mechanical interactions. Thus, it is important to study and understand the factors affecting the stack drilling as it can allow for optimisation of cutting parameters, tool wear behaviour and control of finished hole quality.

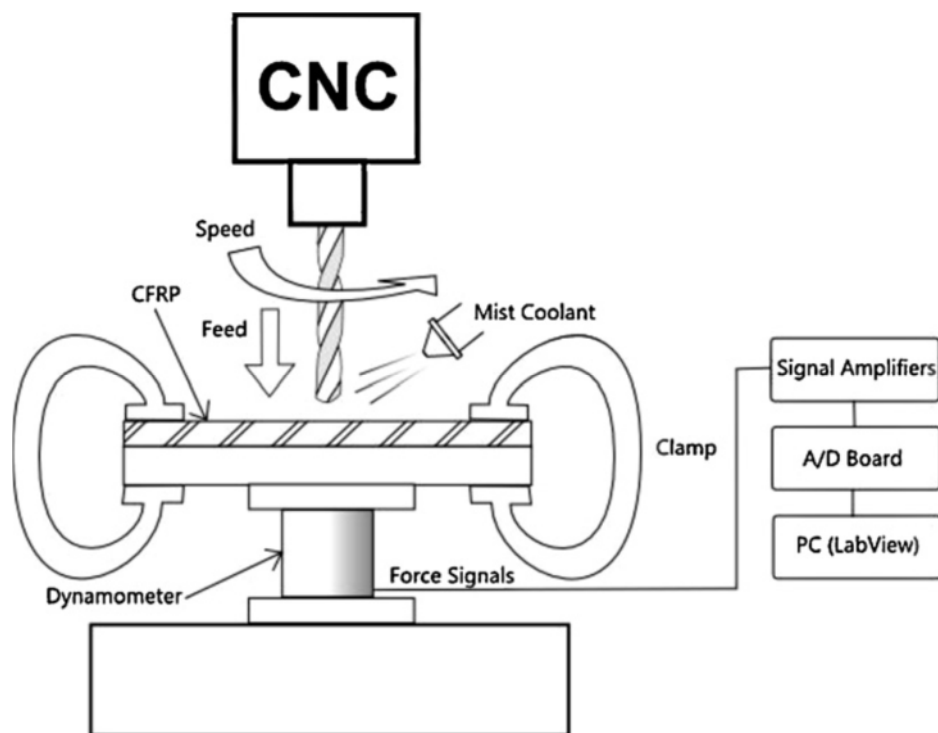


Figure 8. Schematic of the CFRP/Ti cutting sequence [29]

During the stack drilling, the cutting sequence can either be CFRP/Ti or Ti/CFRP; referring to point of tool entrance and exit, i.e. in CFRP/Ti the tool will first drill CFRP and then Ti, and vice versa. It is normally the rational practice to use the CFRP/Ti sequence in drilling as shown in Figure 8. The reason for this so that the titanium underneath acts as a backing plate to stop laminate bending and reduce work piece dynamics in the drilling process. This ensures that there is reduced delamination related damage in CFRP and extend tool life. This sequence has been studied and proven to be best solution in numerous studies and some example can be found in [2-

4]. Isbilir and Ghassemieh [31] studied hole quality of CFRP with and without titanium underneath. Figure 9 shows the resulting damage in CFRP.

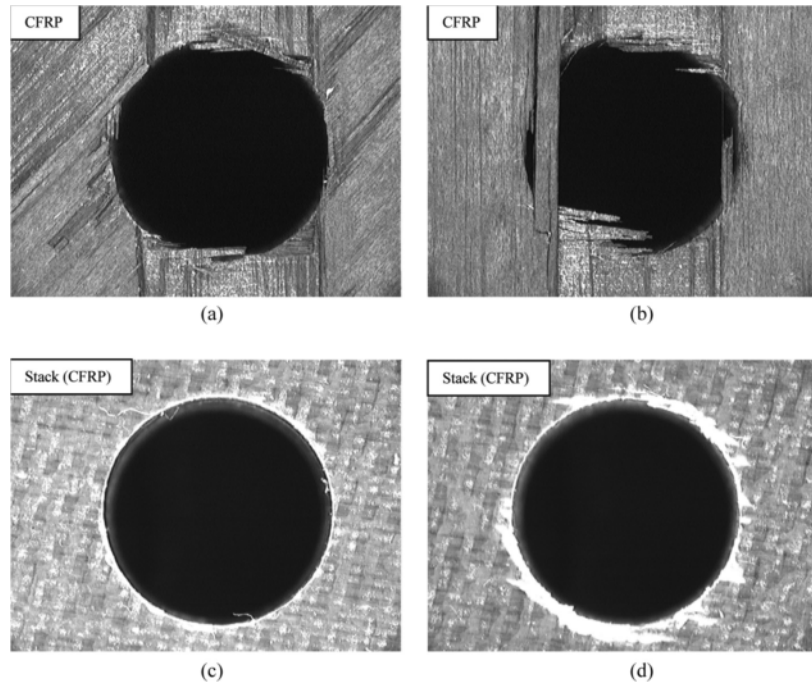


Figure 9. Exit hole delamination in CFRP: (a) without backing plate, 1st hole; (b) without backing plate, 56th hole; (c) CFRP/Ti, 1st hole; (d) CFRP/Ti, 15th hole. [31]

In figure above, the exit hole surface damage is compared in drilling CFRP separately and with titanium as a stack. It can be seen that the CFRP drilled separately has fibre pull-out and delamination, whereas in CFRP/Ti there is considerably less damage. Therefore, it is best to use this sequence to carry out stack drilling.

2.2.1 Drilling in CFRP

The mechanisms during CFRP drilling differ considerably in comparison to drilling metal. This is because of the brittle nature of fibers and heterogeneous fiber/matrix composite. The fibres in this case being carbon fibres and the matrix system can be a range of polymers. The detailed chip formations depend on the mechanisms governing the CFRP drilling.

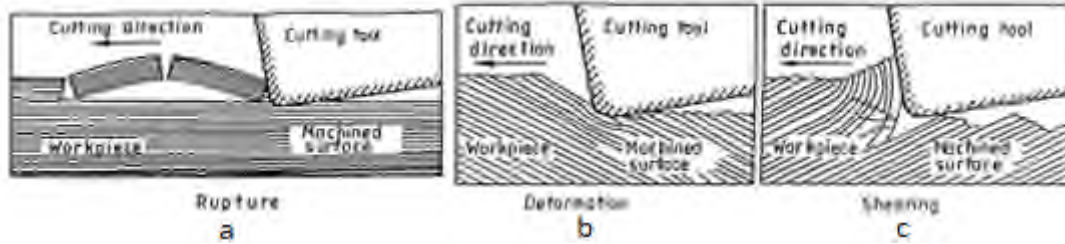


Figure 10. Chip formation mechanisms in carbon/phenolic composites [33]

During composite phase drilling, material is removed via continuous tears supported by the different characteristics and irregular load bearing between the fibers and matrix. This mode of chip formation is caused by brittle fracture when a crack initiates and propagates having been formed as shown Figure 10a [33]. Because brittle fracture is the main mechanism that controls the chip removal, the removed chips resemble power-like dust. Although, the type of chips formed are influenced by the type of matrix and volume of fibers in the composite. According to a study by Hocheng et al [34] on drilling carbon fibre reinforced thermoset (epoxy) and thermoplastic (acrylonitrile butadiene styrene) showed that the chips formed in CFRP/thermoset drilling were discontinuous, whereas in CFRP/thermoplastic they were continuous. The chip formations can be explained by the fact that in the CFRP/epoxy, the mechanism of material removal was brittle fracture, whereas

2.2.2 Interface drilling

During stacked material drilling, the interface region experiences several different cutting actions to remove the material. These cutting actions are the result of different material drilling modes, i.e. fibre composite and metal alloy. Due to this, the interface experiences damage from the inter-connected chip removal method.

Figure 11 shows a schematic of a drilling tool at the stack material interface. The machining occurring at this region is called multi-tool-work, because the drilling tool is involved in cutting both regions at the same time. Hence, the interface drilling process is composed of various cutting phenomena taking place. The dual tool-workpiece interfaces result in severe cutting environment for the tool. The cutting edges on the drill bit encounter varied workpiece-induced damage at the same time.

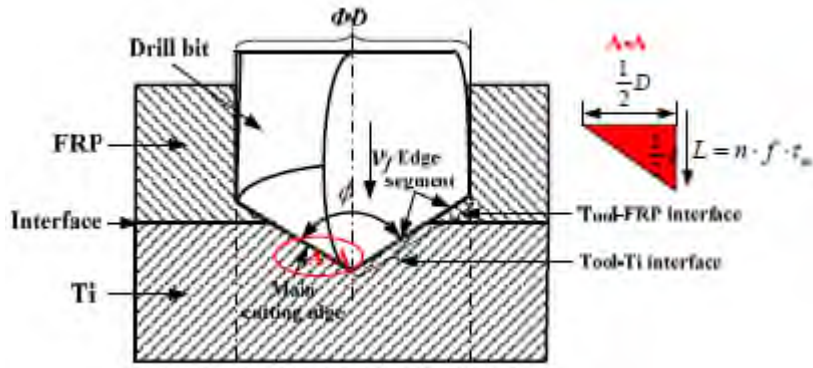


Figure 11. Drilling interface between CFRP and Ti [28]

The main cutting edges on the drill bit experience intermittent and distinct force and heat generation due to multi-tool-work interaction, as a result of that, it causes the tool to become weak and dull. As well as that, they also undergo boundary change. This is when the drilling process transforms from just CFRP contact to CFRP/Ti contact and then to Ti contact. These cause the tool to experience strong force changes resulting in a non-steady drilling process. These occurrences are the primary reasons for the hole quality damage regarding the stacked material interface. Due to different tool-workpiece interactions, the tribology also varies, resulting in tool wear and reducing its life.

The following equation is used to calculate the interaction time between tool and interface:

$$t_m = \frac{D}{2nf} \cot \frac{\phi}{2} \quad [28]$$

where t_m is the interaction time, D is the diameter of tool, n is the spindle speed, f is the feed-rate and ϕ is the tool point angle.

The damage to the tool due to the interface can be reduced by reducing the contact time between tool and interface. This can be achieved by using high speed, feed-rate or bigger point angle. Due to this being a challenging drilling phase, the fundamental mechanism(s) of tool-interface relationship is not researched deeply. Understandably, it is an arduous task to monitor the physical interactions taking place at the interface.

2.2.3 Ti-phase drilling

Once the cutting edge penetrates into the titanium stage, the cutting mode of tool-workpiece converts from interface to titanium drilling, which is dominated by the elastic and plastic machining mode. The chip removal mode in this phase is continuous. With

this being a titanium only phase, the process should be expected to be steady. Nevertheless, the low thermal conductivity and adhesion-ability of titanium to tools lead to poor hole quality and increased tool wear [1], [2].

2.3.1 Hole damage during interface drilling

Due to the starkly contrasting mechanical and physical properties displayed by the FRP and Ti phases, a measure of incompatibility arises within the tool and work interfaces, resulting in significant influence on the cutting performance of the tool. As such, the interface which connects the FRP and the metal phase is seen to be the most fragile area which is susceptible to the formation of damage resulting from the various extreme conditions required within a cutting zone. Such damage is usually in reports as fiber pull-outs, discolouration rings as well as direct damage to the ring. Once the cutting instrument is within reach of the interface between the two phase boundaries, the tool is exhibited to great vibrations and fluctuations as a result of the varying chip separation modes from the interactions between the tool and the FRP, to the tool and Ti interactions conversely. These interactions severely increase the likelihood of the formation of the aforementioned damages which are generally irreparable (see Figure 12) [30], and often lead to the initiation of cracks and fractures in the course of the stack assembly.

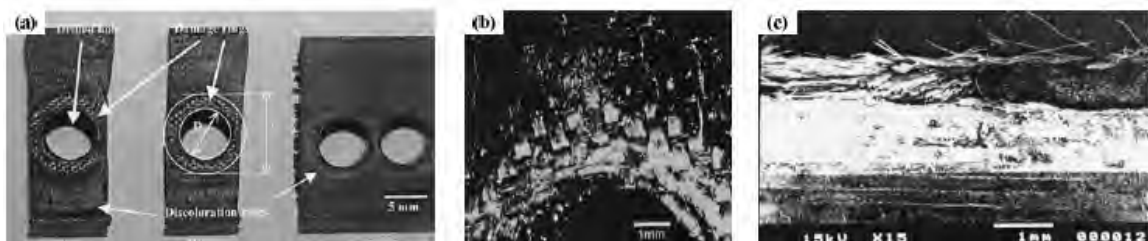


Figure 12. (a) interface damage at CFRP/Ti; (b) damaged region at the top; (c) damaged region from the side [30]

Prior researchers [30], [35] have hypothesised that two crucial factors, cutting temperature and chipping evacuation, have influential roles within the initial formation of damage, as well as its development. Ramulu et al. [30] demonstrated that tool deterioration and rate of feeding also had effect on interface damaging. That is to say when a lowered rate of feed was used, higher levels of damage was produced as a result of more tool to work engagement leading to high Ti thermal and heat production generated onto the material surfaces. However, a more direct cause of damage can be attributed to the distinct physical properties of Ti. Force induced delamination can be seen to be a result of Ti chips which continuously scratch and have an abrasive

effect upon the dual material interface. Moreover, an increase in heat concentration at the interface is seen as a result of Ti within the metal phase having deficient thermal conductivity ($\lambda_s \approx 7-7.9 \text{ W}\cdot\text{m}^{-1}\text{C}^{-1}$), resulting in heat generated within the inter-phase boundaries to be insufficiently dissipated. This build-up of heat from the cutting tool can result in phenomena such as thermal softening and damage of the FRP and Ti interfaces. Other factors which affect damage generation on the material surfaces include tool geometry such as drill size, diameter, and its angle. These can also manifest into interface damage. There is a lack of sufficient theoretical ideas explaining the formation of material damage as and insufficient quantitative studies which could correlate the damage and input modes.

2.3.2 Hole damage during drilling of titanium phase

Elastic-plastic shearing occurs as a result of brittle fractures being attacked by the tool on the Ti phase. Consequently, the surface produced is commonly of better quality, in comparison to that of FRP. Yet, the most crucial issue in these forms of hybrid phase drilling is the poor thermal-conductive properties of the Ti composite which results in the issue of heat accumulation on the surface of the tool-chip interface. Consequently, there is an increased cutting temperature of the tool cutting areas, further increasing damage to the interface and aforementioned surface defections such as heat induced delamination and rough surface. There are several types of surface defects which occur as a possible result of the thermomechanical effect of drilling, which alter depending on the conditions of cutting environment and geometric properties of the tools. Such defects include burrs, drag, and crack formation, surface tears, chipping from microchips, and surface cavity formation [36], [37]. The most significant of such surface defects are burr formations as these defects form in the Ti metal phase and lead to exacerbation of damage as deburring is necessary along with reassembly. The most important factors behind the formation of burrs are the geometries of the tool and orientation.

There are three distinctive types of burrs which are known as Type A, B, and C which are classified based upon where the initial crack formation occurs. Type A burrs occur in a small size in negative shape as a result of brittle composite used, type B burrs form due to elasticity of plastic deformation and are classified to have a 'uniform drill cap', whereas type C burrs are the most severe, being characterised to have roll back

along the edges as well as the production of rings. These classifications were first introduced by authors such as by Ko et al [38], and Dornfeld et al [37].

Shyha et al [2] found that when utilising a stack of “Ti6Al4V/CFRP/Al-7050,” generally, the majority of Ti burrs, both type A and B, were generated at the exit point of holes, whereas type C burrs were most common at the entry point of holes. Exit point burrs are particularly problematic for further stack assembly and in order to reduce burr formation, it is essential that appropriate tool geometry, cutting conditions, as well as higher-grade tool material are used. The use of cutting-fluid in the drilling case can also help improve the reduction of burr formation. This is as wet-cutting and spray mist further prevent burr formation as a result of the beneficial heat dissipation and “thermal effect alleviation”. Furthermore, they also investigated entry and exit points of burr holes in a comparative study where differing bits were used for drilling and different cutting conditions were used. Evidently, new tools (first drilling) showed far greater drilling performance relative to burr height than previously used tools (after the drill had been used several times).

2.4 Tools used in stack drilling

When drilling stack materials, it is important to use tools that have greater thermal and physical properties. As discussed previously, there is multi tool interaction that results in tool wear, so the tool must be able to counter that. As such, the dissimilar properties of CFRP and Ti make it difficult to select the best tool, because the wear modes are different in both materials. The fibers in CFRP cause rounding of edge and flank wear (see Figure 13) [39], [40]. Also, the chips cause heat accumulation to the tip that results in tool chipping.

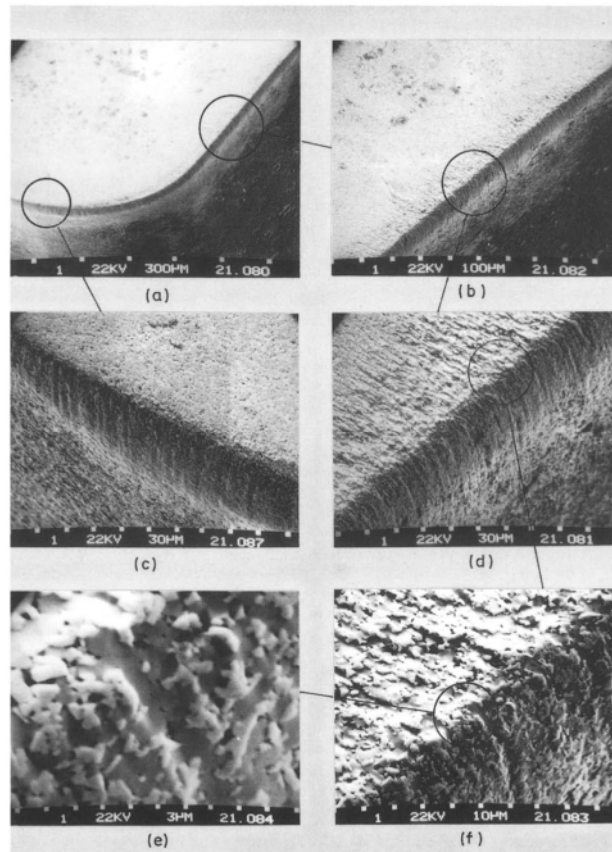


Figure 13. Tool flank wear during CFRP machining [40]

When it comes to drilling Ti, the chips attach to the tool and cause adhesion wear. Ti has low thermal conductivity, so the tool undergoes thermal damage that results in fracture. The damage to tool varies a lot from the two materials. For that reason, it is necessary that that tool has following properties: resistant to wear, extreme hardness, high toughness and high thermal conductivity. Previous studies used tools such as tungsten carbide (WC), high speed steel (HSS) and coatings. Figure 14 below shows the cutting performance of the tools used in stack drilling.

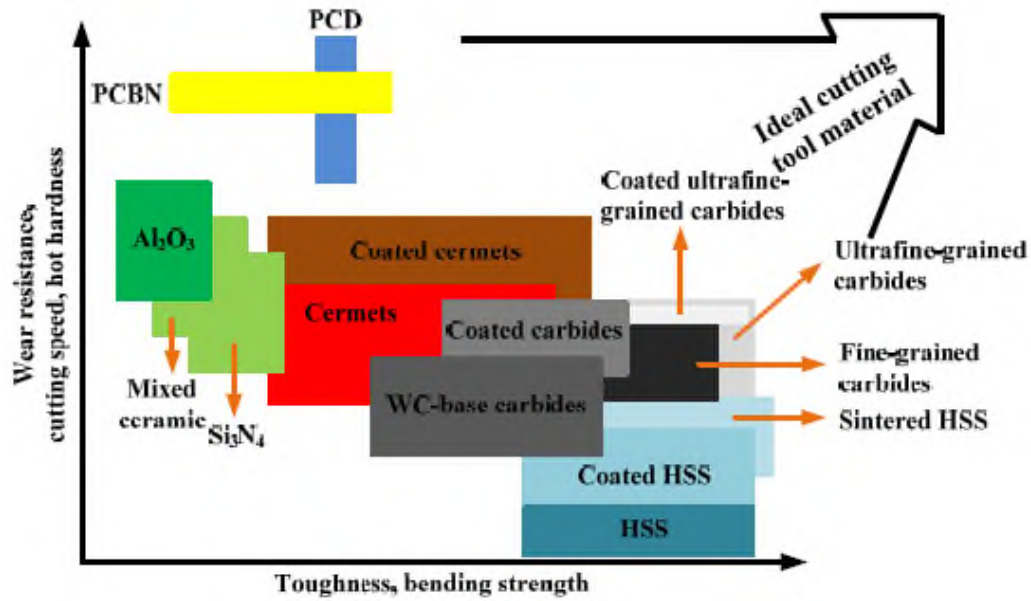


Figure 14. Materials used

Many of the studies have used coated drills in stack drilling as they tend to have superior properties. However, results from previous studies have shown that coatings are not always the best option. Table 1 shows a list of tools and coatings used during stack drilling. Also summarised are the drilling parameters and result. Tungsten carbide is the most common tool material used whether it is coated or uncoated. Some issues of coatings include coating delamination and edge roundness, due to which there is not much difference by using them. For example, Li et al. [28] studied the cutting performance and wear mechanisms of coated tools (diamond coating, TiAlN+AlCrN multilayer coating and TiAlN coating) against uncoated tools in Ti/CFRP stack drilling. Results showed that uncoated tools performed better in achieving lowest cutting force, best hole quality and least tool wear. The nitride coatings resulted in edge roundness which inhibited the cutting performance.

Paper	Tool material	Stack materials	Method	Result
Park et al [35]	WC uncoated	CFRP, CFRP/Ti	First 20 holes CFRP, next 20 CFRP/Ti, so on. (Diameter= 9.525mm)	CFRP abrasion caused edge wear. Ti adhesion and abrasion caused flank wear.
Li et al [28]	WC-12% Co. Diamond coated, TiAlN+AlCrN multilayer coating, TiAlN coated and uncoated	CFRP/Ti	Helical milling. (Diameter= 6mm)	Uncoated- small cutting forces and better hole quality. Diamond- flaking, adhesive wear, chipping. Nitride coated- adhesive wear and micro-chipping due to edge rounding.
Isbilir et al [31]	WC coated with TiAlN	CFRP, Ti, CFRP/Ti	Varying speeds and federate. (Diameter= 8mm)	CFRP- high speed and feed cause high force, 56 holes. Ti- high feed caused high force, 36 holes.
Wang et al [41]	WC-9%Co. AlTiN, nanocomposite and uncoated.	CFRP, Ti, CFRP/Ti	3-axis cnc. Al backing plate. CFRP- 6000, 0.0762. Ti- 500, 0.0508. (Diameter= 9.525 mm)	CFRP- edge rounding. Ti- edge chipping and flank wear. Uncoated tools last longer for CFRP. Coated tools last longer for Ti. Carbon fibers brush away Ti adhesion.
Park et al [32]	WC, PCD	CFRP/Ti	Two different speeds. (Diameter= 9.525 mm)	Ti adhesion on WC. Micro chipping on PCD. PCD showed greater wear resistance.
Shyha et al [2]	Uncoated, CVD diamond, C7 coated	Ti/CFRP/Al	L18 Taguchi method. Through tool coolant and spray mist. (Diameter= 6.35 mm)	Uncoated tools had longest tool life.
Park et al [1]	Uncoated WC, BAM (boron, aluminium, mg)	CFRP/Ti	CFRP- 6000, 2000. Ti- 800, 400. F- 0.051 for both.	BAM more effective than uncoated. Coating delamination after 40 holes. Edge wear by carbon fibers.
Kuo et al [42]	WC DLC and CVD diamond	Ti/CFRP/Al	Ti- 30 m/min. CFRP & Al- 120 m/min. Feed- 0.08 & 0.015 mm/rev. (Diameter= 6.38 mm)	CVD produced superior hole quality. DLC had adhesion and micro chipping. CVD had flaking.

Table 1. List of tool materials and coatings used is open literature

2.5 Coating materials and coating deposition methods

Table 1 lists the main coatings used on tools to drill stacked materials. Mostly used coating materials are aluminium-titanium nitride (TiN), titanium-aluminium nitride (TiAlN), polycrystalline diamond (PCD) and diamond (DLC). The advantages of coatings include increased toughness at elevated temperatures, reduced thermal conductivity, and reduced co-efficient of friction. The coating is usually applied with a thickness of a few microns to avoid cutting-edge rounding and delamination. Sometimes, multi-coatings are applied to achieve a variety of properties such as increased hardness and anti-corrosion. For example, layers of TiN and DLC coatings can be deposited to create multi-layered coating surface.

There are two main methods of coating deposition and thin film: chemical vapour deposition (CVD) and physical vapour deposition (PVD). As the name suggests, CVD involves chemical reactions at temperatures exceeding 1000°C. This method is suited for tools in sintered carbide and gives a uniform deposition. In PVD, the coating

material is condensed into a vapour and it deposits onto the substrate. Compared to CVD, the temperature in PVD is less.

For all of the studies the coated tools are bought or coated by external source, hence the coating methods are not discussed in detail. Issues occurred during the studies involving coated tools include delamination of coating, which affects the drilling performance of the tool. It shows that there is a need to investigate the coating process and coating composition (i.e. thickness) to study the effect on tools during CFRP/Ti drilling.

3 Aim and Objectives

3.1 Aim

The goal of this study is to assess the effect of PVD applied Diamond-like-carbon (DLC) and Boron-Aluminium-Magnesium (BAM) coatings on the tool performance in comparison to uncoated tool during single-shot drilling of CFRP/Ti stack.

3.2 Objectives

The objectives of the study are summarised as the following:

- Apply coatings to tools using physical vapour deposition
- Establish the influence of coatings on key output measures including tool wear, cutting forces and workpiece quality criteria (hole diameter, roundness, surface roughness) when drilling holes in CFRP/Ti stacks
- Evaluate the performance of tools using SEM and microscopy, as well as evaluate drilled holes' quality

3.3 Research questions and hypothesis

As mentioned in the literature review, various coatings have been used during the stack drilling of CFRP/Ti. However, there has not been a study to compare whether factors such as coating deposition, thickness and coating composition have any effect on the tool performance. This particular study will try to understand how varying the PVD process to deposit DLC coating will affect the tool performance. Also studied will be the effect of BAM coating thickness on the tool performance. The performance of both coatings will be compared to uncoated tool.

By using a single tool to drill the two materials can result in reduced tooling cost and machining time. Thus, tool wear and hole-quality are the important parameters investigated in this study. Two different DLC coatings will be deposited: one with higher sp³ content and the other with higher sp² content. For the BAM coating, three different thicknesses will be deposited to study the effect of coating thickness on the tool performance. Different speed and feed will be used for the CFRP and Ti. Drilling force, tool wear, hole diameters, hole roundness and hole wall roughness will be studied using various inspection equipment.

4 Experiment design and procedures

This chapter will discuss the materials and various methods used in this project. Firstly, the coatings and their deposition methods will be described and then the drilling experiments. The characterisation of the tool wear and hole quality will also be described. Figure 15 shows a summary of the method followed in this study.

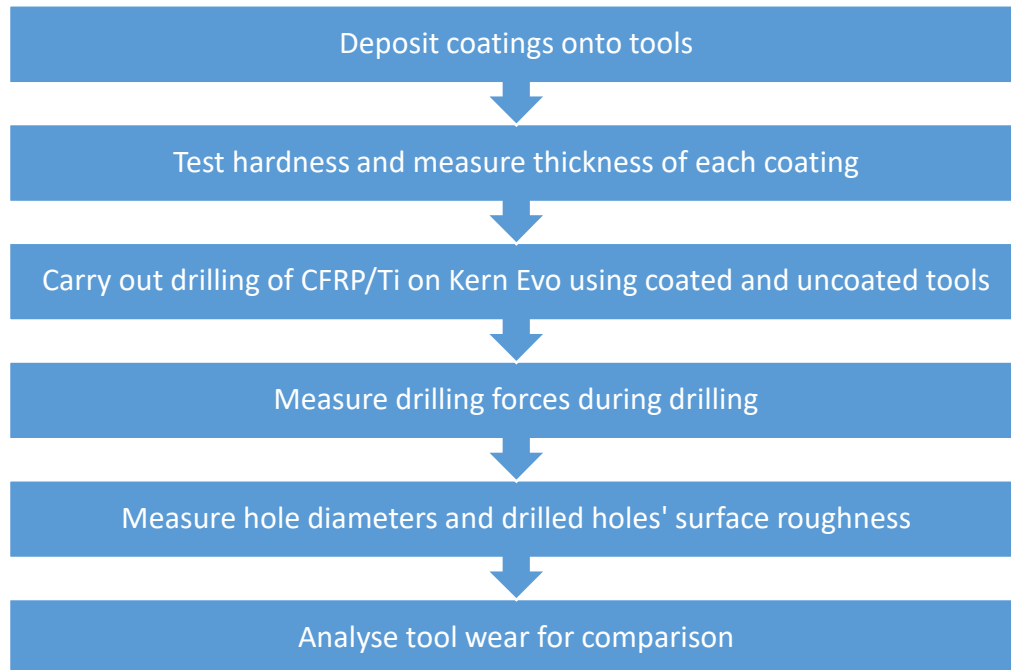


Figure 15. Methodology summary

4.1 WORKPIECE MATERIALS

The workpiece materials used in this study were carbon fibre reinforced polymer (CFRP) and titanium (Ti). These are discussed below.

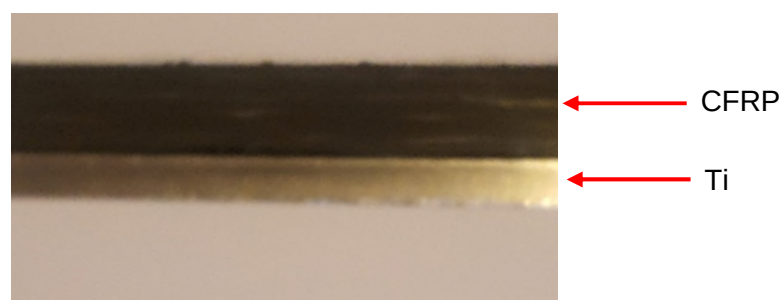


Figure 16. CFRP stacked on Ti

4.1.1 Carbon Fiber Reinforced Polymer (CFRP)

The CFRP samples were acquired from another department of the university. They are manufactured for Boeing aircraft and are of high performance aerospace grade.

They are made of panex 35 intermediate modulus carbon fibres and pre-impregnated with a high performance tough epoxy matrix, M21, which was designed to exhibit excellent damage tolerance. Different characteristics of the M21/35%panex system are shown in Table 2.

Ply mass	Ply thickness	Fibre volume fraction	ILSS	Tensile strength	Tensile modulus
604 g/m ²	0.262mm	56.6 %	60 MPa	3039 MPa	172 GPa

Table 2. CFRP properties

The resin in the CFRP benefits from toughening low-volume percentage rubber particles with a mean diameter of 20-40 μm (Figure 17). The CFRP were samples cut into 100mm by 75mm rectangles. Their thickness was roughly 5mm.

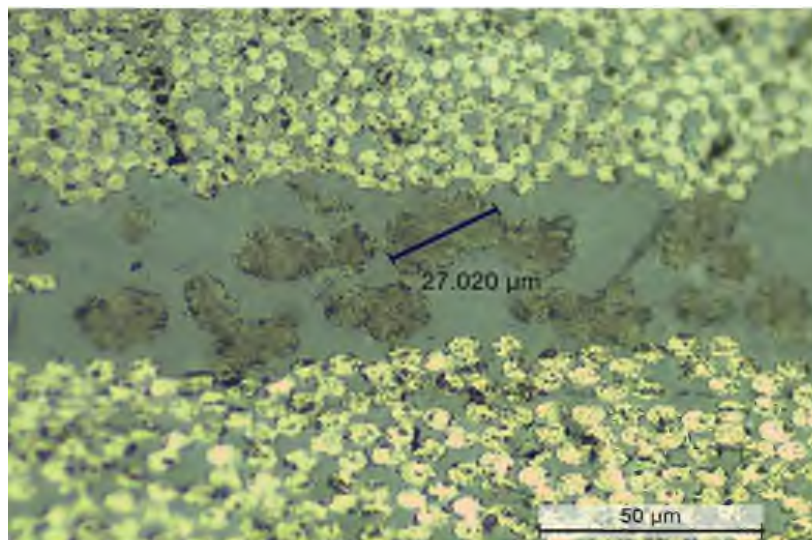


Figure 17. CFRP seen under optical microscope (rubber particles length labelled)

4.1.2 Titanium alloy 834

The titanium material used in this study was Ti 834. The alloy was procured from another department of the university in the form of flat sheets, with a thickness of 2.60mm. The chemical composition of the Ti 834 alloy is given in Table 3.

Element	Al	Sn	Zr	Nb	Mo	Si	C	Fe
Wt.%	5.72	3.98	3.52	0.71	0.54	0.33	0.05	0.009

Table 3. Ti 834 alloying composition

Ti 834 is an advanced alloy used in the aerospace industry. Due its almost- α phase, it can be operated at 600 °C. Alloying elements are added to improve the material properties such as increase strength. The stabilising elements are classed as α or β .

Aluminium allows for reduced density and improve tensile and creep properties of the alloy [37-38]. The presence of β stabilisers (molybdenum and niobium) give the alloy increased strength, harden-ability at reduced temperatures and also provide oxidation resistance [45]. The addition of carbon allows for solid solution hardening and enhances strength. It also raises the β transformation temperature.

4.2 Drilling tools

Standard two-flute tungsten carbide drills were used during this study. The DLC and BAM coatings were deposited in-house using the physical vapour deposition (PVD) equipment. The drill bits have a straight shank with two flutes. The table below shows the tool details:

Tool diameter (mm)	6.0
Cutting length (mm)	25.0
Overall length (mm)	50.0
Shank size (mm)	6.0

Table 4. Tool details

The tools have been named as following:

DLC 1	Higher sp^3 content – 0.5 μm thickness
DLC 2	Lower sp^3 content – 0.5 μm thickness
BAM 1	BAM coating – 0.8 μm thickness
BAM 2	BAM coating – 1.7 μm thickness
BAM 3	BAM coating – 2.5 μm thickness
UNC	Uncoated

Table 5. Tool names

Please see Figure 18 for the tools used in this study.



Figure 18. Tool used in this study

4.3 Coating materials and deposition methods

Two coatings were chosen from the literature review. The first one is DLC and second one is BAM. The deposition methods were different for them both. For DLC, cathodic arc deposition was used and for BAM, HiPIMS was used. These are discussed below.

Tungsten carbide (WC) drills were coated with Diamond like carbon (DLC) and Boron-Aluminium-Magnesium (BAM) coatings. The DLC coating was deposited using cathodic arc deposition (best method for this coating [46]); the variable process parameter is the DC self-bias (voltage). One is with bias and the other without it. This results in two different types of coatings: one with higher content of sp^3 (more diamond-like structure) and the other with higher content of sp^2 (more graphite). The presence of sp^3 results in a harder coating [47]. The presence of sp^2 results in reduced coefficient of friction. The performance of both tools will be compared to other tools. The BAM coating was deposited using high-power impulse magnetron sputtering (HiPIMS). Three thickness were deposited to study whether it has any effect on the tool performance.

4.3.1 Diamond like carbon (DLC)

DLC, which stands for Diamond-like carbon, is defined as an amorphous carbon film that consists of unequal mix of sp^3 bonds (that form diamond structure) and sp^2 bonds (that form graphite structure). Ferrari and Robertson [48] explained the DLC coating using a phase diagram (see Figure 19). The higher the sp^3 content, the more the structure will be diamond-like.

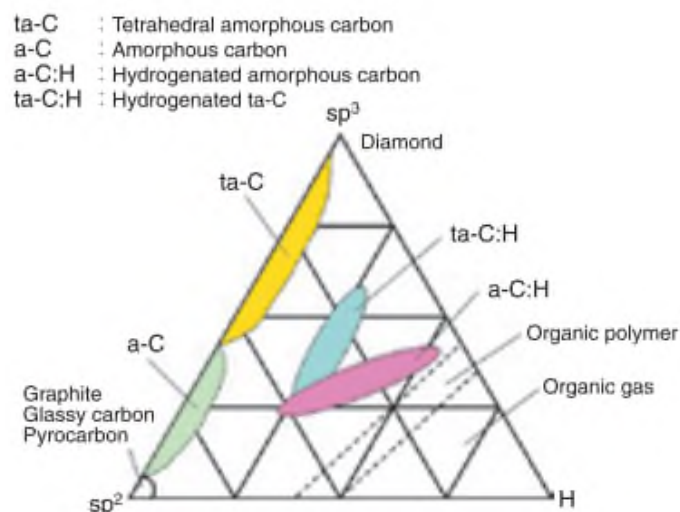


Figure 19. Ternary phase diagram of amorphous carbons [48]

The properties of DLC include increased hardness, high wear resistance, high chemical inertness and wide-band gap semiconductor [46]. DLC is used in many different industries and its applications include tool protective coating, automotive parts, storage devices, biomedical implant coating and optics.

4.3.1.1 DLC coating Deposition method

DLC coatings were deposited using cathodic arc deposition. A chromium (Cr) interlayer was deposited using magnetron sputtering. The reason for chromium interlayer is to provide good adhesion for the DLC coating to the tool [49]. Prior to coating the tools, there were ultra-sonically washed (see Figure 20) in acetone for 15 minutes and then in Isopropyl alcohol (IPA) for 15 minutes to remove any debris on the tool which could affect the coating.



Figure 20. Ultra-sonic bath used to wash the tools

The chromium interlayer was deposited using dc magnetron sputtering, prior to depositing the DLC coating using cathodic arc deposition. Magnetron sputtering and cathodic arc deposition are both built-in on the machine in Figure 21, allowing for different methods to be used.

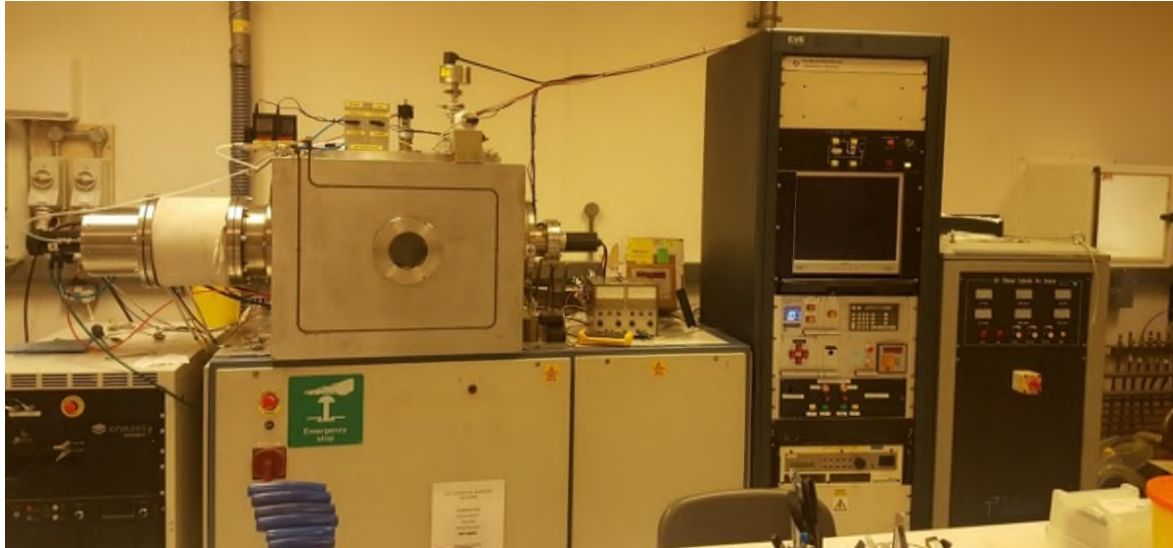


Figure 21. Physical vapour deposition equipment

The reason for using magnetron sputtering to deposit the chromium interlayer was that it allowed the deposition of DLC coating without having to change the target material and also open the chamber which could have caused any foreign particles to affect the final deposition. Magnetron sputtering is a type of PVD process that generates a plasma and uses an electrical field to accelerate positive ions onto a negative charge target (i.e. chromium). The ions collide with the target at high energies (up-to 1000 eV) ejecting atoms from it. The atoms condense onto the surfaces inside the vacuum chamber including the substrate (i.e. tools). Figure 22 represents a schematic of the sputtering process. The gas used was argon. Deposition time was 30 minutes, resulting in a 300nm thick interlayer. Tools and inserts (for thickness measurements) were held in a fixture (Figure 23) that rotated slowly to allow an even deposition.

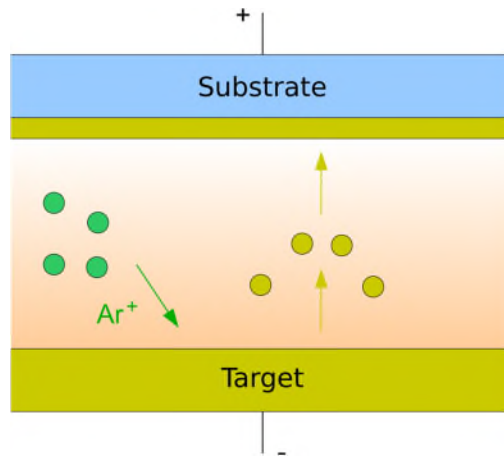


Figure 22. Schematic of sputtering process [50]



Figure 23. Fixture to hold tools during the coating process

To deposit DLC coating, cathodic arc deposition method was employed using the PVD equipment shown in Figure 21. It is a physical vapour deposition (PVD) method in which material is vaporised from a cathode target using an electric arc. In the case of this project, the target material was graphite. A high current with low voltage arc strikes the target surface which results in a high energy discharge area called cathode spot, which is about a few microns square. This produces temperature of up-to 15000 °C resulting in a high speed jet of vapour material. A small crater is created as a result. A new cathode spot self-ignites next to this crater and the process carries on resulting in an

arc-like motion. Figure 24 represents a schematic of the cathodic arc deposition process. The arc is highly power-dense so much that it results in ionisation, charged and neutral particles. The introduction of a gas causes excitation of the evaporation as it interacts with the ions, resulting in thin-film deposition onto the substrate (i.e. tools) in the chamber. The gas used was argon.

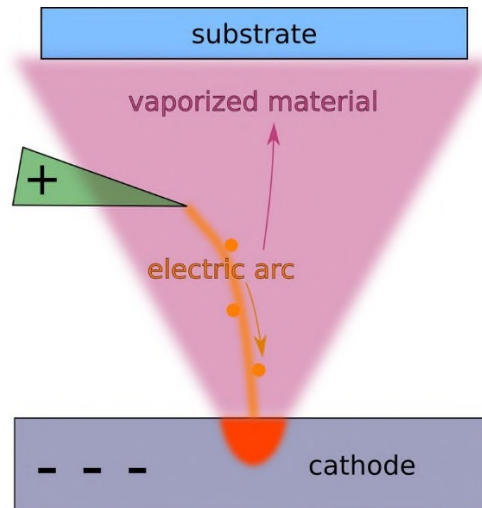


Figure 24. Schematic of cathodic arc deposition [50]

4.3.2 Boron-Aluminium-Magnesium (BAM) coating

Another coating selected for this study was the Boron-Aluminium-Magnesium (BAM) coating. It is a chemical compound created by combining a mix of boron, aluminum and magnesium. It is classed as the world's third hardest material, after diamond and cubic boron nitride. It is also one of the slipperiest materials with a frictional coefficient of 0.02, being slicker than Teflon (0.05) and lubricated steel (0.16). [51]

The coating was deposited using the in-house HiPIMS. Three different thickness were deposited as mentioned in section 4.2 Drilling tools).

4.3.2.1 BAM coating deposition

The BAM coatings were deposited using High-power impulse magnetron sputtering (HiPIMS). It is form of PVD magnetron sputtering technique and the same equipment shown in Figure 21 was used. During the HiPIMS process high-power pulses lasting a few hundred micro-seconds are sent to the target material (BAM target for this project) at a frequency of several hundred Hz [52].

During the release of such pulses, the optimum power density of each pulse can be within the range of tens of kilowatts for every square centimetre, comparatively,

average densities of power are similar to that of DC Magnetron Sputtering (DC MS) pulses, this magnitude of power is enabled through the upgrading the power supply. Both HIPIMS and DC magnetron sputtering occur within equal pressure regimes, and HIPIMS can utilise DC MS magnetic-field assemblies in order to attain stable ignition. Due to this, varying the power input can change plasma's properties (and hence its film's) in the same systems. Figure 25 shows the power module used for the HiPIMS process. It was connected to the same the magnetron on the PVD machine in Figure 21 and the coating depositions were carried out.



Figure 25. HiPIMS control module

4.3.3 Coating thickness

During coatings deposition, a small piece of silicon carbide was placed along the tool in the chamber and also deposited to check the coating thickness. After each deposition, the thickness was measured using the surface profilometer shown in Figure 26. The measurement process begins by placing the sample on the stage. Then using the software on the computer, the stylus is brought down and measurements

are taken across the coating. The stylus measures the step height by the difference between the silicon carbide surface and coating surface.

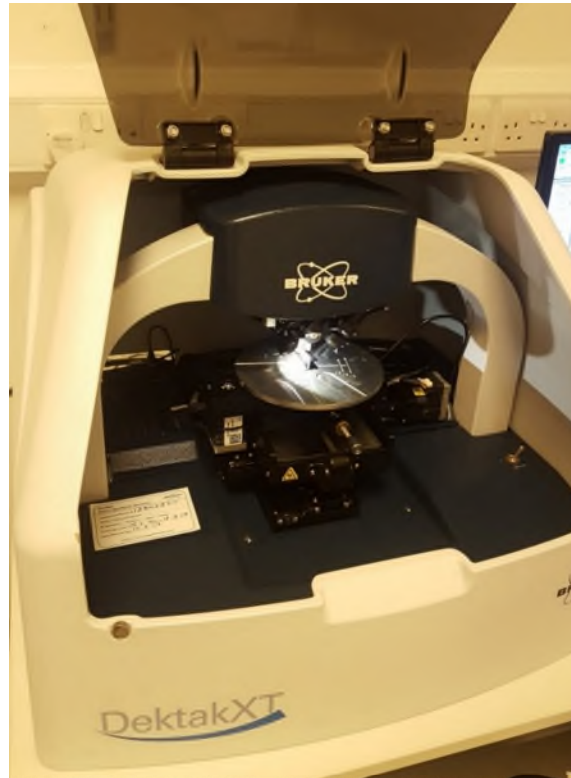


Figure 26. Surface profilometer used to measure coating thickness

4.3.4 Coating hardness

The hardness for coatings was measured using nano-indentation. Five measurements were carried out and an average value was calculated. Table 6 shows the hardness values for the coatings.

Coating	Hardness (GPa)
DLC 1	4.00
DLC 2	4.27
BAM 1	4.55
BAM 2	6.10
BAM 3	8.71

Table 6. Coating hardness values

4.3.5 EDS analysis of coated tools

EDS of the coated tools was carried out to study the coating composition. Figure 27 and Table 7 show the results for the DLC coating. There is clear peak of carbon in the EDS spectrum and element Wt. % composition is 45, confirming that deposition of the DLC coating was successful.

Figure 28 and Table 8 show the EDS results for BAM coating. The results shows presence of boron, aluminium and magnesium to confirm successful deposition of the BAM coating.

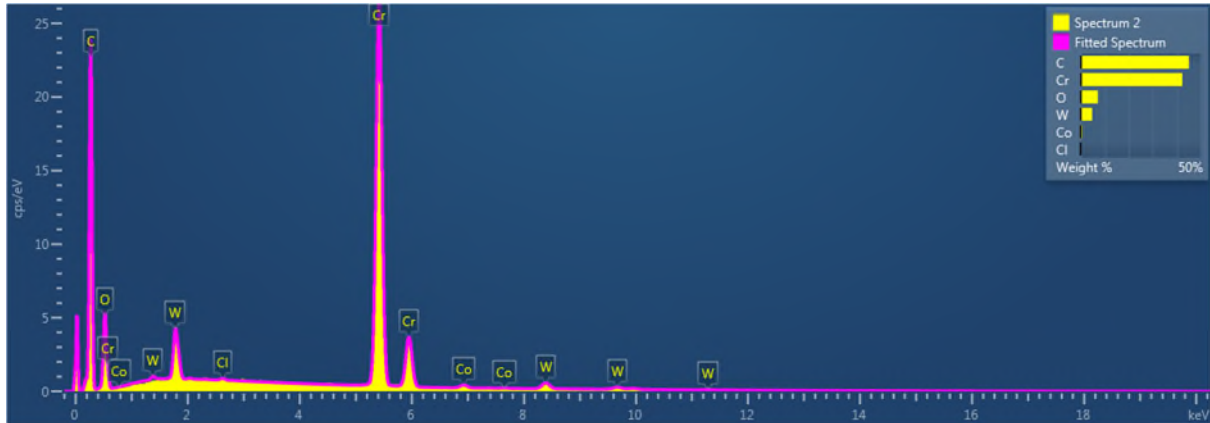


Figure 27. EDS spectrum of DLC

Element	C	O	Cl	Cr	Co	W
Composition %	45.06	7.17	0.08	42.29	0.63	4.76

Table 7. Element results in the DLC EDS analysis

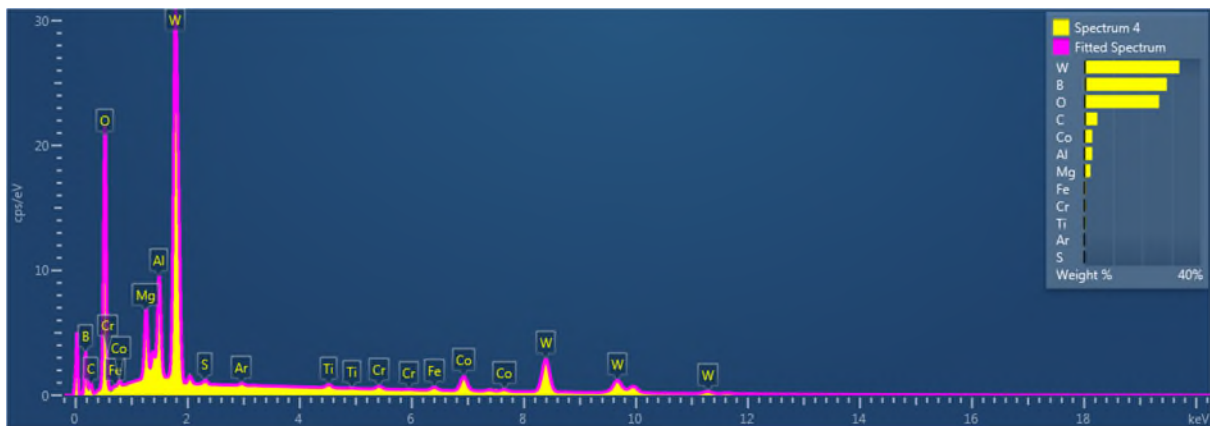


Figure 28. EDS spectrum of BAM tool

Element	B	C	O	Mg	Al	Fe	Co	W
Composition %	28.3	4.46	25.52	2.11	2.73	0.47	2.79	32.5

Table 8. Element results of BAM tool from EDS analysis

4.4 Drilling experiment design, parameters and setup

There were six drill bits used during this study (see 4.2 Drilling tools). These were:

- two with DLC coating

- three with different BAM coating thicknesses- 0.8 μ m, 1.8 μ m and 2.5 μ m
- one uncoated

The drilling sequence was to drill a 5 x 6 matrix of holes as shown in Figure 29. Drilling was started at top left corner and five holes were drilled down the column and then across. For each material, a different speed and feed and was used due to the dissimilar properties of both. Please see Table 9 for speeds and feeds used.

Material	Speed (RPM)	Feed (mm/min)
CFRP	2000	0.0762
Ti	800	0.0508

Table 9. Speeds and feeds used during drilling [1],[31],[35]

For titanium, a lower speed was used to prevent tool failure as the material has a high fracture toughness. When drilling through the CFRP/Ti stack, the machine was programmed to change the drilling speed from CFRP to Ti when the tool was 0.025mm above the Ti material. This was to avoid damage to the drill point from high speed impact with titanium. The drill bits were examined before and after thirty holes using SEM, and after 9 and 23 holes using microscope.

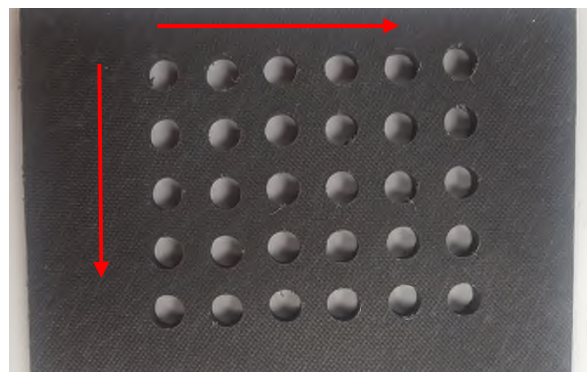


Figure 29. Layout of holes

The drilling was carried out on the Kern Evo precision machine (Figure 30). It is a 5-axis ultra-precision machine with a positional accuracy of ± 0.5 micro-meters [53]. The KERN Evo comprises of five axis, three linear and two rotary. The machine has x-axis travel of 300mm, y-axis travel of 280mm and 250mm vertical travel. The machined is designed with characteristics such as high dynamic stiffness, accurate motion control and thermally stabled. To achieve this, it uses mono-bloc concrete polymer for the

base, which is 10 times better at absorbing vibrations than cast iron. The table working space for machining is 300 by 300mm. The machine can achieve position accuracy of ± 0.5 micron, machining accuracy of up to ± 2 microns and surface quality of $Ra \leq 0.1$ μm . It uses Heidenhain controller. The machine also has various coolant systems to control temperature of work piece, spindle, etc. It uses a laser to measure tool length as well having the component measurement capability. Due to the hazardous effects of carbon fiber, a HEPA vacuum was setup to extract the carbon dust. The vacuum hose was modified to improve the suction during the drilling.

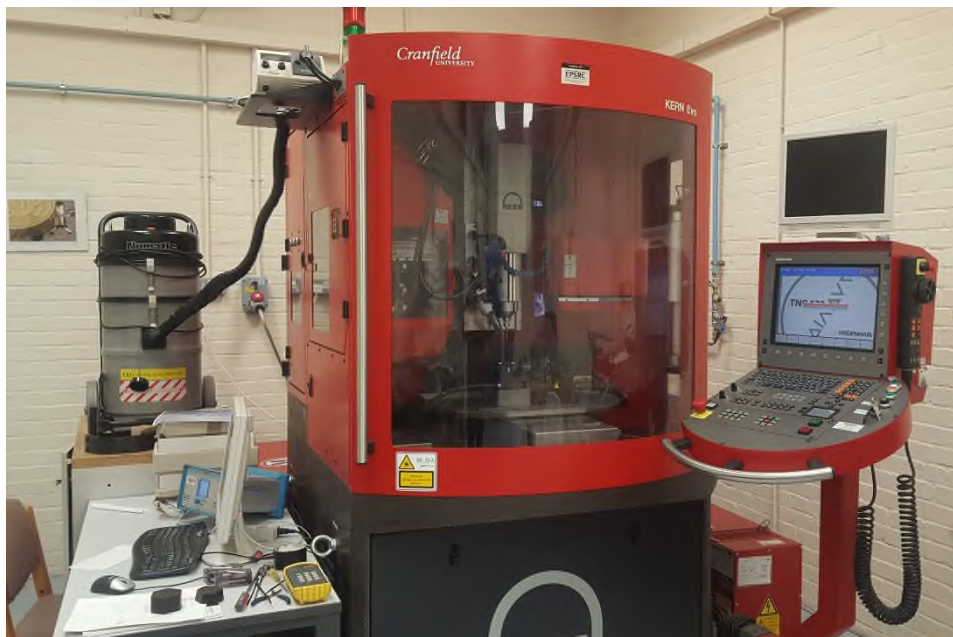


Figure 30. Kern Evo machine with vacuum setup

A dynamometer was fixed to the workpiece holder. A fixture was attached above the dynamometer. A pre-drilled aluminium plate, with 8mm diameter holes, was attached to the fixture. The aluminium plate was used to protect the dynamometer and the pre-drilled holes allowed holes to be drilled through the stacked materials. The CFRP/Ti stack was then clamped to the aluminium plate. Drilling was carried out from the CFRP side.

4.5 Tool performance characterisation

4.5.1 Drilling force measurement

As mentioned above, a dynamometer was used to measure the thrust force. The CFRP/Ti stack was clamped to the fixture using four bolts, strips of steel and washers. The fixture with stack was fixed onto the Kistler dynamometer to capture the resulting

force. The dynamometer was a Kistler 9256C which was setup on the fixture. The dynamometer has four piezoelectric sensor cells that measure charge and send the signals to the amplifier. This charge signal is converted to a relative voltage by the amplifier. A Kistler 5070A signal conditioner was implemented to condition the voltage input and convert the signal into digital output. A computer is connected to the conditioning unit. Once the force signal was captured, the maximum perpendicular (vertical) force component (thrust force) was calculated from the signal generated during drilling. The data is captured onto a software. The data is recorded and processed in the Dynoware software. Please see Figure 31 showing thrust force capture setup connected to the dynamometer.



Figure 31. Kistler dynamometer on the fixture

4.5.2 Scanning Electron Microscope (SEM) and Energy-dispersive X-ray spectroscopy (EDS)

To study the tool wear and material adhesion onto the tool, SEM and EDS techniques were employed in this study. EDS was also utilised to analyse coating composition. The SEM was a model LX30, manufactured by Philips that was used to take images of the tools at low vacuum setting mode. This particular model has following specifications: magnification up-to x500, 000; power: 1 to 50 kV; different modes of operation. The SEM is linked to two computers with the relevant software to operate the machine, as well as to record and process images and EDS results. EDS analyses were carried out to study chemical-element composition of coated tools, as well as the titanium adhesion after drilling. The EDS equipment is part of the SEM with an energy-dispersive X-ray spectrometer that works in junction with an optical profilometer.

Please see Figure 32 for the SEM and EDS equipment used during this study. The main point of using SEM and EDS was the tool inspection before and after drilling, with the focus being the cutting edge wear.

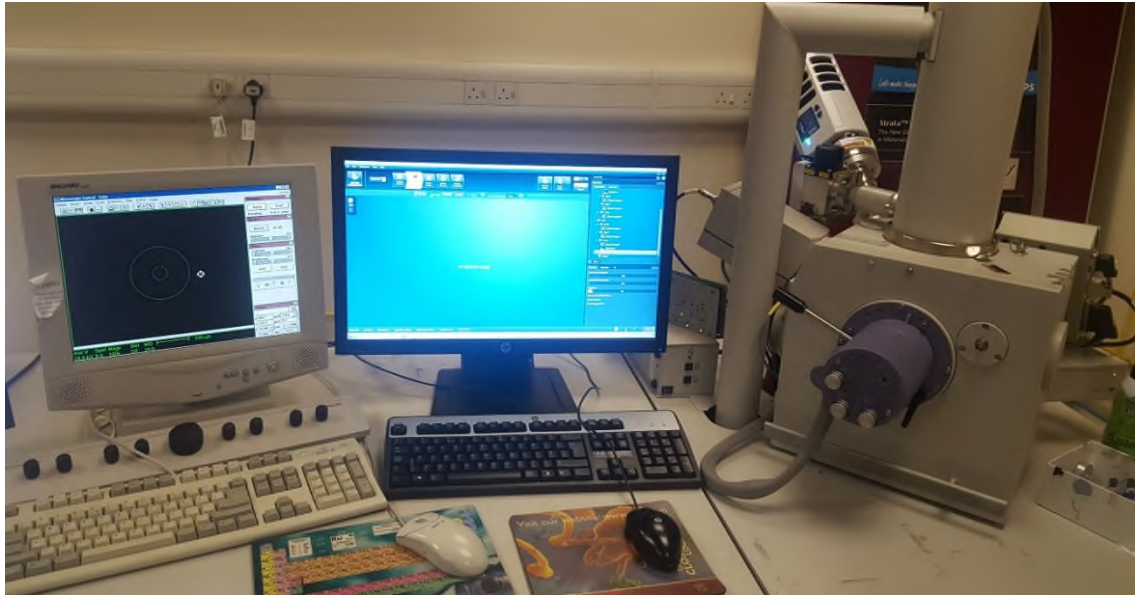


Figure 32. SEM and EDS equipment

4.5.3 Microscope

To study the gradual tool wear, few optical microscopes were used. Microscope images at magnification $\times 5$ were recorded of the tool cutting edge. The microscopes are equipped with cameras allowing software on the computer to capture images. Figure 33 shows one of the microscopes used during this study.



Figure 33. Optical microscope used during this study

4.6 Hole quality characterisation techniques

4.6.1 Co-ordinate measuring machine (CMM)

One of the important requirements of the drilled holes is the dimensional accuracy, in terms of the hole-diameters and roundness error, required for the correct assembly of the stacks, i.e. to allow a tight assembly of rivets. A Tesa Visio 300 DCC machine, shown in Figure 34, was used to measure the hole-diameters and roundness error. It is a three axis machine. The table moves in the X and Y axis, and the probe in the Z axis. A 1-mm radius ruby ball tip was used to carry out the measurements. For each material, measurements were made in the centre of the hole-depth. The stylus touched each hole on 4 points around the hole and the measured co-ordinate points were captured and stored in the software on the computer.



Figure 34. Tesa Co-ordinate measuring machine (CMM)

4.6.2 Surface roughness

Surface roughness was measured to get an indication of the surface finish during stack drilling. It is important to achieve low surface roughness to reduce the wear of the assembly and avoid the material's capability to reduce corrosion. To quantify the finished surface roughness, there are numerous parameters used and include the following:

- Ra- the average value of the peaks and valleys in comparison to the mean
- Rq- root mean square roughness, area under the sine wave graph
- Rz- average of the 5 maximum peaks and 5 minimum valleys
- Rt- highest peak height
- Rp- lowest valley depth

Table 10 shows list of surface roughness parameters.

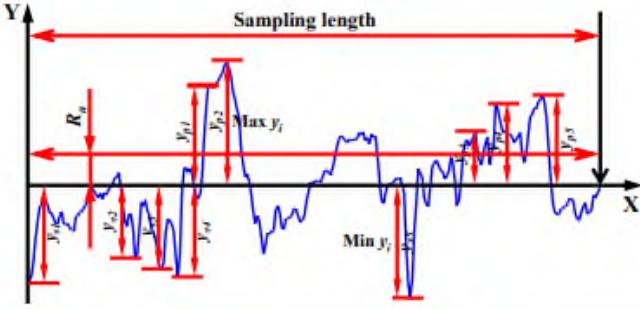
Parameter	Description	General Formula
R_a	Arithmetic mean roughness	$R_a = \frac{1}{n} \sum_{i=1}^n y_i $
R_q	Root mean squared roughness	$R_q = \sqrt{\frac{1}{n} \sum_{i=1}^n y_i ^2}$
R_z	Ten point mean roughness	$R_z = \frac{\sum_{i=1}^5 y_{pi} + \sum_{i=1}^5 y_{vi}}{5}$
R_p	Maximum peak height	$R_p = \max_i y_i$
R_v	Maximum valley depth	$R_v = \min_i y_i$
Scheme of representative roughness parameter definition		

Table 10. Surface roughness parameters

To measure the surface roughness, the materials were cut through the holes using diamond cutter and measurements were carried using a profilometer (Talysurf) by Taylor Hobson. The stylus was moved closer to hole wall surface and using the software, it was controlled to travel across the surface. The surface roughness profiles were evaluated over 3mm for CFRP and 2mm for Ti at 0.5mm/s.

Chapter 5 Results and discussion

In this chapter, the results are presented and discussed. Firstly, the tool wear is discussed; results from SEM and microscope are presented and analysed. Results from EDM are also discussed.

Secondly, results from co-ordinate measurement machine (CMM) are presented and discussed; specifically the hole diameters and roundness.

Thirdly, results from surface roughness measurements are discussed.

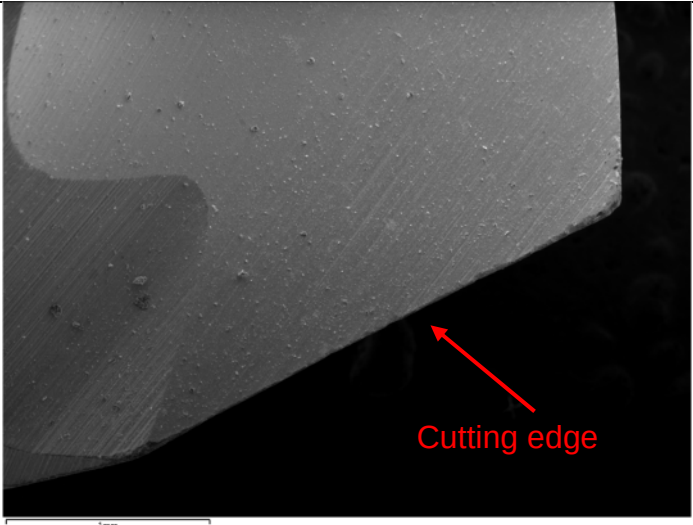
Lastly, the thrust during drilling is presented and discussed.

5.1 Tool wear

As mentioned previously, tool wear was analysed using SEM and optical microscopy. SEM images were taken before drilling and after drilling. Microscope images were taken after 9 and 23 holes. Tool wear for each tool is discussed below.

5.1.1 DLC 1 tool wear

Table 11 shows the SEM and microscope images of cutting edge of DLC 1. The SEM image shows the tool edge is sharp and coating is evenly deposited. There doesn't seem to be much damage to the edge after 9 and 23 holes. The SEM image after 30 holes shows the edge is still sharp without much damage. This shows that after drilling 30 holes in the CFRP/Ti stack, the tool didn't wear too much.

Hole number	SEM/Microscope image
Hole 0	

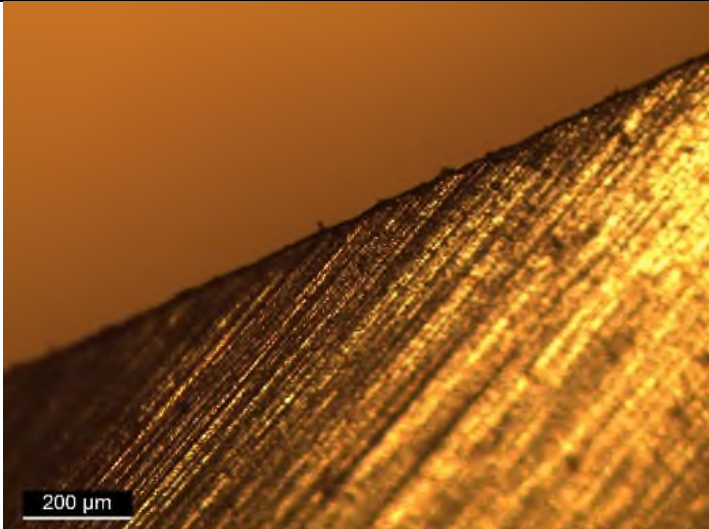
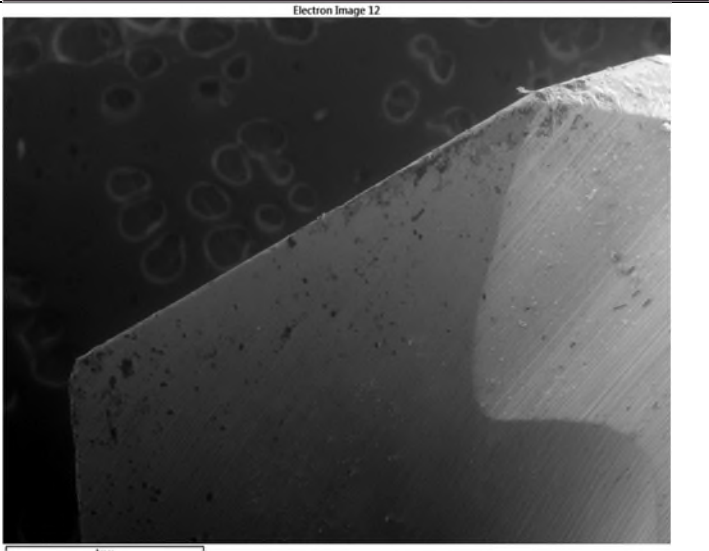
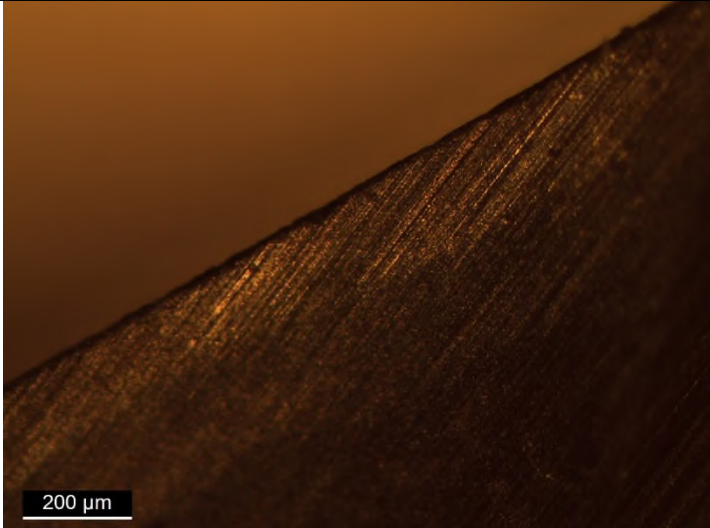
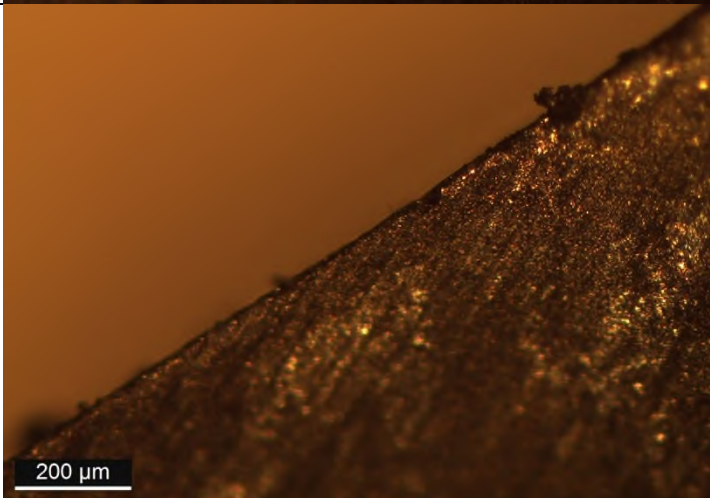
Hole 9	
Hole 23	
Hole 30	

Table 11. SEM and microscope images of DLC 1

5.1.2 DLC 2 tool wear

Table 12 shows the SEM and microscope images of cutting edge of DLC 2. It doesn't seem to be damaged after 9 holes. There was small damage to the cutting edge after

23 holes (see area labelled). The SEM image after 30 holes shows some delamination of the coating, which seems to be peeling off. The cutting edge is not as sharp as DLC 1 after 30 holes, as some microchipping can be observed. The tool did get worn in comparison to the DLC 1. This is could be due to poor adhesion arising from the coating deposition process, as well as damage from the carbon fibres in CFRP and Ti.

Hole number	SEM/Microscope image
Hole 0	
Hole 9	

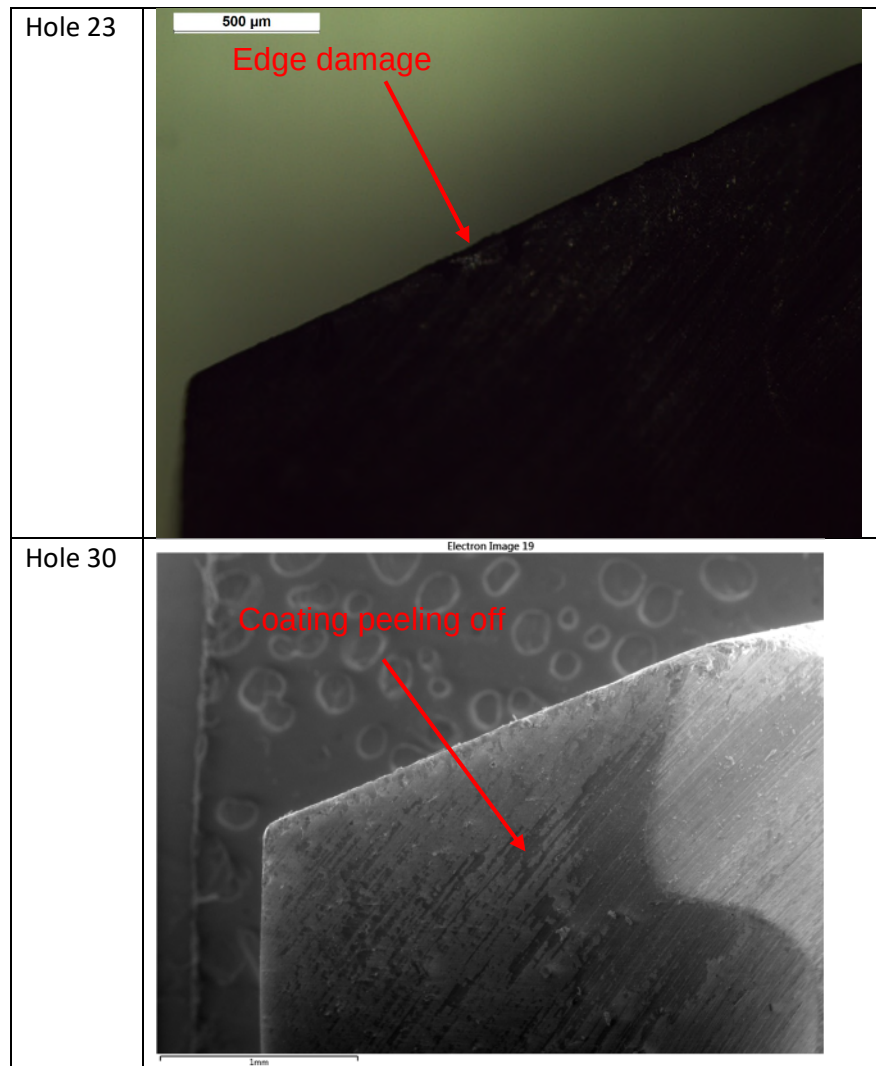
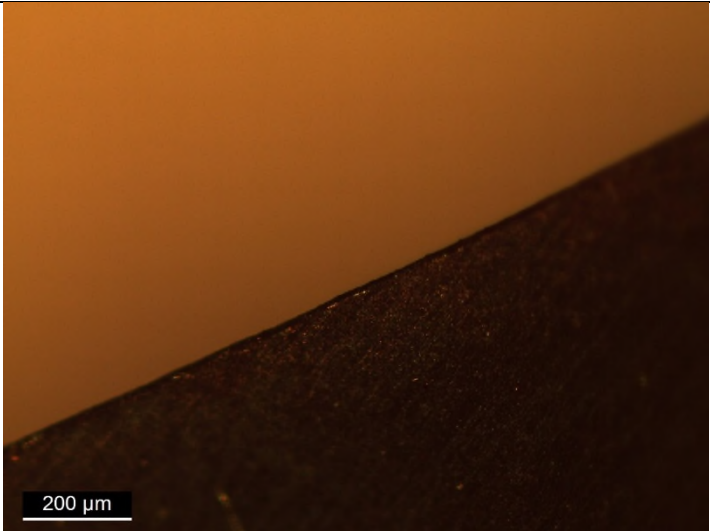
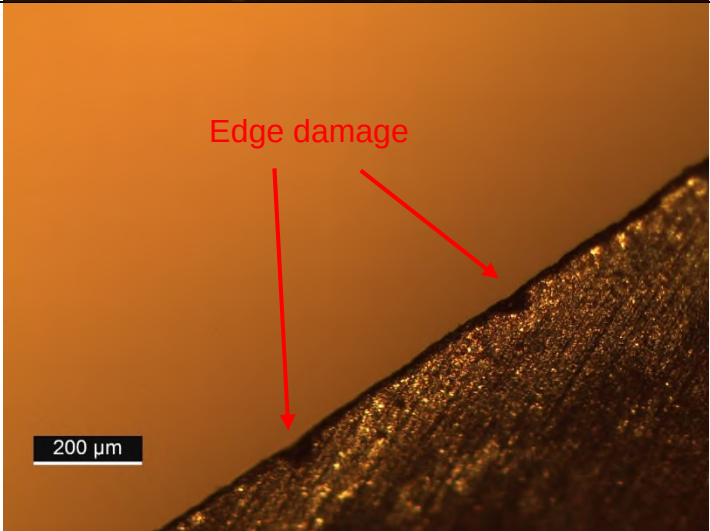


Table 12. SEM and microscope images of DLC 2

5.1.3 BAM 1 tool wear

Table 13 shows the SEM and microscope images of cutting edge of BAM 1. Damage can be seen to the cutting edge after 9 holes. The SEM image shows small damage after 30 holes (some microchips) and the coating seems to have delaminated quite a lot.

Hole number	SEM/Microscope image
Hole 0	 200 μm
Hole 9	 200 μm Edge damage
Hole 23	

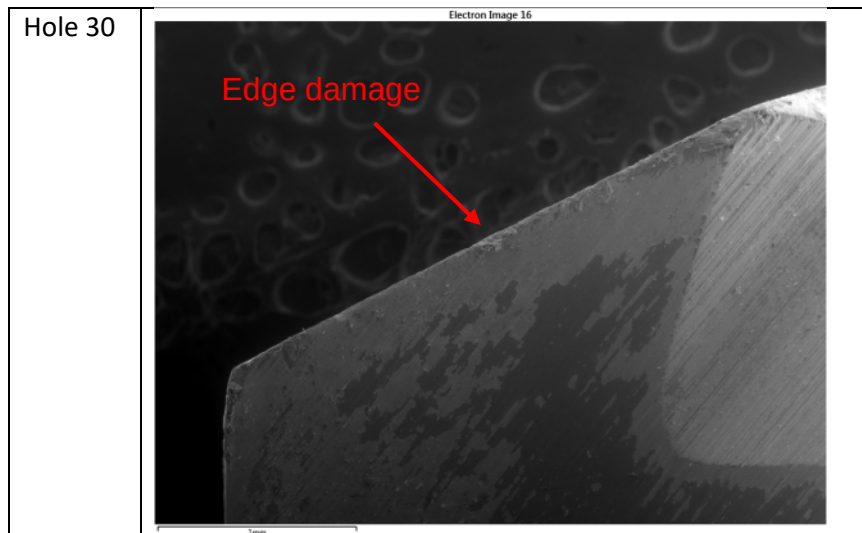
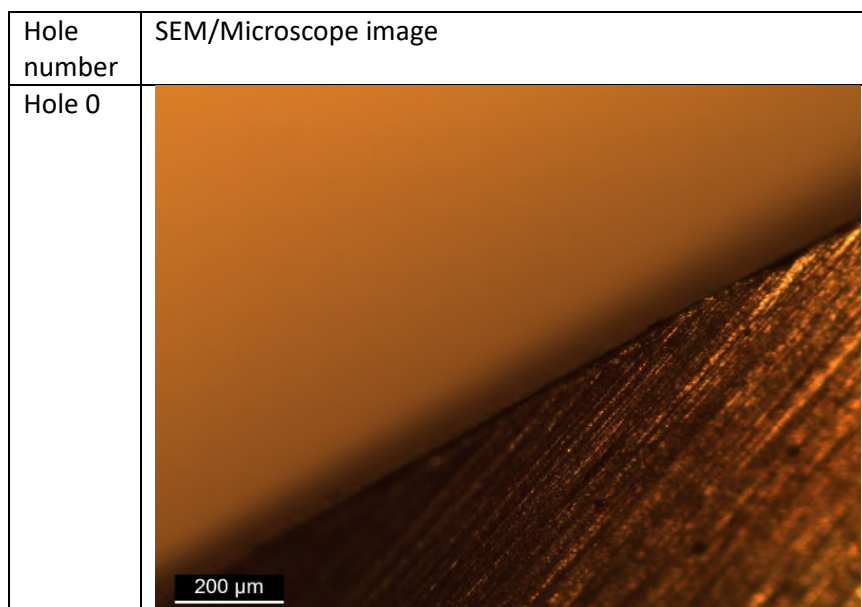


Table 13. SEM and microscope images of BAM 1

5.1.4 BAM 2 tool wear

Table 14 shows the SEM and microscope images of cutting edge of BAM 2. The cutting edge was rounded after 9 holes. There is significant damage to edge after 15 holes, as a big fracture can be observed. The SEM image also shows damage and significant coating delamination. The tool failed after 15 holes. The failure can be attributed to the coating thickness causing edge to lose sharpness and hence being worn too soon.



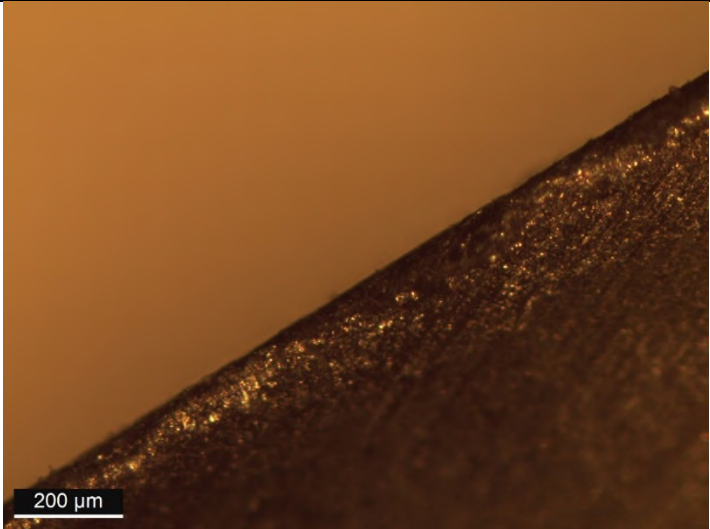
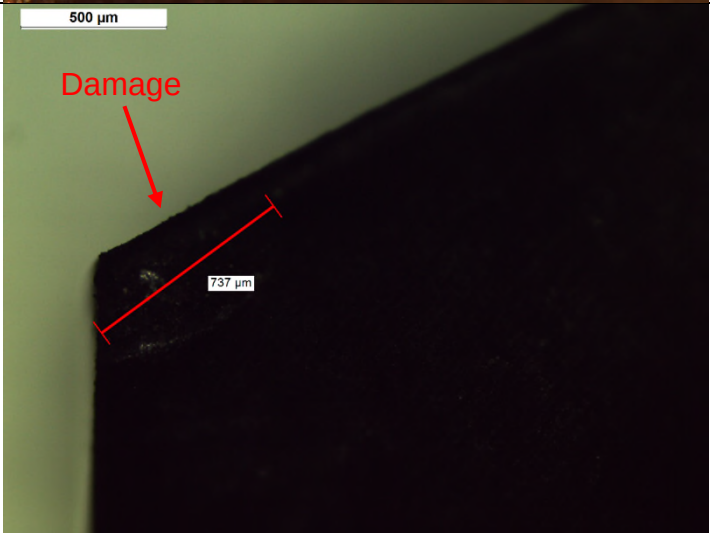
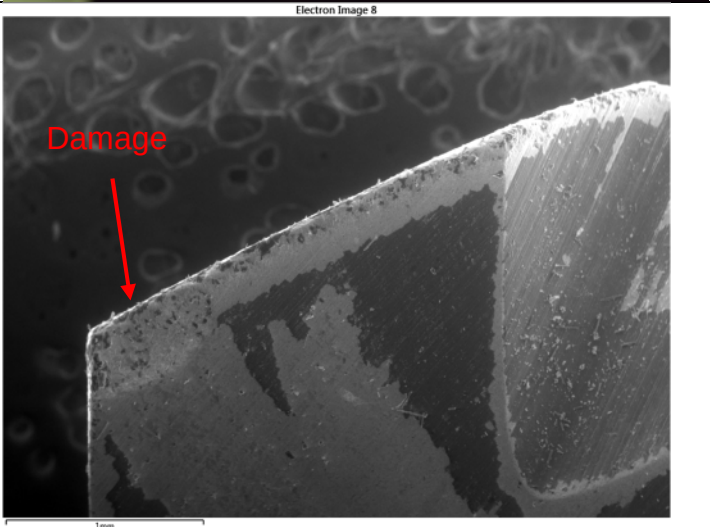
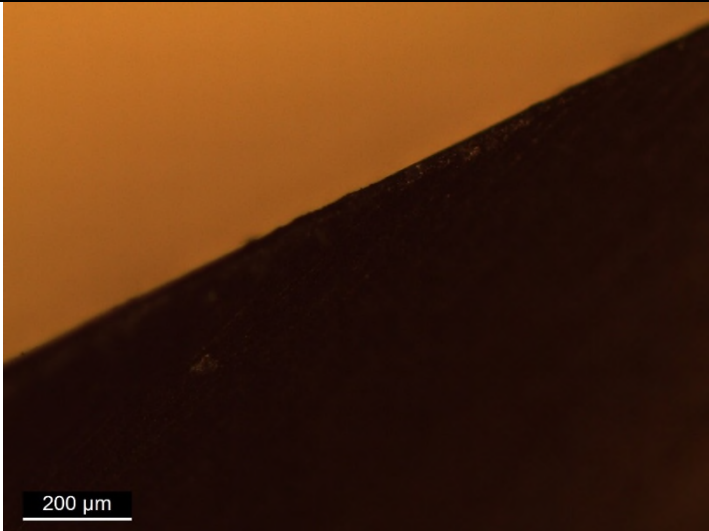
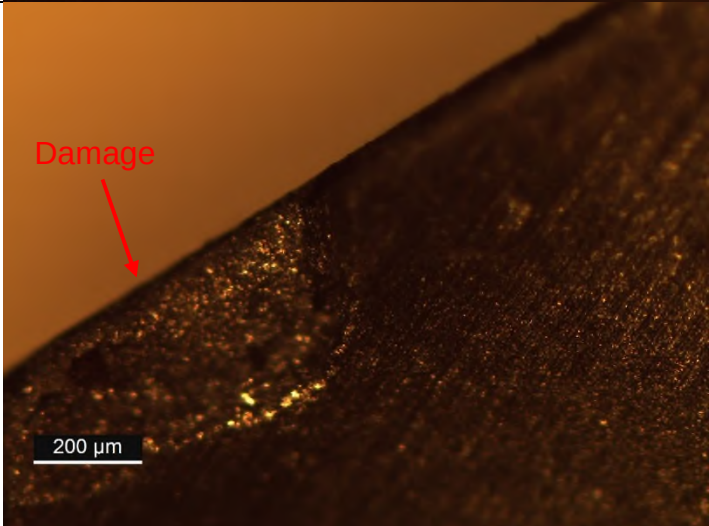
Hole 9	
Hole 15	
Hole 15	

Table 14. SEM and microscope images of BAM 2

5.1.5 BAM 3 tool wear

Table 15 shows the SEM and microscope images of cutting edge of BAM 3. The tool was damaged critically after 9 holes. The SEM image also shows the damage and coating delamination. Similar to BAM 2, this tool also failed, although earlier than BAM 2. This tool had the thickest coating, hence, the failure can be attributed to the coating thickness causing edge to lose sharpness and being damaged after only 9 holes.

Hole number	SEM/Microscope image
Hole 0	
Hole 9	

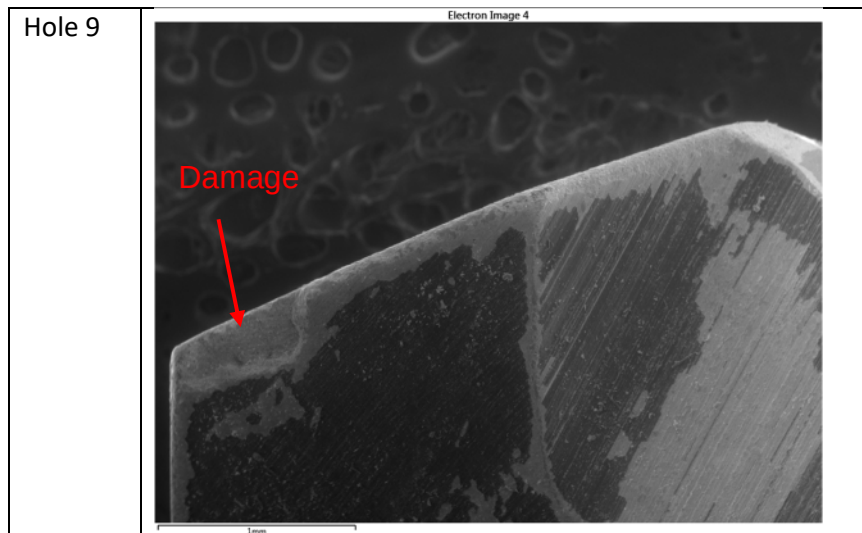
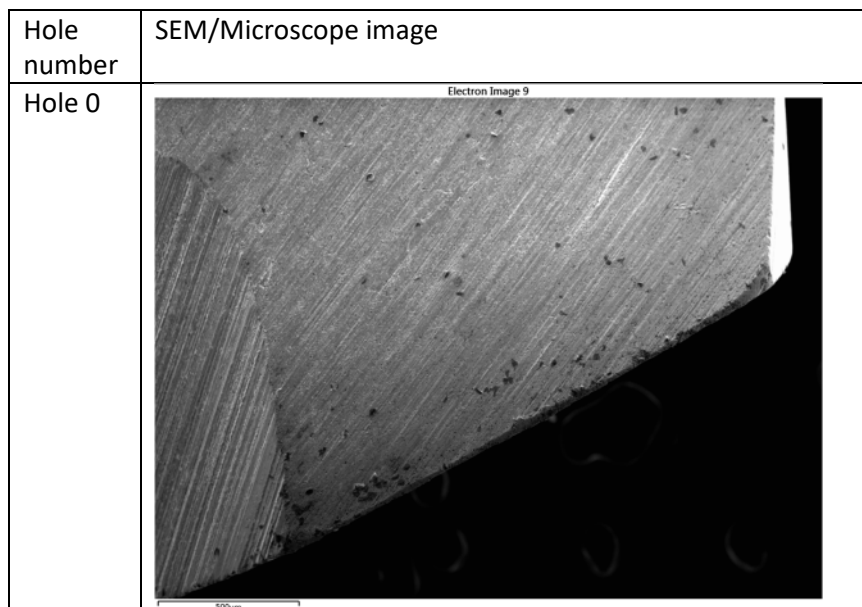


Table 15. SEM and microscope images of BAM 3

5.1.6 UNC tool wear

Table 16 shows the SEM and microscope images of cutting edge of uncoated tool. The cutting edge seems to lose sharpness slightly after 9 holes. Chipping is present after 23 holes. The tool jammed after 25 holes. It wasn't able to drill afterwards.



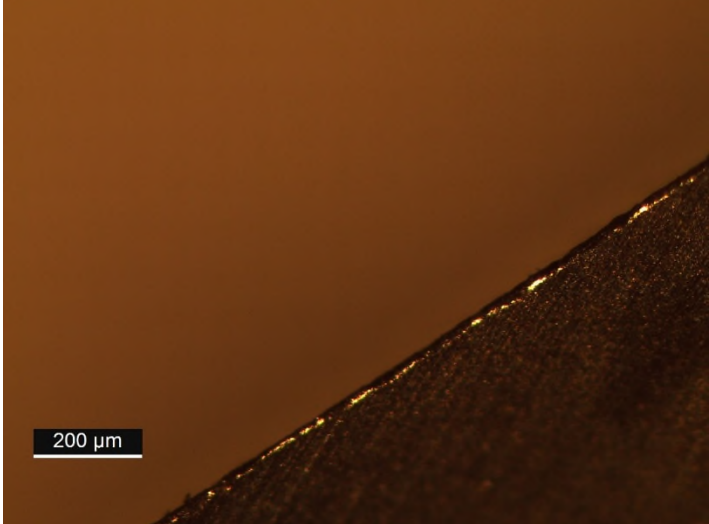
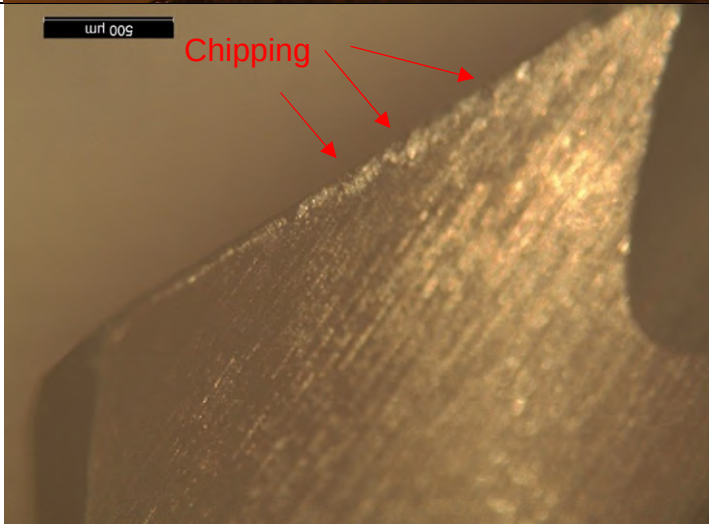
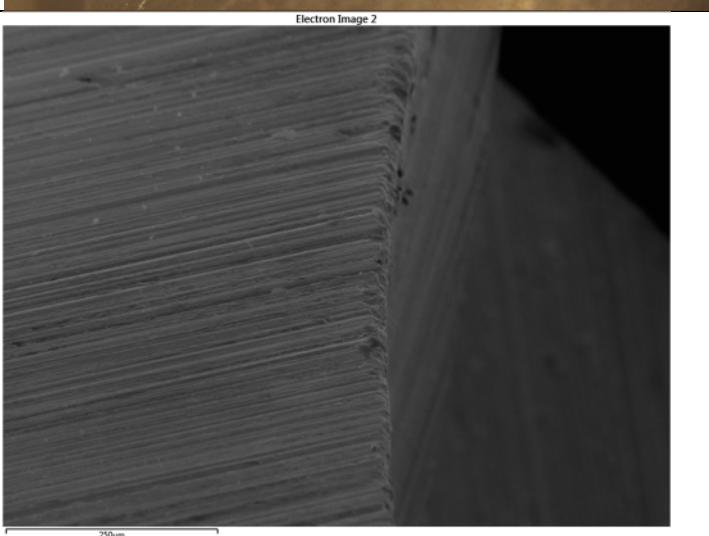
Hole 9	
Hole 23	
Hole 25	

Table 16. SEM and microscope images of UNC

Comparing tool wear for all tools, it can be concluded that DLC tools had the least wear. For DLC 2 and all the BAM coated tools, delamination seems to be an issue. DLC 1 tool didn't have much coating delamination compared to other coated tools.

Also despite coating delamination, DLC 2 showed less wear than BAM coatings. For the BAM coated tools, it can be concluded that the coating thickness greatly affects the tool performance. Increased thickness resulted in the tool being critically damaged. It is possible that by improving the adhesion of the BAM coating and using a thin layer, the tool performance could improve as showed by BAM 1 tool.

5.2 EDS results

Figure 35 - Figure 40 and Table 17 - Table 22 show the results after EDS analysis was conducted on the cutting edges after drilling holes for each tool. It is evident that Ti was present in all of them. It was particularly higher in DLC 2, BAM 2 and BAM 3. Ti adhesion is an issue for tools as results in built-up-edge (BUE) which affects the tool performance by reducing the sharpness of the cutting edges.

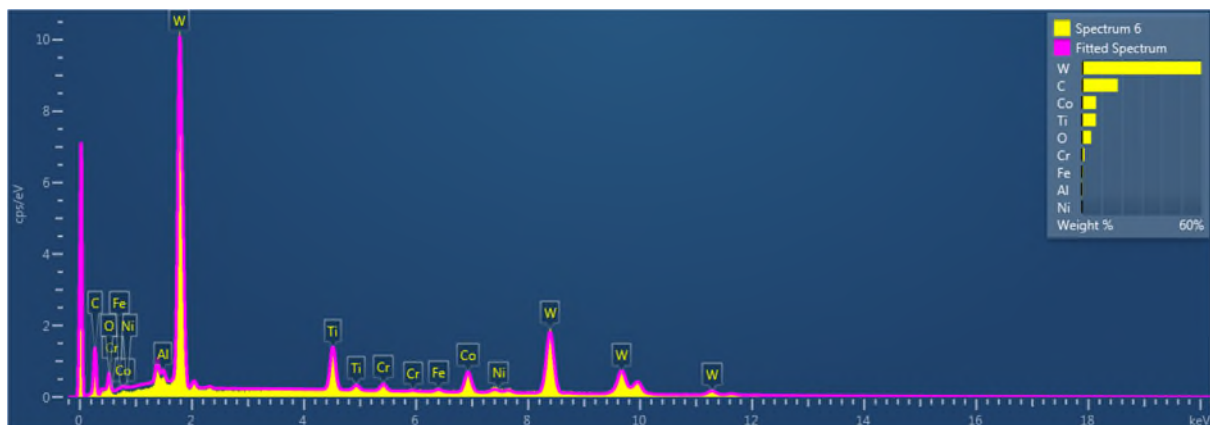


Figure 35. EDS spectrum of DLC 1 tool after 30 holes

Spectrum Label	C	O	Al	Ti	Cr	Fe	Co	W
Composition %	18.04	4.78	0.58	7.16	1.45	0.68	7.17	59.73

Table 17. Element results of DLC 1 tool from EDS analysis

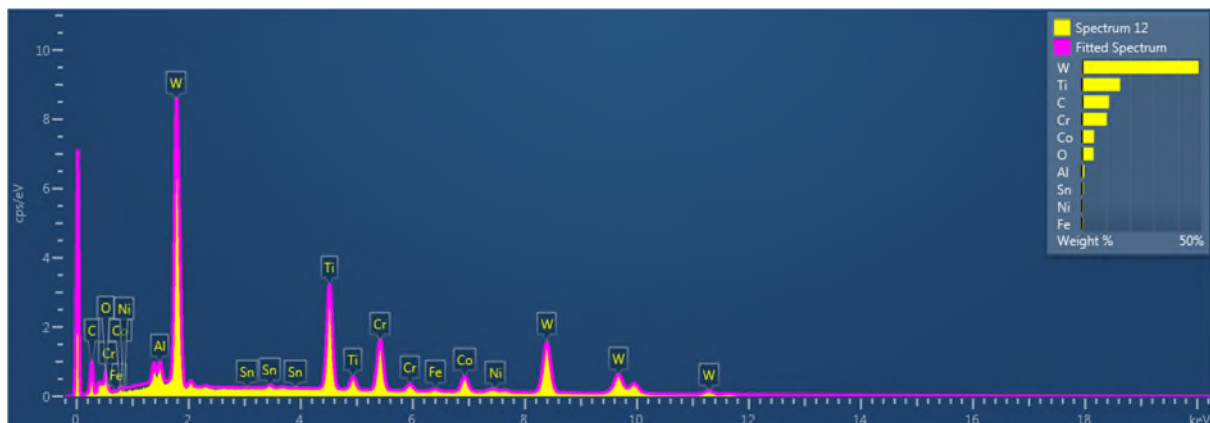


Figure 36. EDS spectrum of DLC 2 tool after 30 holes

Spectrum Label	C	O	Ti	Cr	Fe	Co	W
Composition %	11.43	4.98	15.97	10.45	0.64	5.17	48.69

Table 18. Element results of DLC 2 tool from EDS analysis

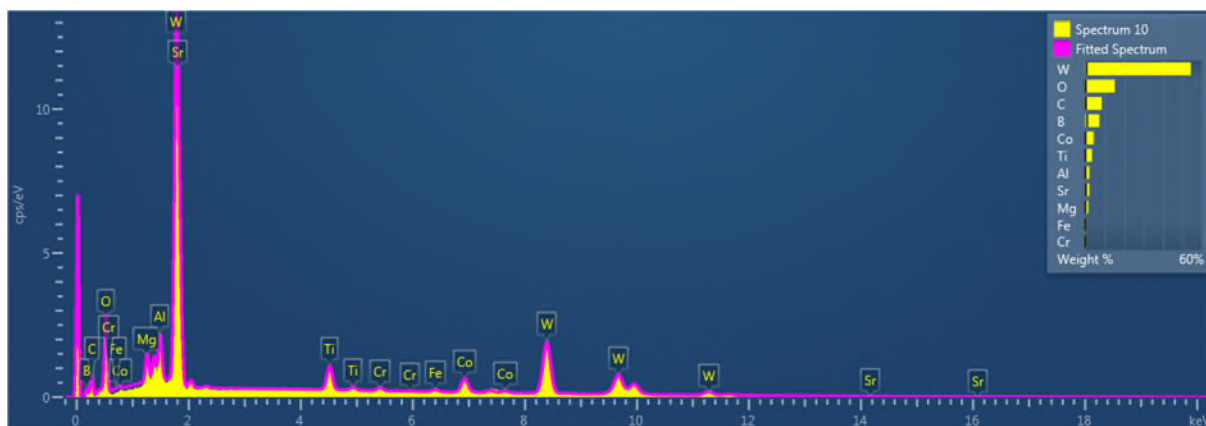


Figure 37. EDS spectrum of BAM 1 tool after 30 holes

Spectrum Label	B	C	O	Mg	Al	Ti	Fe	Co	Sr	W
Composition %	7.24	8.45	15.2	1.53	2.13	3.42	0.63	4.34	2.13	54.36

Table 19. Element results of BAM 1 tool from EDS analysis

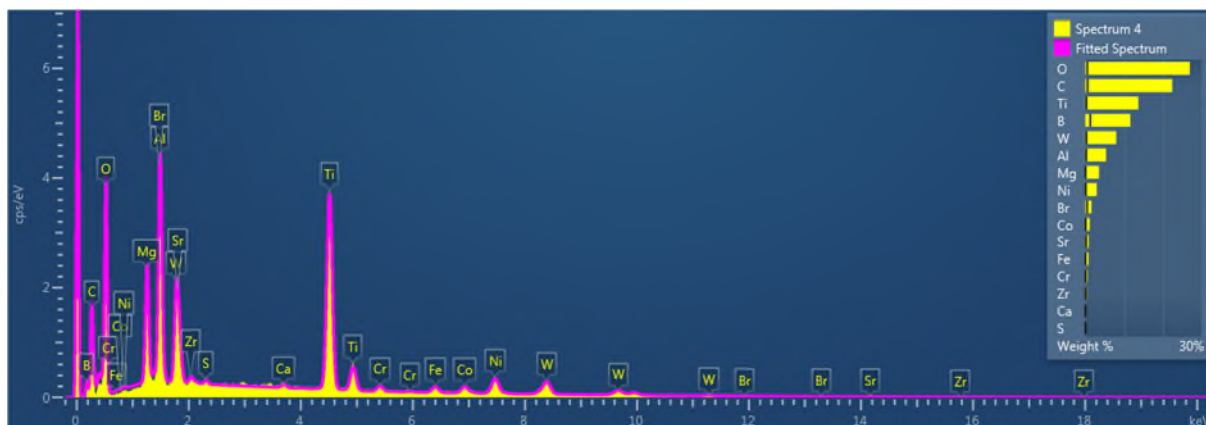


Figure 38. EDS spectrum of BAM 2 tool after 15 holes

Spectrum Label	B	C	O	Mg	Al	Ti	Fe	Co	Ni	W
Composition %	11.86	22.43	27.11	3.59	6.18	13.79	0.81	1.13	2.98	8.04

Table 20. Element results of BAM 2 tool from EDS analysis

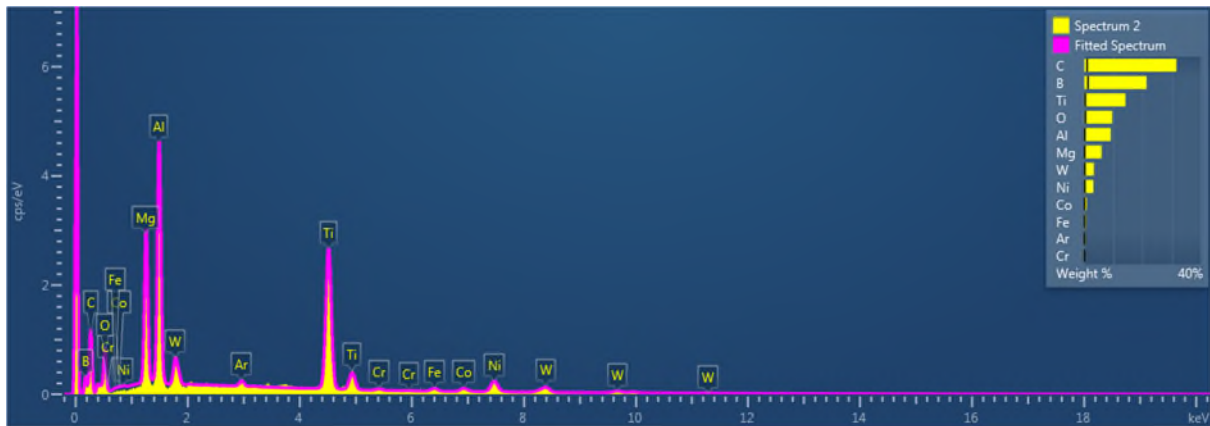


Figure 39. EDS spectrum of BAM 3 tool after 9 holes

Spectrum Label	B	C	O	Mg	Al	Ti	Cr	Fe	Co	Ni	W
Composition %	21.4	31.61	9.54	5.95	9.1	14.14	0.22	0.56	0.81	3.11	3.25

Table 21. Element results of BAM 3 tool from EDS analysis

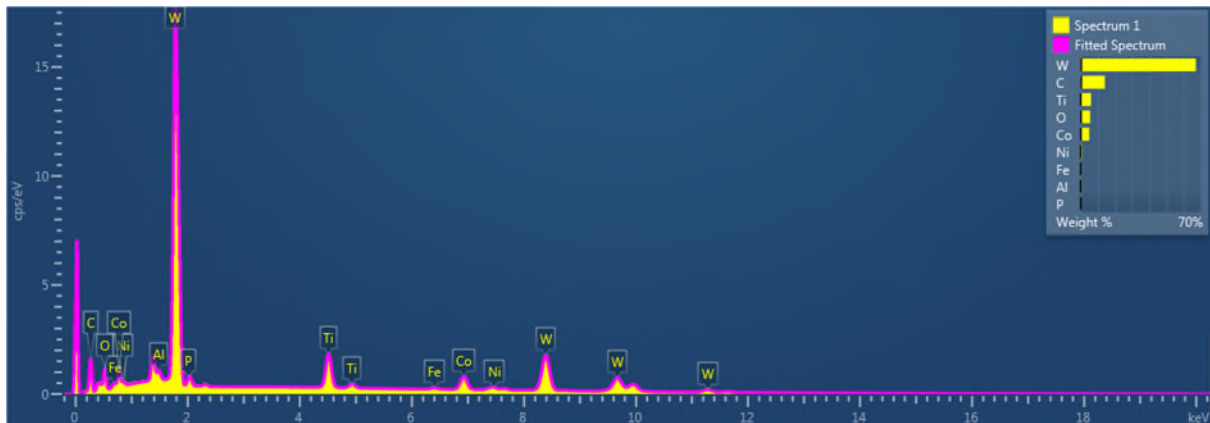


Figure 40. EDS spectrum of uncoated tool after 25 holes

Spectrum Label	C	O	Ti	Fe	Co	Ni	W
Composition %	14.09	5.59	6.02	0.5	4.97	0.88	67.16

Table 22. Element results of uncoated tool from EDS analysis

5.3 Hole diameters and roundness error

During the stack drilling of CFRP/Ti, the hole size produced in the two materials will be affected because of the dissimilar co-efficient of thermal expansion in CFRP laminates and titanium. Thus, hole-diameters and roundness error were measured to observe the affect the different tools.

Figure 41 shows the measured hole diameters during drilling of titanium for all the tools. For all the tools, the diameters are above the nominal drill size of 6mm. It is observed from the graph that the diameters are consistent for DLC 1 and BAM 1. Also for DLC

2, after the first hole, the diameters are fairly consistent. For uncoated tool, the hole diameter in hole number 17 is abnormal, this could be due to tool wear, error during machining or error during measurement. However, the 25th hole produced by the uncoated tool is also large due to tool failure. For BAM 3, the hole sizes were not consistent, despite only drilling 9 holes. It can be concluded that DLC 1 and BAM 1 produce consistent hole sizes in titanium.

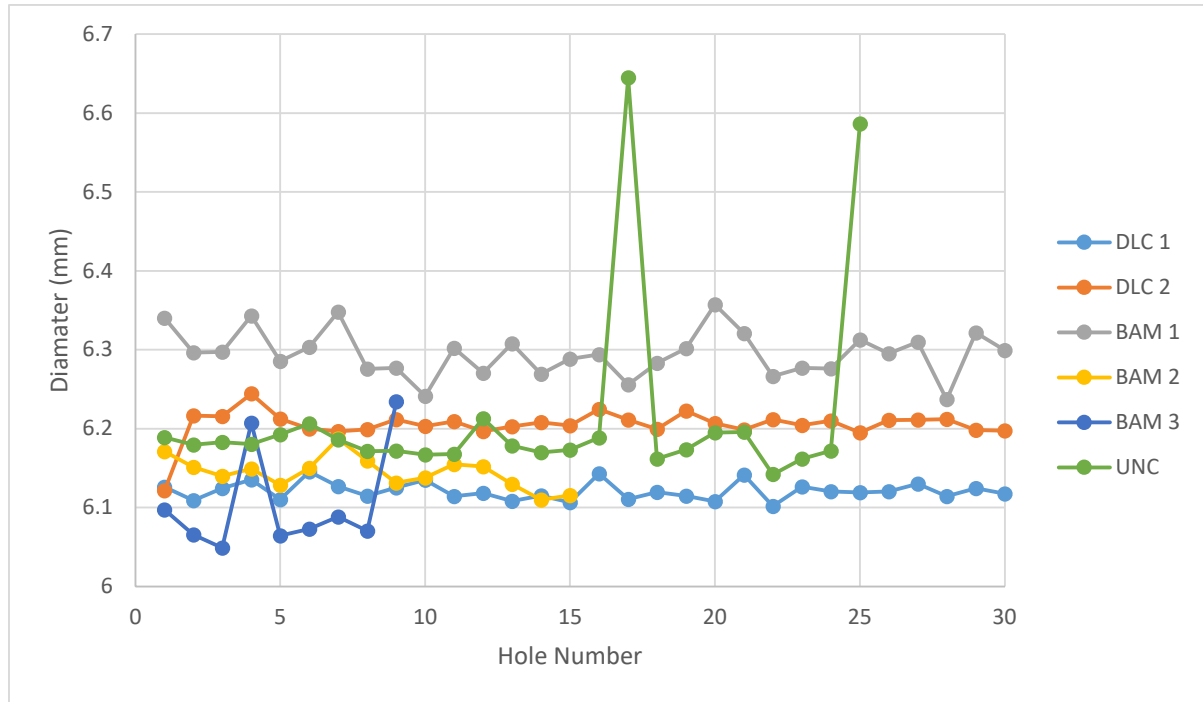


Figure 41. Hole diameters for each tool during Ti drilling

Figure 42 shows the measured hole diameters during drilling of CFRP for all the tools. It is observed that the hole sizes are inconsistent for all tools. This can be attributed to the brittle nature of fibres becoming damaged via Ti chip removal during drilling and causing delamination of layers and hence inconsistent sizes. This shows that CFRP is a difficult material to drill. One approach to investigate for future is to stack Ti on CFRP and carry out drilling to study the effect of such combination.

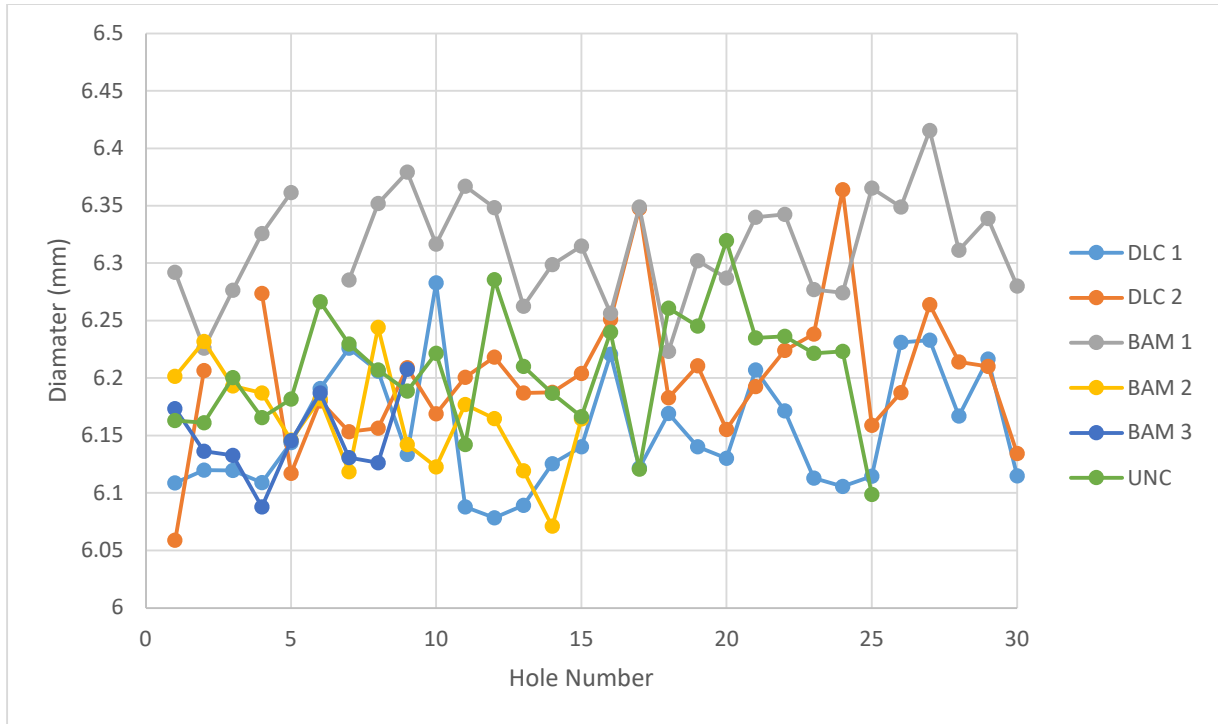


Figure 42. Hole diameters for each tool during CFRP drilling

The roundness was also measured using the CMM. The roundness error is a 2-d measurement allowance that governs the deviation of the feature from a circle. Figure 43 shows the roundness error for holes during Ti phase drilling. It is that observed roundness error is very small for tools except for BAM 2. The range mostly was 0-10 microns, which is excellent.

Figure 44 shows the roundness error for holes during CFRP phase drilling. It can be said that compared to Ti, the roundness error was greater. The holes were not as round as they were in Ti. This is due to the fact that the composite layers delaminate during drilling and this affected the final shape.

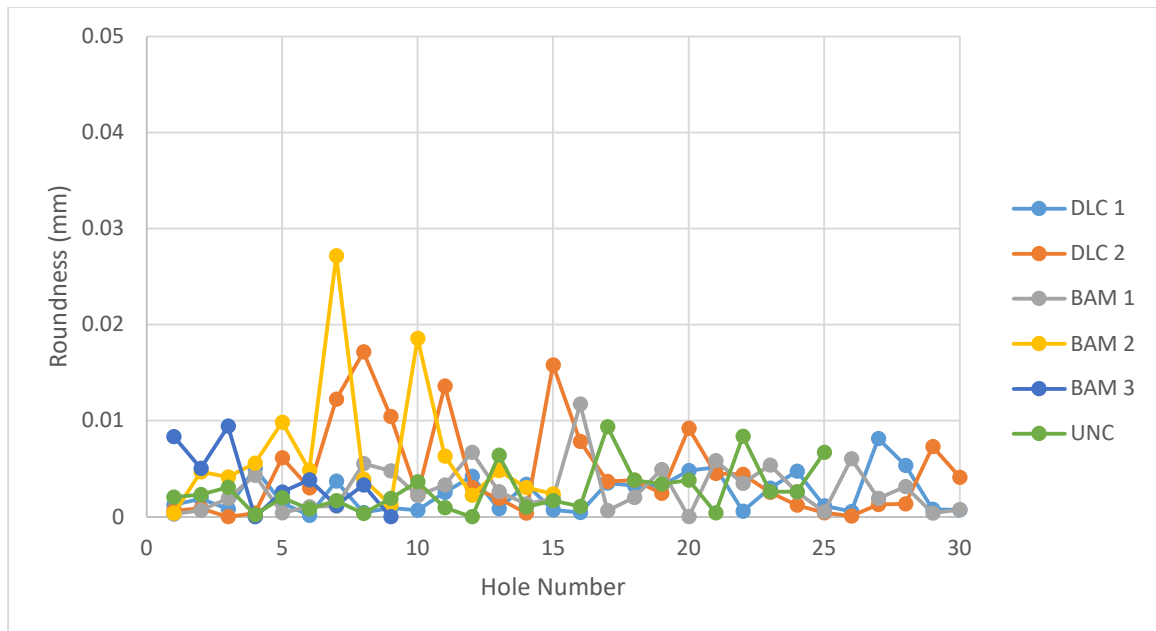


Figure 43. Roundness error during drilling in Ti phase holes

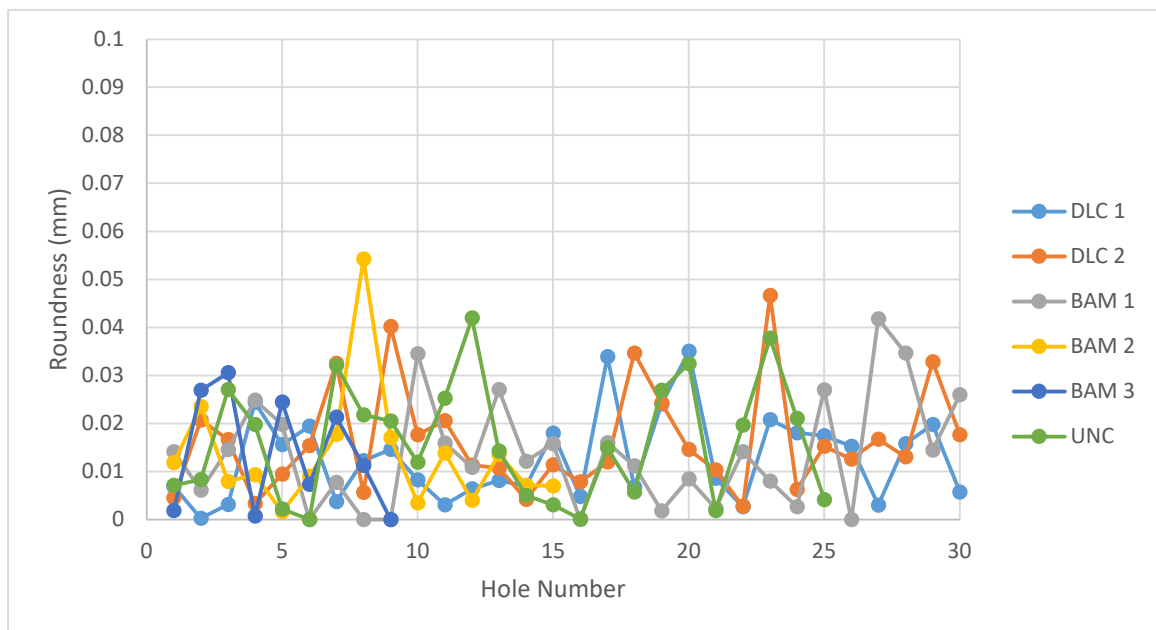


Figure 44. Roundness error during drilling in CFRP phase holes

5.4 Surface roughness

A critical parameter for hole quality is the surface roughness. It governs the required strict dimensional tolerances to allow improved component assembly during manufacture. For CFRP/Ti stacks, the required Ra values are:

- $Ra \leq 1.6 \mu\text{m}$ for Ti
- $Ra \leq 3.2 \mu\text{m}$ for CFRP

Figure 45 shows the surface roughness (Ra) against hole number in Ti holes for each tool. In general, the surface finish is good for all tools ranging between 0.2 to 1.1 microns. It is quite stable for BAM 1. The Ra surface roughness for all tools during Ti was within the requirements. It is concluded that DLC 1 tool provided the lowest surface roughness during Ti drilling.

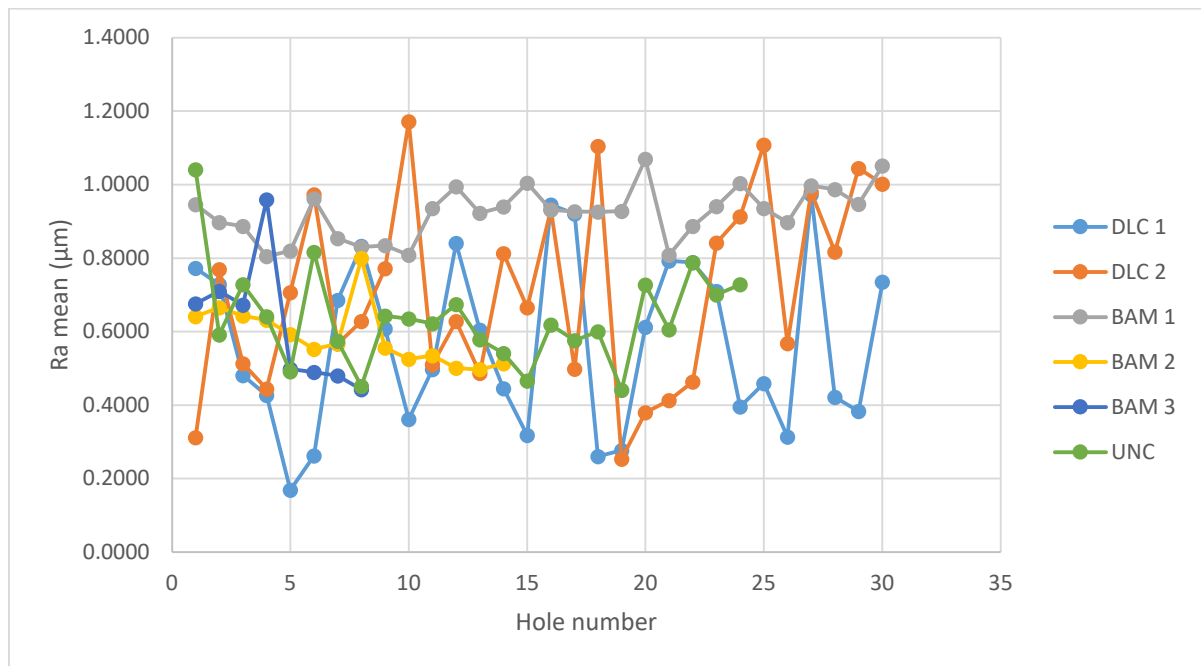


Figure 45. Variation in surface roughness (Ra) of holes in Ti for each tool

Figure 46 shows the surface roughness (Ra) against hole number in CFRP for each tool. Comparing the results to surface roughness in titanium, it is much higher in CFRP. The values are also above the required tolerance of $\leq 3.2 \mu\text{m}$, except BAM 2 tool which drilled most holes with surface roughness less than $3.2 \mu\text{m}$. The large surface roughness values are due to the chip removal of Ti affecting the finished surface roughness. Abrasion from the Ti chips affects the brittle hole wall surface of CFRP deteriorating the hole quality.

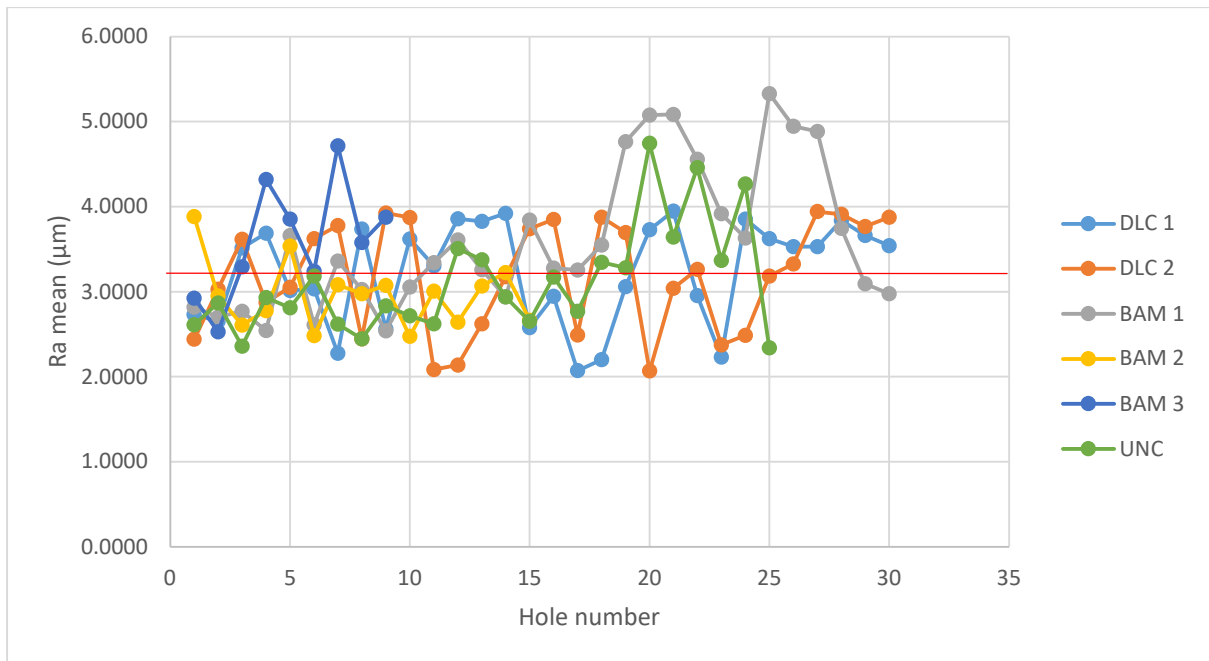


Figure 46. Variation in surface roughness (R_a) of holes in CFRP for each tool

5.5 Force measurements

The thrust force profile for CFRP and Ti changes as drilling is carried out. There were two regions in the force curve recorded during drilling of the stacks as seen in Figure 47. In the first region, the drill first penetrates the CFRP and then the force drops as the tool changes speed and feed. Then in the second region, the tool starts again to start drilling Ti. The maximum thrust reading was obtained from the graph for each phase and used to plot for each tool. For the drilling approach, the drilling was carried out incrementally (a bit like peck drilling), i.e. the material was drilled to a small depth, and then the tool was retracted and drilled again until full depth. The reason for this approach was to reduce swarf build-up tool heating up.

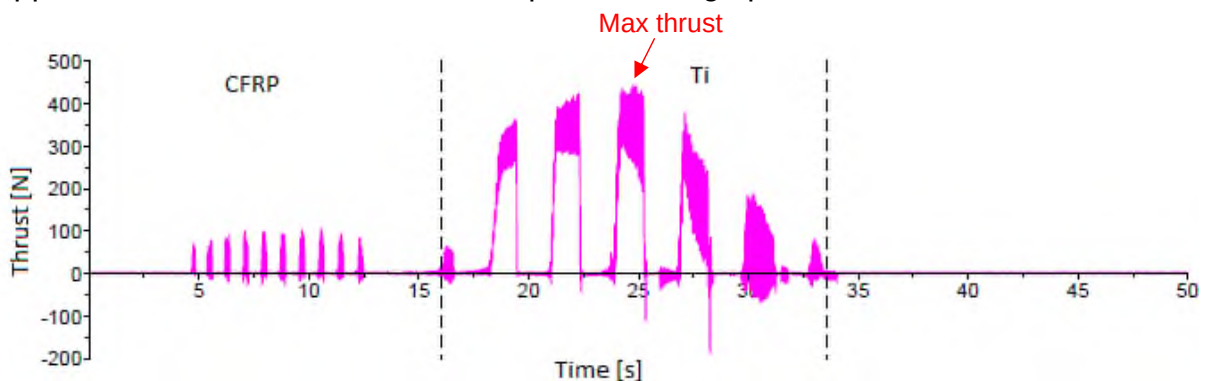


Figure 47. Typical force measurement during stack drilling.

The thrust values against holes are plotted for each tool for CFRP and Ti separately. Figure 48 shows the maximum thrust recorded during Ti drilling at each hole for different tools. It can be seen that for all tools, the force increases as the number of holes increases. This is understandable as the tool wears, it requires more energy to penetrate the materials, hence the reason for the increased trend in thrust. From Figure 48, it is evident that the force for BAM 2 is lowest, however the tool failed after 15 holes as the curve shows increase in thrust at hole 15. For BAM 3, the force rises sharply between holes 8 and 9, indicating that it failed after only 9 holes. Overall, the thrust is lowest for DLC 1, indicating that it didn't wear much in comparison to other tools. Comparing the coated tools to uncoated tool, there doesn't seem to be much difference in thrust for the first 15 holes. After 15 holes, the thrust in uncoated tool showed an increase, indicating that the tool started to wear and eventually failed after hole 25.

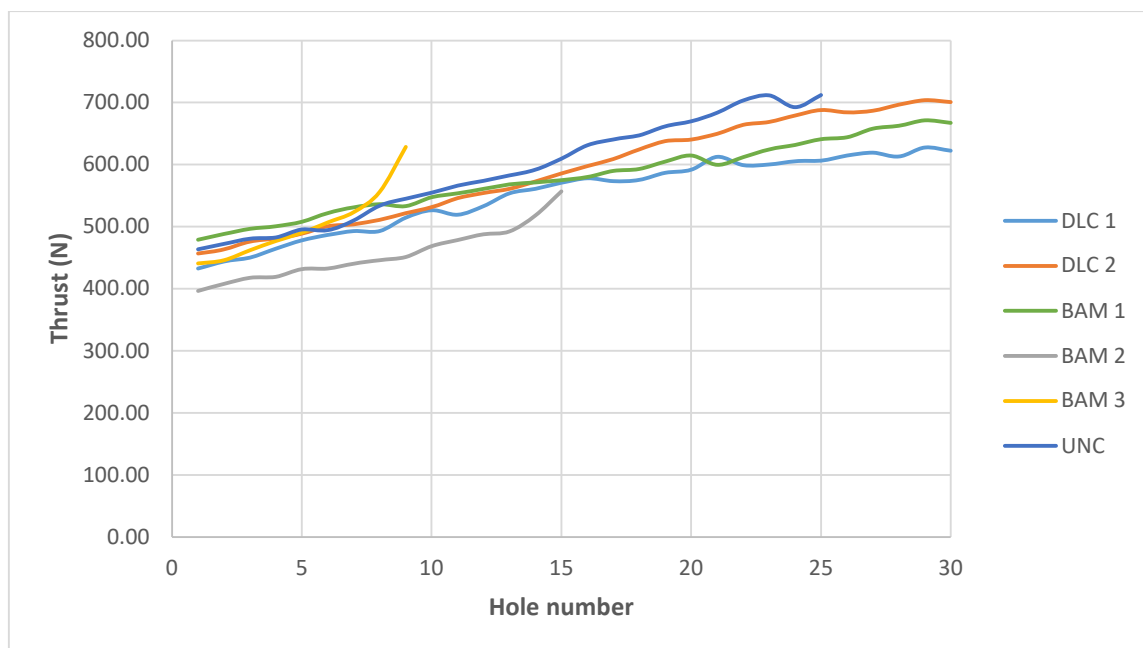


Figure 48. Thrust for each tool during Ti drilling

Table 23 shows percentage increase in thrust during Ti drilling. For DLC 1, the thrust increased by about 44% over 30 holes during Ti drilling. It was lowest for BAM 2 and highest for uncoated tool and DLC 2.

Tool	% Thrust increase
DLC 1	43.80
DLC2	53.47
BAM 1	39.22
BAM 2	40.41
BAM 3	42.67
UNC	53.54

Table 23. Percentage increase in thrust during Ti drilling

Figure 49 shows the maximum thrust recorded during CFRP drilling at each hole for different tools. Again, it can be seen that for all tools, the force increases as the number of holes increases. Expectedly, the thrust is less in comparison to Ti. It can be observed that thrust is lowest for uncoated tool and highest for DLC 2. This could be attributed to the fact that CFRP requires sharp cutting edges to drill and the uncoated tool had this advantage. Whereas the coated tools were slightly less sharp due to the coatings and that could have affected the machining performance.

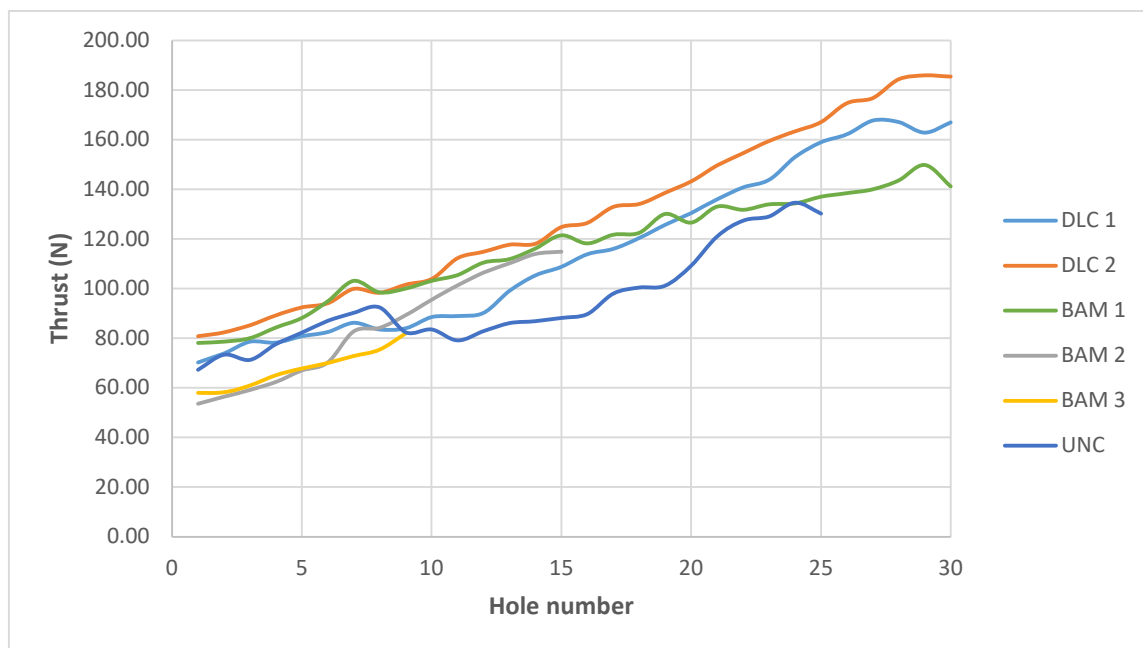


Figure 49. Thrust for each tool during CFRP drilling

Table 24 shows percentage increase in thrust during CFRP drilling. Over 30 holes, it was lowest for BAM 1 and highest for DLC 1. For BAM 2, it was quite high considering only 15 holes were drilled.

Tool	% Thrust increase
DLC 1	137.53
DLC2	129.25
BAM 1	80.79
BAM 2	114.07
BAM 3	41.39
UNC	93.52

Table 24. Percentage increase in thrust during CFRP drilling

5.6 Summary of results

This chapter has presented the results of experimental study on drilling hybrid CFRP/Ti stacks using coated and uncoated tools. The effectiveness of different coating materials in CFRP/Ti drilling has been systematically investigated, and their results are compared correspondingly. The experimental work has highlighted the effect of using coatings in order to extend tool life in affecting the final CFRP/Ti drilling responses. Based on the experimental investigations, the following key findings are drawn.

Drilling hybrid CFRP/Ti stacks basically involves five cutting stages with regards to the tool-workpiece interaction. The interface phase is the most challenging cutting process because of the multi-tool-work interaction. Here, coupled chip separation modes and severe transitions of mechanical/physical responses preponderate. Moreover, the ordinarily used methods for standard CFRP machining and single Ti alloy machining are unsuitable for stacked CFRP/Ti interface drilling. Knowing that the interface region requires different machining technique/method, it should help future studies to develop a new concept of the machinability of the interface zone. In interface drilling, particular care should be given to the careful control of the coupling effects in chip separation, the unsteadiness of the tool-work interaction, as well as the tool wear and cutting-induced damage.

Hole quality including machined surface roughness, hole diameters and hole size accuracy were investigated to study the effect of coated and uncoated tools. For surface roughness inspection, the CFRP/Ti stacking sequence is a key factor that greatly influences the drilled hole surface finish in the two materials. This is due to the abrasion from the Ti chips affecting the hole wall roughness in the CFRP. Moreover, for all tested trials, the arithmetic mean roughness (Ra) values of drilled Ti phase holes

are found to be fully controlled below the benchmark value of $R_a = 1.6 \mu\text{m}$, whereas for the machined CFRP holes, the R_a values are partly achieved below the benchmark value of $R_a = 3.2 \mu\text{m}$. For hole diameters, pretty much all tools produced hole diameters greater than the tool diameter for both materials, except for DCL 1 in Ti.

The force analysis shows that coated drills promoted lower drilling forces than the uncoated drill under the same cutting parameters. The findings probably indicate that the coatings resisted wear during the stack drilling, hence the lower forces. Although, where a thicker coating was used, the tool failed quickly. This may be attributed to the cutting edge rounding, where the sharpness of the cutting edge of the drill bit is reduced to cut the materials. This indicates that an optimum thickness of coating must be coated in order to achieve a longer tool life. The hole size roundness error was fairly good for all tools in both materials.

In general, the DLC coated drills yielded a better tool performance than the uncoated and BAM coated drills in terms of various drilling responses (e.g. Tool wear, force generation) when performed under the identical cutting conditions. The findings suggest that when drilling hybrid CFRP/Ti stacks, the selection of optimal coating thickness should be a more effective method to improve the machinability of the bi-material system. The thicker BAM coating had least influences on the tool performance mainly due to the occurrence of severe chipping failure or coating peeling even after drilling quite a few number of CFRP/Ti holes, which makes the drill edges lose effective coating protection for producing high hole quality.

Conclusion

An experimental study on drilling performance evaluation of coated and uncoated tools during drilling of CFRP/Ti stacks was conducted. The effect of DLC and BAM coatings was investigated with regards to tool wear and hole quality. The tools were coated using PVD method and their wear and workpiece hole quality were assessed. The following conclusions can be drawn from the study:

- The tool wear results showed that DLC coated tools had best performance, showing least wear. For the BAM coatings, the tool failed quickly for the higher thickness. DLC 2 and all the BAM coated tools showed delamination of coatings. Uncoated failed after 25 holes, less than DLC 1, DLC 2 and BAM 1.
- Comparing the hole diameters, the coated tools produced more consistent sizes in Ti compared to uncoated tool. DLC 1 produced sizes close to the nominal size of 6mm. Uncoated tool produced the least consistent hole diameters. In CFRP, the Ti chip removal affected the hole sizes, hence the diameters were not consistent for all tools.
- Comparing the surface roughness in Ti, all tools achieved the required Ra value below 1.6 μm . However, for CFRP, again the chip removals from Ti affected the hole wall surface roughness.
- Comparing the thrust in Ti drilling, BAM 1 and DLC 1 produced the least thrust. In CFRP drilling, uncoated and BAM 1 tools gave the lowest thrust.

The study has proven that coated tools can perform better than uncoated tool. However, the delamination of coatings is still an area of concern, as seen in the BAM coatings, which can be improved in future experiments.

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Appendix A- Thrust force values

DLC 1	Max thrust (N)	
	CFRP	Ti
Hole 01	70.32	432.83
Hole 02	73.91	444.11
Hole 03	78.62	450.40
Hole 04	78.27	464.58
Hole 05	80.82	478.29
Hole 06	82.55	486.71
Hole 07	86.21	493.06
Hole 08	83.59	492.89
Hole 09	84.01	514.68
Hole 10	88.54	526.86
Hole 11	88.96	519.46
Hole 12	90.28	533.48
Hole 13	99.08	554.06
Hole 14	105.35	561.37
Hole 15	108.75	570.90
Hole 16	113.87	578.39
Hole 17	116.01	573.55
Hole 18	120.41	575.56
Hole 19	125.73	587.04
Hole 20	130.54	592.04
Hole 21	136.02	612.73
Hole 22	140.81	599.27
Hole 23	143.85	600.27
Hole 24	153.05	605.82
Hole 25	158.95	606.82
Hole 26	162.17	614.61
Hole 27	167.71	619.45
Hole 28	167.07	613.10
Hole 29	162.81	627.65
Hole 30	167.03	622.39

DLC 2	Max thrust (N)	
	CFRP	Ti
Hole 01	80.87	456.93
Hole 02	82.40	463.50
Hole 03	85.27	476.27
Hole 04	89.27	481.27
Hole 05	92.39	488.82
Hole 06	94.08	500.83
Hole 07	99.88	504.08
Hole 08	98.33	511.37
Hole 09	101.65	521.92
Hole 10	103.88	531.60
Hole 11	112.29	546.23
Hole 12	114.90	554.66
Hole 13	117.66	561.29
Hole 14	118.14	572.99
Hole 15	124.77	586.05
Hole 16	126.49	597.81
Hole 17	132.95	609.43
Hole 18	134.11	624.87
Hole 19	138.63	637.88
Hole 20	143.26	640.76
Hole 21	149.64	650.12
Hole 22	154.61	664.20
Hole 23	159.51	669.20
Hole 24	163.41	679.27
Hole 25	167.10	688.36
Hole 26	174.74	684.40
Hole 27	176.84	687.31
Hole 28	184.36	696.81
Hole 29	185.90	704.04
Hole 30	185.39	701.25

BAM 1	Max thrust (N)	
	CFRP	Ti
Hole 01	78.13	479.43
Hole 02	78.69	488.25
Hole 03	80.00	496.76
Hole 04	84.37	500.82
Hole 05	88.13	508.03
Hole 06	94.89	522.15
Hole 07	103.09	531.43
Hole 08	98.50	536.46
Hole 09	100.06	533.33
Hole 10	103.17	547.57
Hole 11	105.47	553.95
Hole 12	110.54	561.03
Hole 13	111.88	568.20
Hole 14	116.19	571.68
Hole 15	121.50	575.10
Hole 16	118.20	580.05
Hole 17	121.74	590.11
Hole 18	122.47	593.39
Hole 19	130.05	605.24
Hole 20	126.62	614.76
Hole 21	133.09	599.95
Hole 22	131.75	612.13
Hole 23	133.96	624.71
Hole 24	134.36	632.08
Hole 25	137.01	641.19
Hole 26	138.47	644.27
Hole 27	140.05	658.09
Hole 28	143.65	662.80
Hole 29	149.86	671.54
Hole 30	141.24	667.44

BAM 2	Max thrust (N)	
	CFRP	Ti
Hole 01	53.66	396.90
Hole 02	56.43	408.14
Hole 03	59.17	417.88
Hole 04	62.40	419.45
Hole 05	67.01	431.89
Hole 06	70.22	432.93
Hole 07	82.74	440.73
Hole 08	84.23	446.21
Hole 09	89.29	451.48
Hole 10	95.58	468.78
Hole 11	101.30	478.81
Hole 12	106.46	487.96
Hole 13	110.19	492.61
Hole 14	114.01	518.40
Hole 15	114.87	557.27

BAM 3	Max thrust (N)	
	CFRP	Ti
Hole 01	57.99	440.88
Hole 02	58.20	446.11
Hole 03	61.01	462.10
Hole 04	65.12	477.25
Hole 05	67.80	490.33
Hole 06	70.01	506.99
Hole 07	72.85	523.55
Hole 08	75.41	555.86
Hole 09	81.99	629.01

UNC	Max thrust (N)	
	CFRP	Ti
Hole 01	67.32	463.86
Hole 02	73.41	472.48
Hole 03	71.29	480.88
Hole 04	77.65	482.94
Hole 05	82.26	495.45
Hole 06	86.98	494.51
Hole 07	90.18	510.12
Hole 08	92.43	534.09
Hole 09	82.44	545.47
Hole 10	83.54	555.08
Hole 11	79.10	566.13
Hole 12	82.92	574.37
Hole 13	86.06	582.71
Hole 14	86.89	591.95
Hole 15	88.25	609.85
Hole 16	89.77	631.16
Hole 17	97.97	640.78
Hole 18	100.42	647.55
Hole 19	101.18	661.99
Hole 20	109.31	669.88
Hole 21	121.13	683.92
Hole 22	127.42	703.40
Hole 23	129.12	711.64
Hole 24	134.65	692.65
Hole 25	130.28	712.22

Appendix B- CMM measurements

DLC 1			
Ti	Rnd error	CFRP	Rnd error
6.12619	0.00125	6.10866	0.00687
6.10887	0.00189	6.11994	0.00030
6.12434	0.00081	6.11963	0.00310
6.13550	0.00505	6.10909	0.02438
6.11005	0.00144	6.14377	0.01558
6.14560	0.00016	6.19105	0.01946
6.12695	0.00373	6.22605	0.00374
6.11475	0.00046	6.20583	0.01226
6.12510	0.00093	6.13357	0.01456
6.13508	0.00067	6.28295	0.00829
6.11433	0.00255	6.08780	0.00305
6.11817	0.00423	6.07848	0.00641
6.10832	0.00086	6.08911	0.00815
6.11521	0.00337	6.12550	0.00702
6.10654	0.00071	6.14017	0.01798
6.14326	0.00045	6.22078	0.00481
6.11052	0.00351	6.12170	0.03390
6.11961	0.00326	6.16922	0.00680
6.11475	0.00326	6.14028	0.02403
6.10780	0.00481	6.13005	0.03503
6.14145	0.00516	6.20720	0.00861
6.10188	0.00058	6.17135	0.00264
6.12634	0.00297	6.11303	0.02079
6.12024	0.00475	6.10566	0.01808
6.11913	0.00114	6.11451	0.01747
6.12041	0.00054	6.23099	0.01528
6.13006	0.00816	6.23303	0.00297
6.11437	0.00533	6.16691	0.01576
6.12458	0.00078	6.21647	0.01982
6.11753	0.00070	6.11484	0.00572

DLC 2			
Ti	Rnd error	CFRP	Rnd error
6.12170	0.00066	6.05875	0.00454
6.21661	0.00088	6.20643	0.02070
6.21577	0.00000		0.01669
6.24441	0.00037	6.27379	0.00330
6.21253	0.00616	6.11704	0.00949
6.20003	0.00301	6.18015	0.01542
6.19646	0.01223	6.15334	0.03254
6.19906	0.01716	6.15646	0.00569
6.21152	0.01043	6.20894	0.04018
6.20305	0.00230	6.16894	0.01765
6.20933	0.01362	6.20079	0.02060
6.19652	0.00305	6.21828	0.01134
6.20280	0.00192	6.18689	0.01076
6.20820	0.00037	6.18748	0.00422
6.20376	0.01581	6.20415	0.01141
6.22478	0.00785	6.25122	0.00787
6.21111	0.00367	6.34776	0.01202
6.19966	0.00383	6.18272	0.03464
6.22271	0.00245	6.21069	0.02423
6.20693	0.00920	6.15530	0.01462
6.19884	0.00451	6.19249	0.01035
6.21180	0.00443	6.22400	0.00278
6.20453	0.00254	6.23815	0.04663
6.20990	0.00122	6.36381	0.00625
6.19522	0.00042	6.15889	0.01527
6.21077	0.00009	6.18730	0.01259
6.21132	0.00128	6.26384	0.01671
6.21208	0.00134	6.21405	0.01307
6.19829	0.00730	6.21009	0.03288
6.19762	0.00412	6.13424	0.01768

BAM 1			
Ti	Rnd error	CFRP	Rnd error
6.34022	0.00029	6.29192	0.01414
6.29631	0.00067	6.22600	0.00615
6.29712	0.00192	6.27633	0.01456
6.34292	0.00430	6.32575	0.02486
6.28546	0.00043	6.36148	0.01978
6.30332	0.00104		0.00000
6.34801	0.00110	6.28525	0.00772
6.27588	0.00555	6.35207	0.00000
6.27703	0.00478	6.37918	0.00000
6.24136	0.00222	6.31656	0.03453
6.30193	0.00332	6.36701	0.01594
6.27043	0.00671	6.34828	0.01086
6.30779	0.00263	6.26257	0.02707
6.26935	0.00135	6.29877	0.01216
6.28834	0.00189	6.31481	0.01580
6.29385	0.01173	6.25629	0.00000
6.25578	0.00065	6.34882	0.01601
6.28290	0.00203	6.22336	0.01118
6.30160	0.00492	6.30204	0.00178
6.35729	0.00000	6.28714	0.00843
6.32069	0.00586	6.33984	0.00231
6.26623	0.00348	6.34259	0.01415
6.27688	0.00537	6.27710	0.00797
6.27618	0.00258	6.27431	0.00265
6.31256	0.00050	6.36545	0.02698
6.29524	0.00604	6.34888	0.00000
6.30981	0.00190	6.41548	0.04179
6.23702	0.00316	6.31126	0.03466
6.32177	0.00038	6.33892	0.01445
6.29920	0.00074	6.28021	0.02598

BAM 2			
Ti	Rnd error	CFRP	Rnd error
6.17109	0.00037	6.20160	0.01188
6.15104	0.00469	6.23183	0.02352
6.13994	0.00414	6.19322	0.00792
6.14926	0.00558	6.18691	0.00931
6.12846	0.00986	6.14613	0.00165
6.15009	0.00485	6.18203	0.00900
6.18743	0.02716	6.11842	0.01775
6.15948	0.00393	6.24414	0.05426
6.13124	0.00126	6.14205	0.01703
6.13776	0.01857	6.12276	0.00349
6.15484	0.00630	6.17710	0.01387
6.15216	0.00226	6.16477	0.00398
6.12982	0.00481	6.11921	0.01362
6.10987	0.00306	6.07103	0.00710
6.11570	0.00237	6.16442	0.00697

UNC			
Ti	Rnd error	CFRP	Rnd error
6.18882	0.00204	6.16311	0.00714
6.17947	0.00233	6.16109	0.00834
6.18274	0.00309	6.20050	0.02702
6.18042	0.00022	6.16558	0.01979
6.19276	0.00199	6.18179	0.00217
6.20641	0.00081	6.26631	0.00000
6.18606	0.00167	6.22954	0.03209
6.17169	0.00035	6.20714	0.02178
6.17199	0.00192	6.18877	0.02051
6.16700	0.00364	6.22148	0.01191
6.16766	0.00096	6.14212	0.02523
6.21307	0.00000	6.28553	0.04196
6.17833	0.00640	6.21002	0.01427
6.16993	0.00100	6.18685	0.00501
6.17327	0.00168	6.16651	0.00308
6.18843	0.00109	6.23995	0.00012
6.64475	0.00938	6.12058	0.01490
6.16190	0.00380	6.26092	0.00570
6.17371	0.00342	6.24515	0.02691
6.19486	0.00382	6.31954	0.03244
6.19583	0.00043	6.23488	0.00184
6.14221	0.00839	6.23647	0.01967
6.16160	0.00263	6.22168	0.03776
6.17191	0.00261	6.22323	0.02103
6.58650	0.00670	6.09882	0.00412

BAM 3			
Ti	Rnd error	CFRP	Rnd error
6.09719	0.00833	6.17344	0.00189
6.06551	0.00505	6.13638	0.02689
6.04907	0.00943	6.13280	0.03057
6.20709	0.00000	6.08796	0.00071
6.06449	0.00257	6.14546	0.02448
6.07311	0.00384	6.18710	0.00731
6.08837	0.00119	6.13078	0.02129
6.07059	0.00333	6.12622	0.01127
6.23428	0.00000	6.20758	0.00000

Appendix C – Surface roughness measurements

	DLC 1	
	Ra mean (μm)	
Hole	CFRP	Ti
Hole 01	2.7329	0.7723
Hole 02	2.6530	0.7286
Hole 03	3.5133	0.4809
Hole 04	3.6860	0.4272
Hole 05	3.0152	0.1691
Hole 06	3.0312	0.2620
Hole 07	2.2768	0.6857
Hole 08	3.7359	0.8327
Hole 09	2.5642	0.6078
Hole 10	3.6192	0.3611
Hole 11	3.3033	0.4971
Hole 12	3.8556	0.8408
Hole 13	3.8283	0.6048
Hole 14	3.9203	0.4450
Hole 15	2.5776	0.3182
Hole 16	2.9459	0.9448
Hole 17	2.0719	0.9206
Hole 18	2.2010	0.2607
Hole 19	3.0601	0.2771
Hole 20	3.7270	0.6120
Hole 21	3.9481	0.7931
Hole 22	2.9542	0.7880
Hole 23	2.2327	0.7095
Hole 24	3.8522	0.3954
Hole 25	3.6247	0.4588
Hole 26	3.5306	0.3136
Hole 27	3.5282	0.9732
Hole 28	3.8366	0.4219
Hole 29	3.6614	0.3835
Hole 30	3.5412	0.7351

	DLC 2	
	Ra mean (μm)	
Hole	CFRP	Ti
Hole 01	2.4436	0.3114
Hole 02	3.0308	0.7692
Hole 03	3.6158	0.5133
Hole 04	2.8755	0.4440
Hole 05	3.0501	0.7068
Hole 06	3.6225	0.9733
Hole 07	3.7763	0.5672
Hole 08	2.4461	0.6284
Hole 09	3.9262	0.7717
Hole 10	3.8704	1.1719
Hole 11	2.0832	0.5108
Hole 12	2.1357	0.6284
Hole 13	2.6232	0.4865
Hole 14	3.1755	0.8127
Hole 15	3.741	0.6652
Hole 16	3.8491	0.9324
Hole 17	2.4908	0.4978
Hole 18	3.8765	1.1049
Hole 19	3.6933	0.2538
Hole 20	2.0690	0.3795
Hole 21	3.0391	0.4131
Hole 22	3.2612	0.4636
Hole 23	2.3748	0.8412
Hole 24	2.4864	0.9130
Hole 25	3.1815	1.1078
Hole 26	3.3269	0.5681
Hole 27	3.9422	0.9801
Hole 28	3.9094	0.8170
Hole 29	3.7676	1.0448
Hole 30	3.8754	1.0016

	BAM 1	
	Ra mean (μm)	
Hole	CFRP	Ti
Hole 01	2.8188	0.9459
Hole 02	2.7022	0.8975
Hole 03	2.7696	0.8871
Hole 04	2.5423	0.8051
Hole 05	3.6628	0.8195
Hole 06	2.6120	0.9619
Hole 07	3.3607	0.8534
Hole 08	3.0265	0.8301
Hole 09	2.5387	0.8348
Hole 10	3.0550	0.8085
Hole 11	3.3404	0.9357
Hole 12	3.6092	0.9947
Hole 13	3.2596	0.9229
Hole 14	2.9375	0.9402
Hole 15	3.8407	1.0047
Hole 16	3.2781	0.9315
Hole 17	3.2551	0.9269
Hole 18	3.5489	0.9257
Hole 19	4.7631	0.9273
Hole 20	5.0764	1.0701
Hole 21	5.0820	0.8080
Hole 22	4.5577	0.8866
Hole 23	3.9186	0.9404
Hole 24	3.6313	1.0032
Hole 25	5.3293	0.9358
Hole 26	4.9448	0.8973
Hole 27	4.8825	0.9977
Hole 28	3.7428	0.9870
Hole 29	3.0947	0.9472
Hole 30	2.9768	1.0511

	BAM 2	
	Ra mean (μm)	
Hole	CFRP	Ti
Hole 01	3.8822	0.6414
Hole 02	2.9486	0.6658
Hole 03	2.6057	0.6427
Hole 04	2.7758	0.6312
Hole 05	3.5379	0.5923
Hole 06	2.4839	0.5525
Hole 07	3.0826	0.5674
Hole 08	2.9779	0.7996
Hole 09	3.0736	0.5553
Hole 10	2.4756	0.5250
Hole 11	3.0083	0.5352
Hole 12	2.6399	0.5005
Hole 13	3.0684	0.4970
Hole 14	3.2254	0.5126

	BAM 3	
	Ra mean (μm)	
Hole	CFRP	Ti
Hole 01	2.9226	0.6760
Hole 02	2.5303	0.7098
Hole 03	3.2915	0.6725
Hole 04	4.3211	0.9592
Hole 05	3.8542	0.4979
Hole 06	3.2410	0.4898
Hole 07	4.7149	0.4800
Hole 08	3.5780	0.4428

	UNC	
	Ra mean (μm)	
Hole	CFRP	Ti
Hole 01	2.6122	1.0411
Hole 02	2.8654	0.5912
Hole 03	2.3610	0.7281
Hole 04	2.9307	0.6408
Hole 05	2.8110	0.4909
Hole 06	3.1814	0.8162
Hole 07	2.6180	0.5744
Hole 08	2.4463	0.4510
Hole 09	2.8323	0.6425
Hole 10	2.7149	0.6350
Hole 11	2.6244	0.6219
Hole 12	3.5077	0.6740
Hole 13	3.3741	0.5780
Hole 14	2.9383	0.5412
Hole 15	2.6536	0.4662
Hole 16	3.1729	0.6183
Hole 17	2.7710	0.5758
Hole 18	3.3457	0.5998
Hole 19	3.2813	0.4411
Hole 20	4.7442	0.7272
Hole 21	3.6420	0.6058
Hole 22	4.4587	0.7884
Hole 23	3.3668	0.7005
Hole 24	4.2669	0.7286