Tribology of Composite Materials and Coatings in Manufacturing

M. H. Sulaiman, N. A. Raof, and A. N. Dahnel

Abstract The chapter presents studies regarding the tribological performance of composite materials and multilayer composite coated tools in manufacturing processes carried out by the authors. Two manufacturing processes were investigated—metal forming and metal cutting. In metal forming, the study aimed to explore lubricant-free forming utilizing multilayer DLC composite hard coating as the potential tool coating. The experimental studies on the coating include characterization of the coating, and tribological analysis of the coating using commercially available pin-on-disk, laboratory tribology simulative test and industrial ironing of stainless steel. In order to examine the influence of temperature and contact pressure along the tool/workpiece interface on friction, Finite Element analysis was performed. Meanwhile, in metal cutting, two environmentally benign machining techniques were investigated to determine their potentials in delaying tool wear progression. First, sustainable machining by coupling multilayer ceramic composite coated-tool with cryogenic coolant as the cutting fluid. Second, the machining of Carbon Fibre Composite and Titanium alloys stacks using Ultrasonic Assisted Drilling (UAD) technique. Both techniques include investigations on machining conditions with varied cutting tool speeds. The examinations on the experimental results were focused on temperature, tool wear, surface integrity and metallurgical structure of near-surface region.

Keywords Manufacturing · Lubricant-free forming · Cryogenic machining · Composite coating · Ultrasonic assisted drilling (UAD) · Carbon fibre composite (CFC) · Titanium alloy composite

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1 Introduction

While lubrication has been the leading edge to improve tribological performance in manufacturing processes, environmental-friendly manufacturing with or without inclusion of lubricants is new and presents extremely demanding solutions for sustainable manufacturing. Driven by environmental concerns and the enforcement of restrictive legislations to ban the use of lubricants, extensive studies on environmental-friendly manufacturing, either by looking at new alternative to lubrication or manufacturing techniques, has attracted great attention from worldwide researchers. Since a large amount of lubricant is necessary for a high volume manufacturing production, this will further increase the risks to health hazards. Up to these days, efficient lubricant containing environmentally hazardous extreme pressure additives is being employed in production as the only reliable solution to impede tool wear. Such lubricants are activated by gradual temperature increase and due to repetitive sliding between the workpiece and the tool surface, thereby a good boundary film is created by the reaction with the material of workpiece, usually involving the combination with coated tools for improved tool wear resistance (Bay 2013; Ceron et al. 2014). Aside from the good boundary lubricants, increasing trends of using vegetable oils (Syahrullail et al. 2011; Zulhanafi and Syahrullail 2019) and tailor-made ionic liquids (Amiril et al. 2017) in manufacturing and industrial engineering has become future prospects of better lubrication with anti-friction and anti-wear properties as opposed to a lot of biolubricants, and mineral oils that are synthetic and petroleum-based.

Manufacturing processes with effective boundary lubricants alone may not necessarily improve tool wear resistance unless other mechanical engineered surface techniques are applied. For instance, anti-seizure tool materials, structured surface topographies, and anti-seizure tool surface treatments (either by coatings or by thermochemical diffusion). To date, some of them are being used in real manufacturing processes, i.e., application of structured workpiece surfaces with the use of big rolls roughened by Shot Blast Texturing (SBT) or Electro Discharge Texturing (EDT) (Kijima and Bay 2007). Apart from that, hard coating is largely used today. Composite coating, for example, is known to decrease tool wear of approximately 2–50 times in abrasive wear conditions while for sliding conditions, beyond four times compared to the reference uncoated steel (Holmberg et al. 2014). For hard coatings in regard with manufacturing applications, the design of coating architecture is important to release residual stress and to avoid the initiation and generation of cracks so that the life span of a tool can be lengthened. In metal stamping, multilayer Diamond-Like Carbon (DLC) composite coating has shown positive influence to promote an improved adhesion strength for DLC and the tool substrate, thus a longer tool lifetime (Sulaiman et al. 2017a). The multilayer coating structure allows the coating in restraining and decelerating crack initiation and propagation rate. Owing to successive microcrystalline coatings with a smoother surface and columnar grain structures, the multilayer DLC composite coating worked satisfactorily so that the coating damage resistance is improved, and even performed well in dry friction condition (Sulaiman et al. 2017b).

A study of WC-Co tools with monolayer, MCD/NCD coating and multilayer diamond/β-SiC composite hard coating using Rockwell and scratch tests has demonstrated that the multilayer composite tool is superior to other hard coatings. The experiment revealed the positive impact of using multilayer diamond/β-SiC composite hard coating which improved the mechanical properties, by means of high hardness, high Young modulus and residual stress that is low, leading to enhanced adhesion and crack propagation resistance (Yuan et al. 2020). Composite hard coating has such mechanical properties that are excellent that it has been supported by optimized thermal expansion coefficient matching amidst the substrate and coating as well as contributed directly by internal mechanical interlock effect of the co-deposition of diamond and β-SiC phase. As a result, this has improved interfacial adhesion of the substrate and MCD/NCD multilayer top coating, in which the diamond functions as high strength structure phase while the bonding phase is represented by β-SiC. A similar result in metal cutting, engineered nano-scale multilayer TiAlN/Al_2O_3 composite coating has enabled for an optimum combination between the high adhesion strength and the tool substrate along with the work material adhesion to the tool surface that is minimum (Vereshchaka et al. 2014). The experimental results after the dry machining concluded that the multilayer TiAlN/Al_2O_3 composite coating can work effectively to decrease the wear rates, thereby promoting longer operational life of the cutting tool significantly. On the other hand, there is a number of researches on exploring new environmentally benign machining techniques of composites materials. For example, drilling of aerospace composite materials using cryogenic lubrication technique (Barnes 2013; Barnes and Ascroft 2015) and using Ultrasonic Assisted Drilling (UAD) technique (Dahnel et al. 2015, 2016). Both techniques are feasible alternatives to provide low friction and wear rate at controlled temperatures below 300 °C besides enhancing the tool lifetime and drilling hole quality. However, utilizing cryogenic lubrication technique during the machining of the composite materials has no significant influence on tool wear, despite reduced temperature between work material and cutting tool.

The aim of this chapter is to present the discussion of the mechanical and tribological behaviour of composite tool coatings with environmental-friendly lubrication system or without applying lubricants at all, and the tribological performance in environmental-friendly machining techniques of composite materials. Most work are centered on evaluating the tribo-mechanical performances with and without lubricants on how severe the tool wear and product surface quality are. Some studies were carried out at elevated temperatures and hence the discussions are made separately for room and high temperature, categorized by the types of manufacturing processes. The broader impact of the chapter ends with concluding remark of the present tribological composite work in manufacturing processes which are needed for exploring the tribological behavior of new and greatly classes of composite specifically, and for tribology generally.

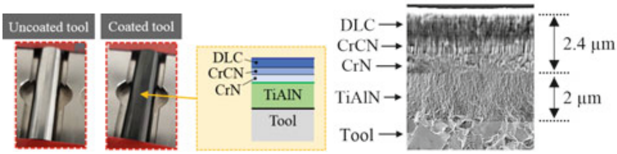
2 Metal Forming

2.1 *Forming of Stainless Steel Sheets with DLC Composite Hard Coating*

Studies on eliminating the harmful lubrication in metal forming is growing tremendously. Although adopting anti-seizure hard coatings is imperative to improve tribological performance of tool surface in metal forming, the coated tool lifetime is limited when forming is operated under dry friction condition. This is associated with coating architectures and adhesion bond that is weak which connects top coating layer and tool substrate at high loads (Chuan et al. 2013; Merklein et al. 2015). A solution to this adhesion strength issue is the introduction of interface layer, i.e. TiAlN (Wang et al. 2007; Biksa et al. 2010; Lukaszkowicz 2011; Sulaiman 2017). With the aim to enable lubricant-free forming and to promote environmental-friendly tribosystem, a new multilayer DLC/CrCN/CrN/TiAlN composite coating was developed and deposited onto the tool substrate. The composite coating was tested and evaluated using three different tribological test methodologies. First, tribological pin-on-disk test (Sulaiman et al. 2019a). Second, simulative tribology test (Sulaiman et al. 2017a). Lastly, simulation of industrial ironing of stainless steels (Sulaiman et al. 2019b). All involved approaches adopted experiments at room and elevated temperatures. To investigate the effects on the tool wear following the experimentation, the measurement on the workpiece surface roughness was taken using a tactile roughness profilometer. This was followed by the detection of material transfer to the die surface in the area of contact utilizing a light optical microscope (LOM). Lastly, in order to examine the wear scar elements at the top of coated die surface following the experiment, scanning electron microscopy and energy-dispersive X-ray spectroscopy (SEM–EDX) were used. Before the experimentation, a cleaning process was performed on all worn surfaces by immersing them repetitively in acetone bath. A Finite Element simulation combining analyses on mechanical and thermal were conducted to discover material deformation along with heat generation impact towards the stress conditions of workpiece during forming operation and the friction at the interface of die–workpiece.

2.1.1 Properties of Multilayer DLC Composite Coating

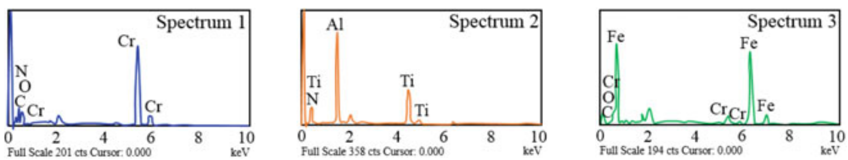
Figure 1 displays the transection perspective of the multilayer DLC/CrCN/CrN/TiAlN composite coating. The coating is formed by DLC film (top layer) and TiAlN film (bottom layer) on top of the substrate (tool steel Vanadis 4, with 62 HRC surface hardness). The die roughness following the coating was equivalent as the previous one: $Ra = 0.02$ µm. The coating was accumulated through the process of Physical Vapour Deposition (PVD) which is related to unbalanced magnetron sputtering (Neergaard 2017). The table next to Fig. 1, presents the coating's mechanical properties and surface characteristics, in which



Properties	Value
Hardness	3,000 HV
Roughness *Ra*	0.026 μm

Fig. 1 Design, microstructure, surface characteristics and mechanical properties of the multilayer DLC composite coating

the uncertainty values constitute three to five times of the variations observed in the examined regions. The framework for every DLC/CrCN/CrN/TiAlN composite coating layer disclosed their coating films thickness which were 2.4 and 2 μm, each. Based on the SEM images, TiAlN film (intermediate layer) was found to bond ideally with DLC coating film (top layer) and the Vanadis 4 substrate (bottom layer). It was due to Cr interlayer, as specified by the EDX results in Fig. 2 (top), in which the stress gradient at the interface amidst the DLC and TiAlN coating films was released (Kim et al. 2016). It was also indicated from the EDX results that adhesion strength was enhanced because of the use of the elements, Cr and Ti, in the multilayer DLC/CrCN/CrN/TiAlN composite coating, which then produced low energy, a chemical bond that is stable and strong, and a low stress gradient at the interface (Hong et al. 2001b; Strano et al. 2013; Yasa et al. 2012). A composition that is congregated and rough was exhibited from the first DLC layer, different compared to the framework of the TiAIN layer which was fine and smooth. Good composite coating adhesion is explicable by the composition of CrCN/CrN interlayer under the first DLC layer, that is big and has columnar grain (Kaynak 2014; Dhar et al. 2001). Figure 2 (bottom right) shows the thick microstructure of TiAIN coating that has a steady cylindric architecture with several pores along with inclusions. Meanwhile, Fig. 2 (middle) shows TiAIN coating that contains high level of Al, which causes the multilayer DLC/CrCN/CrN/TiAlN composite coating to enhance its rigidity. It is therefore suggested that the TiAIN interlayer is weak in cutting stress for the sake of enhancing the strength of adhesion amidst the DLC film and the Vanadis 4 substrate,



DLC/CrCN/CrN coating

Element	Weight%	Atomic%
Cr	73.54	41.92
N	13.88	29.38
C	8.77	21.63
O	3.81	7.07

TiAlN coating

Element	Weight%	Atomic%
Ti	45.01	24.80
Al	31.33	30.64
N	23.65	44.56

Tool steel, Vanadis 4

Element	Weight%	Atomic%
Fe	87.82	72.08
Cr	5.16	4.55
O	3.57	10.22
C	3.45	13.15

Fig. 2 Elemental compositions of the multilayer DLC/CrCN/CrN/TiAlN composite coating

as the adhesion strength is increased by Cr interlayer by the means of stress gradient reduction between TiAIN and DLC coating films (Sulaiman et al. 2019b). Hence, the combination of these effects could result in reduced sliding-originated surface tensile stresses of the multilayer DLC/CrCN/CrN/TiAlN composite coating, which helps with the prevention of severe wear and die lifetime extension.

2.1.2 Tribological Pin-on-Disk Experiment with Multilayer DLC Composite Coating

Commercially available pin-on-disk test was adopted for studying tribological effects of the composite hard coating. Figure 3 shows the experimental setup for two conditions; lubricated and dry friction for a friction pair comprised a 100Cr6 steel ball along with a Vanadis 4 tool steel flat surface with and without the multilayer DLC/CrCN/CrN/TiAlN composite coating. Table 1 shows the list of test parameters application in the pin-on-disk experiment. In order to examine the wear scar on DLC coated and uncoated tool steel surfaces following the experimentation, a tactile roughness profilometer and a Light Optical Microscope (LOM) were applied.

The remarkable influence of engineered tool surface by using hard coating is apparent. When there is no application of coating to the tool steel at the time of operation, bigger friction coefficient is observable easily in Fig. 4 (left). For specimens with multilayer DLC/CrCN/CrN/TiAlN composite coating, the value

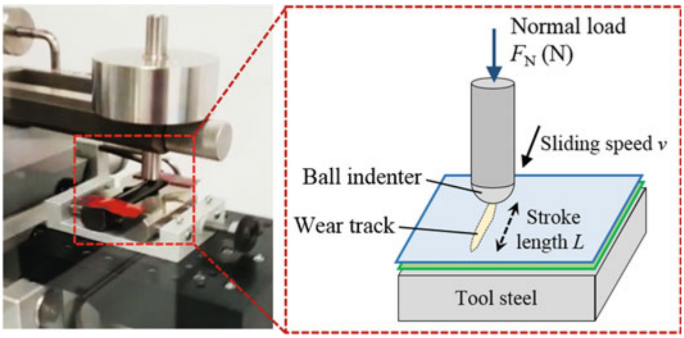


Fig. 3 Schematics of pin-on-disk experimental setup

Table 1 Test parameters

Test parameters	Values
Sliding speed v	100 mm/s
Normal load F_N	10 N
Stroke length L	16 mm
Max. strokes	500 laps
Temperature	32 °C

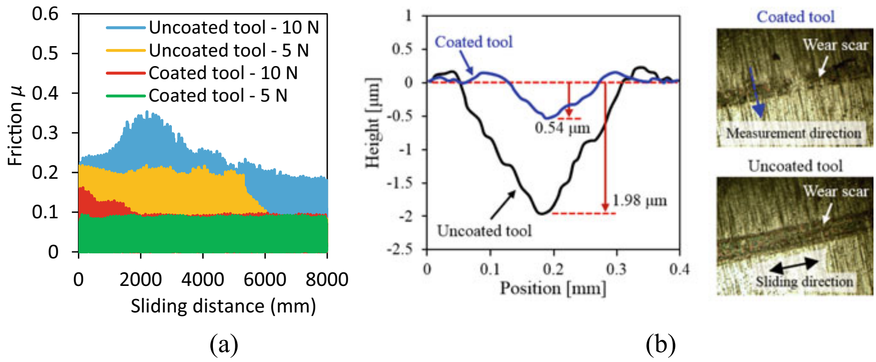


Fig. 4 Friction μ (left) and wear depth profiles after pin-on-disk experiment (right)

of friction coefficient in stable-state condition was observed at its lowest in both conditions of lubricated and dry friction. This explains the capability of multilayer DLC/CrCN/CrN/TiAlN composite coating in frictional effects reduction and also its capability to reach value that is stable after a long experiment. The positive influence of using such composite coating is supported by roughness measurement on the wear scar profiles with an optical profilometer, in which there was a discovery of only minor scratches on the wear track of the multilayer DLC/CrCN/CrN/TiAlN composite coated tool, see Fig. 4 (right). In having good mechanical properties and wear resistance for the multilayer DLC/CrCN/CrN/TiAlN composite coating, the coating characteristics have shown positive improvements in adhesion between the coating and tool substrate to lessen the tool steel wear, hence the tool lifetime is improved.

2.1.3 Tribological Strip Reduction Test (SRT) with Multilayer DLC Composite Coating

In performing the off-line evaluation of the same multilayer DLC/CrCN/CrN/TiAlN composite coated tool as described in Fig. 1, a Strip-Reduction Test (SRT) was chosen, see Fig. 5 to the far right. The SRT was chosen because the simulative test

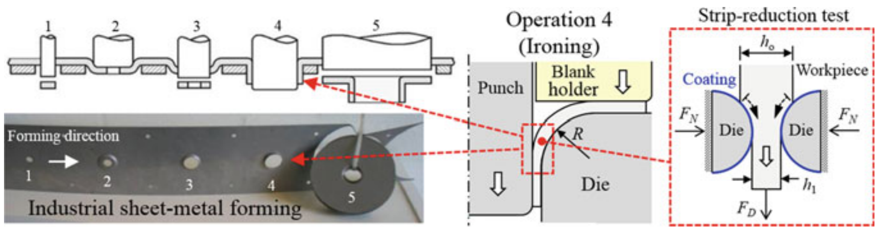


Fig. 5 Experimental strip reduction emulating industrial ironing (Ceron and Bay 2013)

imitates operation 4—industrial ironing of stainless steel sheets, see Fig. 5 to the far left. The selection of test parameters was made in congruence with the industrial production process: 24% reduction, 50 mm/s drawing speed, idle time between each stroke of 1.8 s and 10 mm sliding length. The materials and lubricant for the test are detailed in Tables 2 and 3, respectively.

The multilayer DLC/CrCN/CrN/TiAlN composite-coated tool was tested under dry friction condition and lubrication with environmentally benign mineral oil with no Extreme Pressure (EP) additives, refer to Table 3. Figure 6a shows constant drawing load and stable tool rest temperature despite following 1000 strokes, and none of the pick-up signs on the tool surface was remarked. The verification is made through sheet roughness *Ra* measurement as in Fig. 6b, in which the original workpiece roughness was found to be higher than sheet surfaces performed under conditions of lubricated and dry friction. Hence, the findings have revealed the capability of the multilayer DLC/CrCN/CrN/TiAlN composite coating to ironing the stainless steel sheets with no lubrication, or else will be highly susceptible to galling. Thereby, adopting the multilayer composite coating film by depositing an interlayer metallic coating film like TiAlN, CrCN and CrN in between the DLC film and the tool substrate can therefore improve adhesion strength of the DLC composite coating

Table 2 Test materials for the strip-reduction test

Components	Dimension (mm)	Roughness *Ra* (μm)
Tool (Vanadis 4)	Ø15 × 34	0.02
Workpiece (EN1.4307)	*W*30 × *t*1.0	0.14

Table 3 Properties of the test lubricant

Oil type	Product name	Kinematic viscosity *η* (cSt @ 40 °C)
Mineral oil	CR5 Houghton Plunger	660

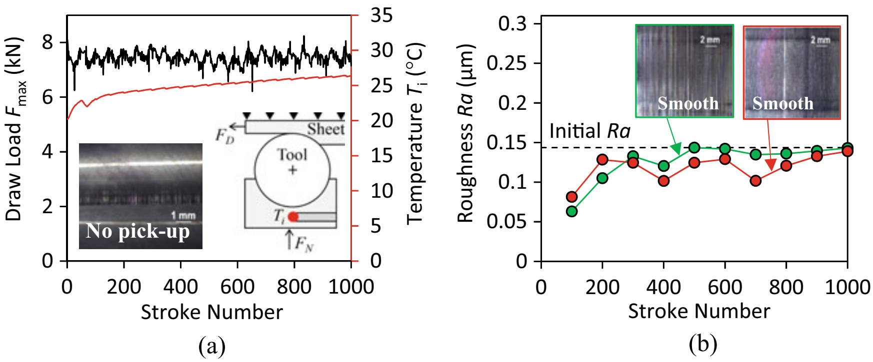


Fig. 6 **a** Forming load F_D and **b** workpiece roughness *Ra* in ironing with dry friction condition

and even perform well under the extreme test conditions in ironing of stainless steel. A coupled mechanical and thermal simulation analysis utilizing Finite Element (FE) software LS-Dyna shown in Fig. 7a has supported the experimental findings. As seen in Fig. 7b, a minimum quantity of the hazard free lubricant is sufficient to minimize the friction, and no significant difference of the normal pressure along the contact region, reaching 400 and 1000 MPa in dry and lubricated conditions, see Fig. 8a. However, it is anticipated that the temperature would be higher at the tool/workpiece assemblage by the Finite Element analysis using strip reduction test in dry condition as opposed to that of lubricated, see Fig. 8b. This indicates the temperature change ΔT alongside the assemblage of the tool/workpiece has been reduced due to a smaller friction coefficient and thereby, no lubricant film breakdown. This further suggests that the composite coating improves wear resistance for the DLC coated tool surface for the sake of protecting the DLC coated tool for a longer tool lifetime.

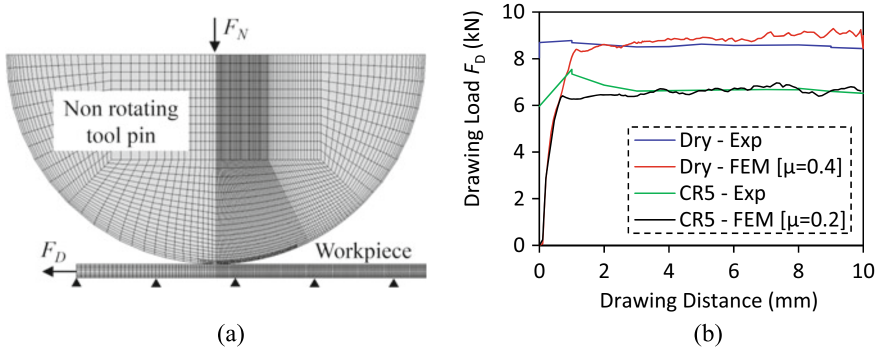


Fig. 7 **a** Numerical simulation of ironing, and **b** friction coefficient

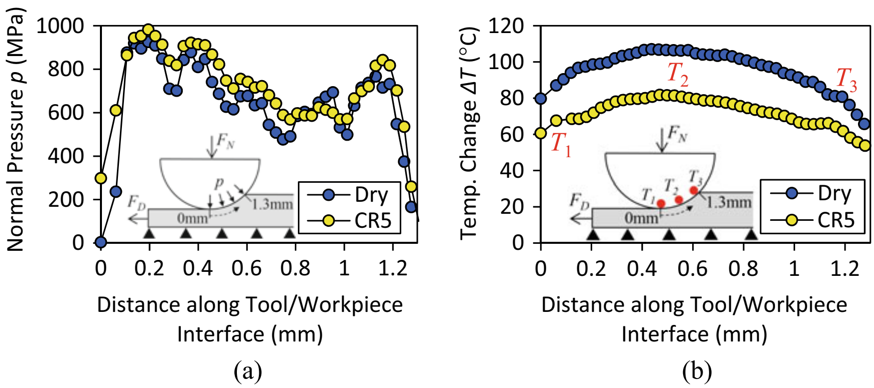


Fig. 8 Distributions of **a** contact pressure and **b** temperature along the tool/workpiece interface

3 Machining

Machining is important in almost all manufacturing processes. However, drawbacks of poor machinability are becoming prevalent in industry. This is especially pronounced when machining aerospace and automotive composite materials. The primary problems concerning machining in regard with such work materials are mostly associated with tool wear and also surface quality. Contributed by the generation of heat which occurs near the tool/workpiece sliding surfaces, many machining techniques have been developed so that the amount of heat generated can be controlled, for instance, the application of cutting fluid. Recent trends of environmental-friendly machining with the use of cryogenic cutting fluid are becoming popular. The cryogenic machining employed varied cryogen types like helium (LHe), liquid nitrogen (LN), ethane, argon, methane, and oxygen in reducing the cutting temperature (Shokrani et al. 2012). Due to this, researches have been conducted concerning the impacts of cryogenic application in various kinds of work materials, namely Inconel 718 (Courbon et al. 2013; Kaynak 2014; Wang and Rajurkar 2000), Ti-6Al-4V (Wang and Rajurkar 2000; Bermingham et al. 2011; Hong et al. 2001a, b; Strano et al. 2013; Yasa et al. 2012), various steels (Dhar et al. 2001; Paul and Chattopadhyay 1996; Venugopal et al. 2007; Pušavec et al. 2011; Rotella et al. 2012), shape memory alloys (Kaynak et al. 2011, 2013a, b), magnesium alloys (Pu 2012) and the rest of engineering materials (Wang and Rajurkar 1997), which showed positive improvements towards the machining outputs like the cutting temperature, cutting forces, surface quality, and tool wear. In drilling, two elements that are acknowledged in common to be hard in materials machining are Carbon Fibre Composite (CFC) and titanium (Ti) alloys. Therefore, it is highly desirable for techniques that can substitute conventional drilling as alternative in which drilling performance of such materials can be improved. A new alternative to replace the conventional way of drilling of CFC/Ti stacks with Ultrasonic Assisted Drilling (UAD) has demonstrated that the life of Tungsten Carbide (WC) drills has improved by 300%. Owing to titanium adhesion and flank wear reduction, reducing cutting temperatures is achievable as cutting tool vibration during drilling resulted in improved evacuation of the hot titanium chips from the cutting zone and leading to the cooling of cutting tool (Dahnel et al. 2015; Pecat and Brinksmeier 2014). In regard with burr formation upon drilling, the report observation stated that there was improved hole quality with less burr on aluminum alloy 1100 and Inconel 738-LC holes with the use of Ultrasonic Assisted Drilling (UAD) (Dahnel et al. 2015). This, however, requires ultrasonic amplitude of 4–10 μm and the frequency of 20–21 kHz (Chang and Bone 2005; Azarhoushang and Akbari 2007). While for CFC drilling, surface roughness and circularity of the drilled holes experienced 50% improvement with the aid of ultrasonic (Makhdum et al. 2014). The UAD techniques have shown positive influence to enhance tool wear resistance with remarkable cutback of thrust force and torque. This section reported studies on tribological composite in machining processes—cryogenic turning with composite coated tool (Raof et al. 2019) along with Ultrasonic Assisted Drilling (UAD) of CFC/Ti stacks (Dahnel et al. 2015, 2016;

Dahnel 2017). Comparisons were made between the investigated machining techniques and the conventional ones. The assessment of machinability was conducted for its thrust forces, surface integrity, tool wear, burr and delamination. Dominant types of tool wear were also studied.

3.1 Cryogenic Turning

AISI 4340 alloy steel that had gone through quenching and tempering, with the diameter of 100 mm and 317 HB hardness, was the material for the test. Figure 9 shows a typical lath-martensitic structure microstructure of the work material was examined before the turning experiment. A CNC lathe machine with a CVD TiCN/Al_2O_3 composite ceramic carbide insert was used to turn on the work material. Table 4 shows the listing for cutting parameters. For cryogenic flushing, a connection was made between a flexible hose and Liquid Nitrogen (LN) tank, and a copper pipe functioned as the nozzle pointing to the clearance face of the insert.

3.1.1 Effects of Cryogenic Turning Condition on Temperature, Tool Wear and Surface Integrity

The measured cutting temperatures occurring during turning in dry and cryogenic flushing are shown in Fig. 10. Cryogenic LN application during turning has managed to cut down the cutting temperature as much as 35–55% in comparison to dry turning, particularly when this was done at cutting speeds that were higher. Cryogenic

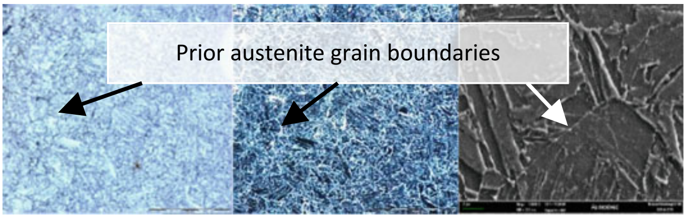


Fig. 9 Microstructure of the work materials before the turning experiment

Table 4 Test parameters in turning experiment

Parameters	Description
Cutting speed (m/min)	160, 200, 240
Feed rate (mm/rev)	0.3
Depth of cut (mm)	1.0
Coolant	Dry and cryogenic (LN)

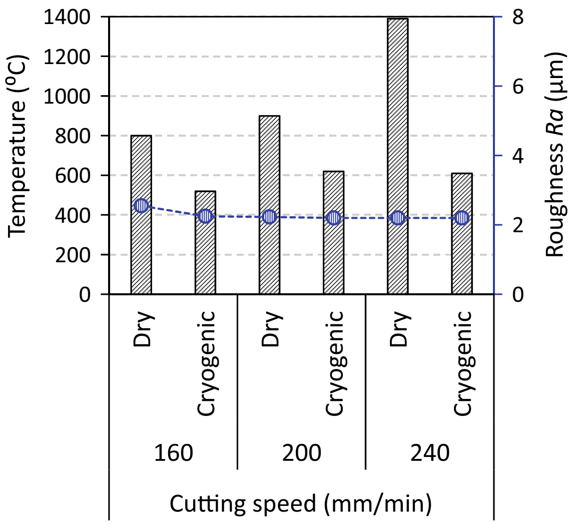


Fig. 10 Cutting temperature and Roughness *Ra* of the work materials (Kijima and Bay 2007; Holmberg et al. 2014)

machining has lower temperatures which is beneficial as machined surface amendments due to thermal activity can be reduced. Nevertheless, in terms of *Ra* values of the work material at distinct cutting speeds, there was not much apparent and significant difference observed in cryogenic turning. It was discovered that when using higher speeds, effective result was generated in producing cryogenic cooling effect that controlled the generation of heat caused by cutting speeds. This phenomenon is related to the formation of chip morphology that occurs during the cutting. When higher speeds are used, the chip will become curlier and thinner. Sudden cooling by cryogenic will harden the chips and improve their fragility. Thus, this will ease the LN to penetrate into the chip-tool interface, hence the reduction in cutting temperature.

In this research, the impact of cutting tool wear towards the roughness of machined surface was also examined. Figure 11 illustrates the readings of average surface roughness as a function of cutting tool condition. The measurement of *Ra* values occurred at flank wear, $V_B = 0$ µm (new tool), $V_B \geq 0.15$ µm (medium wear), and $V_B \geq 0.3$ µm (wear). Based on the observation, a few patterns of the graph relation were recorded between the roughness of surface and tool wear. Various conditions of machining resulted in better surface roughness when a worn tool was used in cutting. This might be explained by the efficient flattening of the tool nose due to increased worn flat on the tool flank (More et al. 2006), which in turn increasing the tool nose radius as in Fig. 12, hence a better quality of machined surface is produced. Using a worn tool at cutting speed of 240 m/min in cryogenic condition generated critical reduction in roughness value which might be due to the combination of higher speed and cryogenic application that improves surface roughness as in previous discussion.

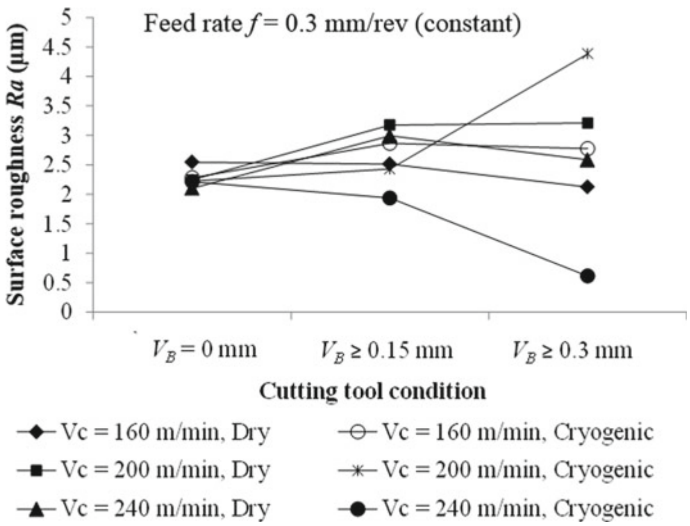


Fig. 11 Roughness *Ra* of AISI 4340 alloy steel surface with different cutting speeds under dry and cryogenic environment (f = 0.3 mm/rev)

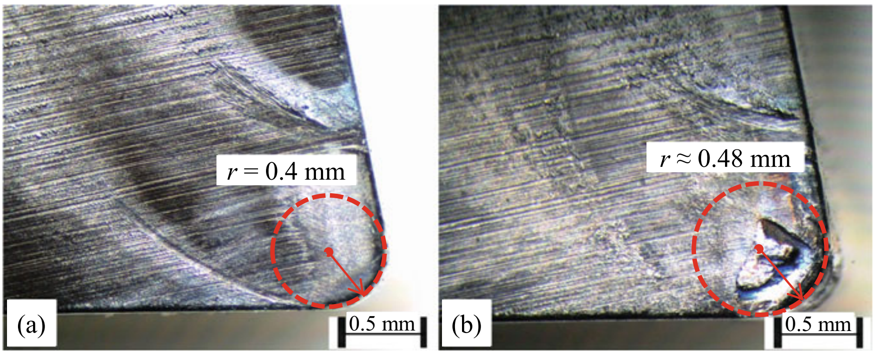


Fig. 12 Measurements of tool nose radius and surface condition of CVD TiCN/Al_2O_3 composite ceramic carbide insert **a** before and **b** after machining

The improved wear resistance of the CVD TiCN/Al_2O_3 composite ceramic as protective coating for the carbide insert is explicable by the examination of microstructure of the CVD TiCN/Al_2O_3 composite hard coating. Figure 12c shows the cross-section of TiCN/Al_2O_3 composite coating (Gassner et al. 2018). TiCN coating coupled with Alumina Oxide Al_2O_3 top layer were accumulated on cemented carbide insert. Due to its hardness and firmness which are high, the use of the TiCN/Al_2O_3 composite coated carbide insert exhibited less flank wear for the cryogenic turning. In applications involving elevated temperatures and shear stresses as in turning of steels, the Alumina Oxide Al_2O_3 top layer coupled with TiCN coating could enhance the cutting performance by increasing adhesion (Gassner et al. 2018), thereby improve tool life.

Meanwhile, several other machining conditions produced rougher machined surface when cutting using a worn tool. Increasing machining time leads to deterioration of tool sharpness and degradation of surface roughness (More et al. 2006). Apart from that, one factor that may contribute towards bad finishing surface is the work material adhesion between the tool edge and the tool flank face. When cutting was performed using a worn tool at the cutting speed of 200 m/min in cryogenic condition, it was found that the roughness value increased significantly. In this machining condition, the cutting tool used was found to have fracture wear on the tool flank face when observed closely. This might result in more deterioration of the machined surface as opposed to the rest of machining conditions.

3.1.2 Effect of Cryogenic Turning Condition on Metallurgical Structure of Near-Surface Region

In this study, the machining introduced two surface layers that have different characteristics: the refined grain layer (RL) and also the transition layer (TL), see Fig. 13. There are distinct attributes between the two layers; the mechanical features and chemical structure in comparison to bulk material. Many factors have been identified to influence the layers' properties and also thickness which are the temperature produced and the rate of heating–cooling during machining, original size of grain, and the original mechanical features that belong to the bulk material. As seen in Fig. 14, the increased hardness of the machined surface is greater, while lower hardness is marked with increasing profile depth.

A greater hardness value was observed for cryogenically machined surfaces as opposed to dry machined surfaces in all variations of speeds. The reason is the degradation of thermal softening effect and the strain hardening of the work which occur at low temperatures, resulting in higher density of refined carbide particles in cryogenically machined surfaces. This is closely associated to ultrafine white

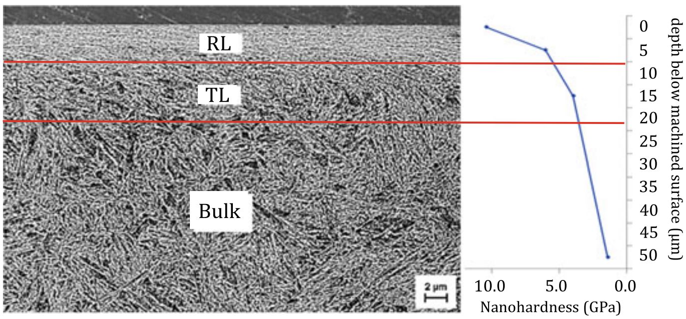


Fig. 13 Hardness distribution profile of the machined surface

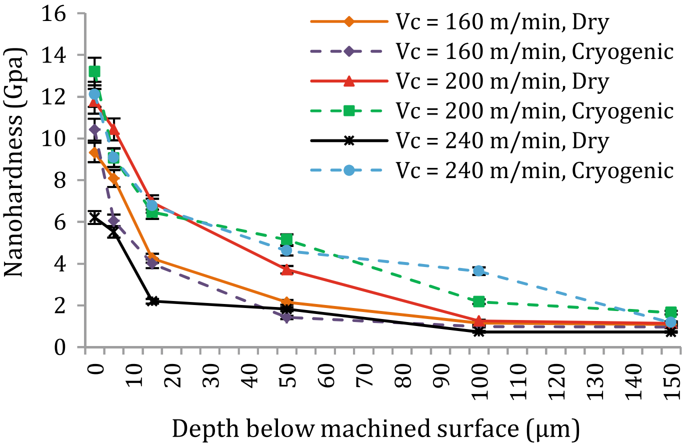


Fig. 14 Hardness distribution of machined surface (Holmberg et al. 2014)

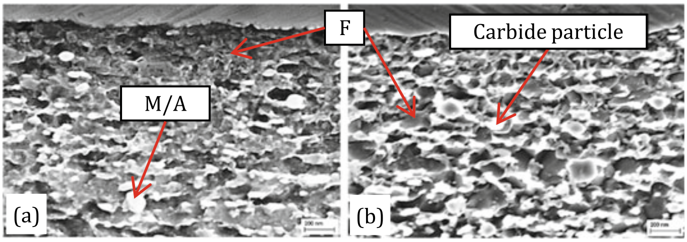


Fig. 15 Ultrafine particles of the machined surface in **a** dry, and **b** cryogenic cutting (160 m/min)

globular particles with a diameter smaller than 200 nm as noted in dry and cryogenic machining, see Fig. 15 for 50k× magnification of a Fe-SEM microstructure of machined cross-section. Significant heat builds up in dry turning has led to a high hardness characteristics of M/A island particles, Fig. 15a, and this has been an influential contributing factor in initiating cracks and brittle fractures. Alternatively, cryogenic turning is advantageous since it has shown positive impact in controlling the heat production below the austenitizing temperature. This, in turn, leads to enhancement towards carbide particles precipitation into martensite matrix, and encourages carbide particles purification with a more identical ultrafine white globular carbide particle distributions within the martensite matrix, see Fig. 15b, that has increased the hardness (Shokrani et al. 2013; Jawahir et al. 2016). This investigation has revealed that excessive heat caused by high cutting speed is undesirable. As a result, there will be thermal damage occurring at the machined surface and subsurface which affects the surface quality, increases tensile residual stresses, and reduces the dimensional accuracy that belongs to the work material.

3.2 *Ultrasonic Assisted Drilling (UAD)*

Titanium alloys and Carbon Fibre Composite (CFC) have been placed in a limelight in a lot of industries following the demands for materials of high performance, lightweight that keep increasing. It was in preference to drill CFCs using tungsten carbide cutting tools, with the cutting speed of 100–200 m/min and 0.01–0.05 mm/rev feed rates (Liu et al. 2012). Nevertheless, such materials drilling can possibly lead to stratification (CFC), formation of burr (titanium) and accelerated tool failure (Wang et al. 2014; Shyha et al. 2011). Therefore, new alternative to drill such difficult-to-machine materials like CFC/Ti stacks is desired. Ultrasonic Assisted Drilling (UAD) technique was proposed in this research. This includes a comprehensive evaluation on UAD tribological performance on CFC/Ti6Al4V stacks with regard to tool wear as well as tool life when three cutting speeds that are different and consistent feed rate are used instead of conventional drilling. UAD can be understood as a process of composite machining of which its cutting motion is such a superimpose of that of conventional drilling, having high frequency ultrasonic vibration in centre direction (Babitsky et al. 2007). In this study, drilling experiments were performed on aerospace materials—4 mm thick CFC (multidirectional (0°, 45°, 90°, 135°) carbon fibres with Bismaleimide (BMI) resin) and 4 mm thick titanium alloy Ti6Al4V. DMG Ultrasonic 65 Monoblock machine tool and 6.1 mm diameter tungsten carbide 2-flutes twist drills were used in the experimentation to compare between conventional drilling and UAD of CFC/Ti6Al4V stacks. The empirical setup for conventional drilling of CFC/Ti6Al4V stacks (with cutting fluid) and with ultrasonic using 0.05 mm/rev feed rate is shown in Fig. 16. Table 5 illustrates the cutting parameters.

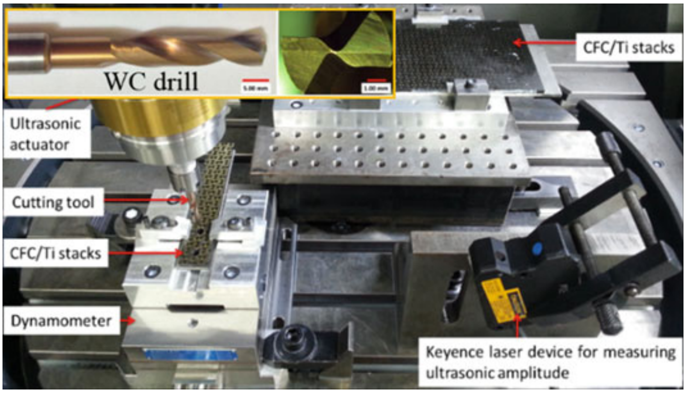


Fig. 16 Experimental setup for ultrasonic assisted drilling (UAD)

Table 5 Drilling parameters

Drilling experiment		Cutting speed (m/min)	Total no. of holes
1	Conventional	25	40
	UAD		
2	Conventional	50	80
	UAD		
3	Conventional	75	80
	UAD		

3.2.1 Effects of UAD Drilling Speed on Tool Wear and Surface Integrity

Figure 17 shows the comparison between the flank wear rate among the drills utilized in conventional drilling and of UAD with 25, 50 and 75 m/min cutting speeds. Based on the graph, the result of using UAD lowered the rate of tool wear and extended the tool life at all cutting speeds that were used. According to ISO 3685 standard, once the flank wear reaches 300 μm, that is when the tool life ends (Tool-life testing with single-point turning tools 1993). The observation shows that when CFC/Ti6Al4V stacks drilling was conducted, the characteristics of tool wear were the adhesion of titanium, edge chipping, along with dull cutting edges. Using 75 m/min cutting speed, conventional drilling showed failure of the cutting tool after 28 holes were being drilled, while UAD showed failure after 34 holes as the edge chipping and wear reached 300 μm. Meanwhile, when lower cutting speed of 50 m/min was used, it extended the tool life in which conventional drilling lasted with 62 holes drilled, and UAD with 80 holes. Therefore, in regard with tool life, the optimum cutting speed

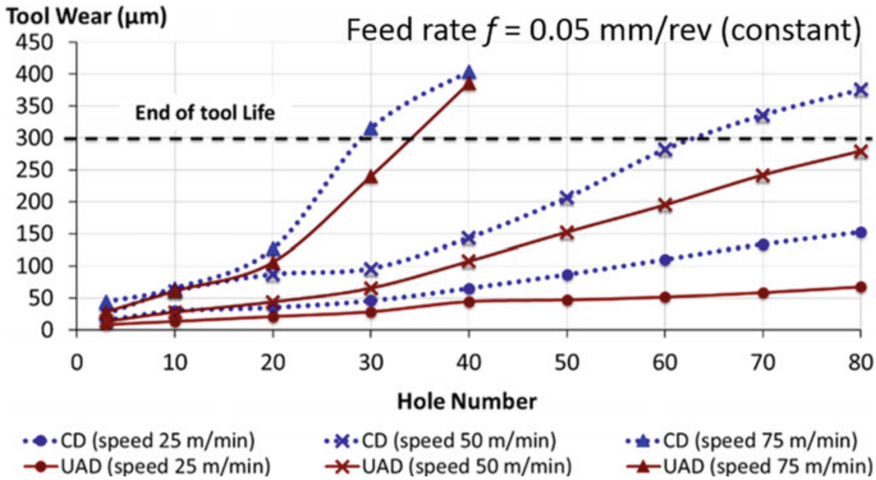


Fig. 17 Tool wear at different cutting speeds of 25, 50 and 75 m/min for UAD and conventional drilling of CFC/Ti6Al4V stacks

is 25 m/min as it showed the lowest tool wear rate, and UAD is proven to provide tool life which is longer compared to conventional drilling, see Fig. 17.

As opposed to drilling conventionally, UAD resulted in lower tool wear which reduced the thrust forces (for both CFC and titanium) that is desirable to improve the hole quality. Figures 18 and 19 show the result in UAD using 25 m/min cutting speed which led to 10–42 N lower thrust forces for CFC, while 36–78 N lower thrust forces for titanium alloy, as opposed to conventional drilling. Meanwhile, when cutting

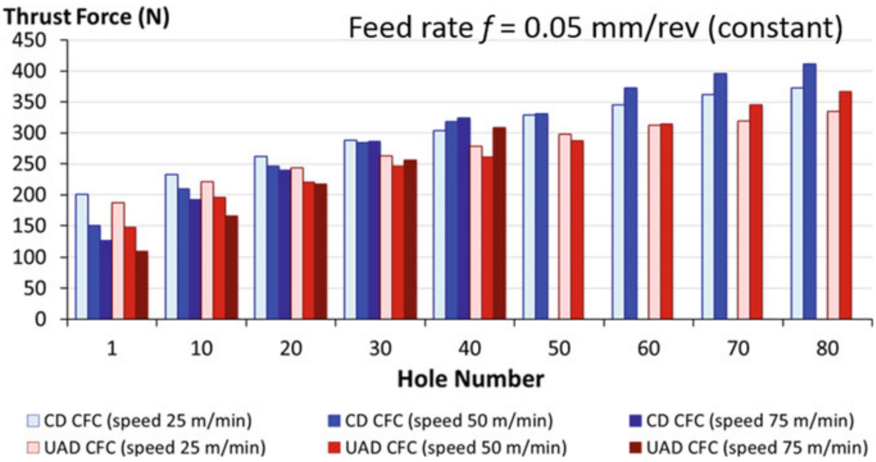


Fig. 18 Thrust forces at different cutting speeds of 25, 50 and 75 m/min for conventional drilling (CD) and UAD of CFC stacks

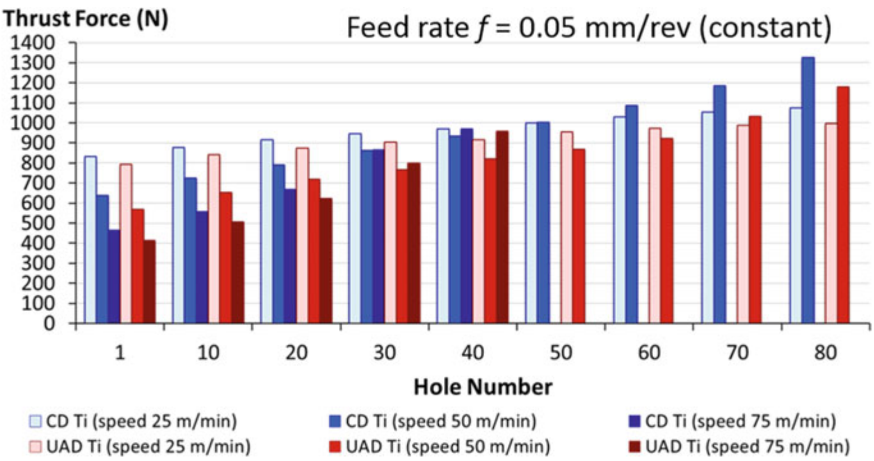


Fig. 19 Thrust forces at different cutting speeds of 25, 50 and 75 m/min for conventional drilling (CD) and UAD of Ti6Al4V stacks

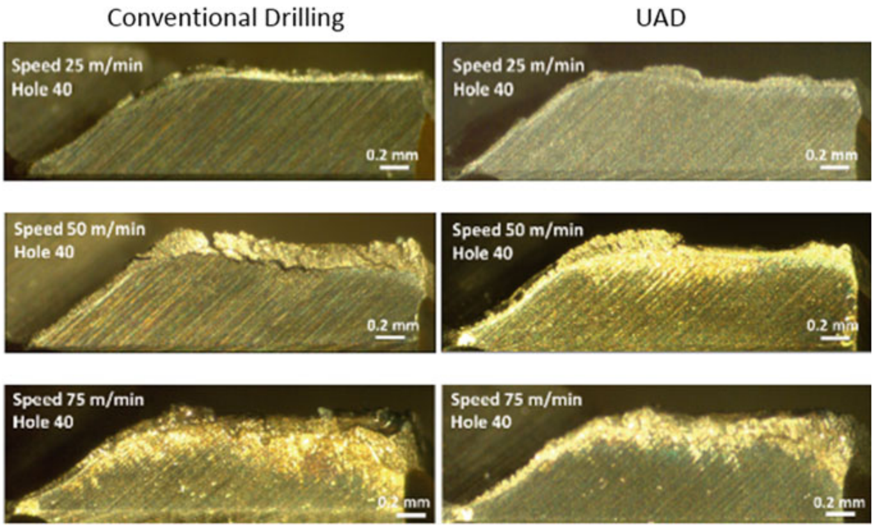


Fig. 20 Tool wear at different cutting speed of 25, 50 and 75 m/min for UAD and conventional drilling of CFC/Ti6Al4V stacks (images were taken after drilling 40 holes)

speed was changed to 50 m/min in UAD, lower thrust force was generated by 3–58 N for CFC, and 70–164 N for titanium alloy compared to conventional drilling. When the cutting speed was raised to 75 m/min, the outcome was similar in which the thrust forces were lower in UAD (by 15–40 N for CFC; by 13–66 N for titanium) in comparison with conventional drilling.

Figure 20 exhibits the cutting edges state after 40 holes were drilled in CFC/Ti6Al4V stacks with 25, 50 and 75 m/min cutting speeds. As observed, using higher cutting speeds led to more adhesion of titanium, which occurred most probably as a result of higher cutting temperatures being used. Despite there was no measurement of cutting temperatures in this study, Li and Shih's work (Li and Shih 2007) in regard with drilling of titanium-only had established that increasing the cutting speed from 24 to 73 m/min raised the cutting temperature from 480 to 1060 °C.

Titanium is a material that is reactive and the stimulation of chemical reaction between titanium and the material of cutting tool will occur when the temperature during drilling increases (Hosseini and Kishawy 2014). During the drilling process, instead of sliding along the cutting edges, there were separation and adhesion on the cutting edges for part of the titanium chip that was in contact with the tool. When there was removal of titanium, chipping of the cutting edges happened and part of the tool material was also taken away. In addition, in regard with hole quality, it was not desired for the adhered material upon the cutting edges as it is unstable and has uneven surface which causes the dimension to be inaccurate and the machined part to have poor surface finishing (Dahnel et al. 2015). Based on the observation as in Fig. 20, during UAD, there was fewer titanium adhesion on the cutting edges in comparison with conventional drilling; caused by the vibration of tool that partly prevented the titanium chip from continual connection with the cutting edge. In Fig. 21, the new cutting edge state is shown, while the state of chipped cutting edge is shown in Fig. 22, in which irregular and coarse tungsten carbide grains were disclosed. As a consequence, such conditions caused the cutting edges to be more prone towards bigger tool fracture during drilling, and resulted in rapid tool failure.

With 75 m/min as the cutting speed used for drilling, the main instrument for tool wear is edge chipping resulting from removal of adhered titanium. Conventional drilling had more edge chipping as opposed to UAD. However, drilling with lower cutting speed of 25 m/min resulted in no edge chipping at all until 80 holes for both conventional drilling and with ultrasonic; the drills were also wearing out by galling instrument. Recurrent cutting is the reason that correlates to slower progression of tool wear in UAD. It was a challenge to determine the wear after 40 holes were drilled in the stacks with the cutting speeds of 50 and 75 m/min resulting from compelling titanium amount that covered the majority of the cutting edges. Figure 20 shows the images taken of the cutting edges following the drills exit through titanium layer in the stacks. Therefore, after 40 holes were drilled, for clear cutting edges and graph

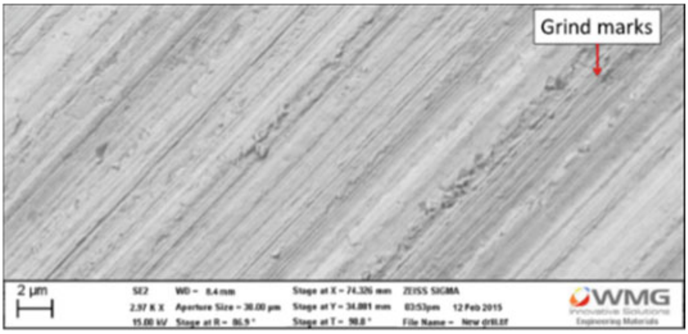


Fig. 21 Cutting edge on the tool surface with remarkable grind marks due to tool sharpening

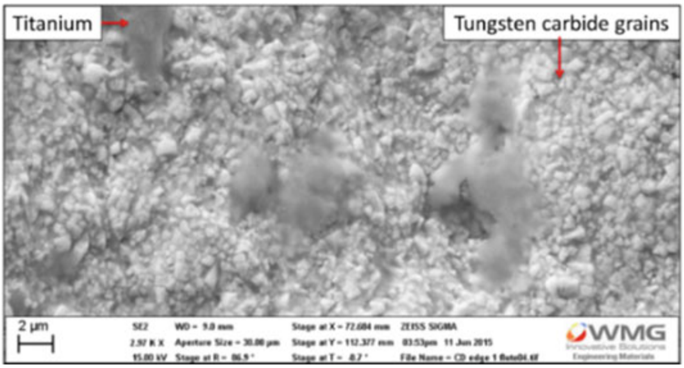


Fig. 22 Chipped cutting edge of tungsten carbide tool

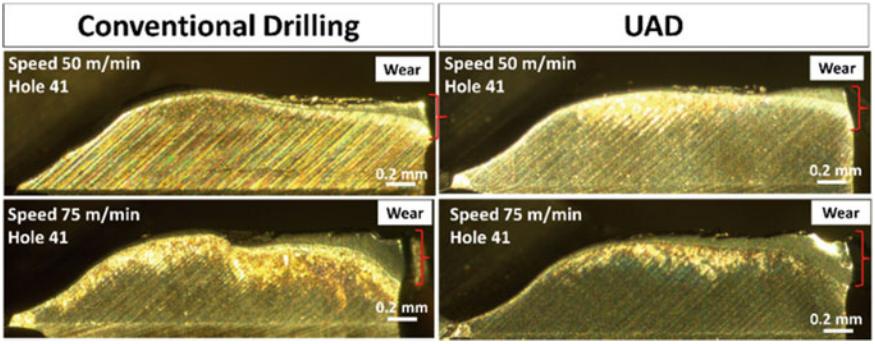


Fig. 23 Tool wear images just right after CFC drilling and before drilling titanium

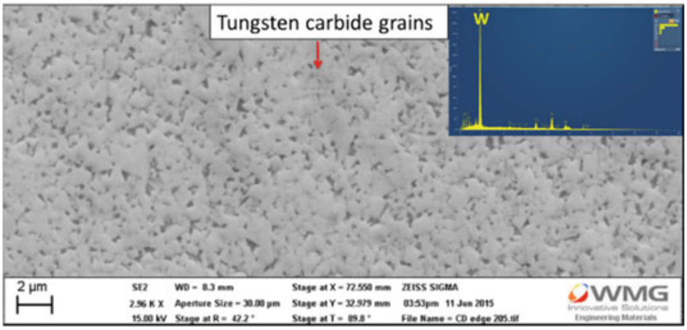


Fig. 24 Abrasive wear on the tungsten carbide tool surface

plotting of the tool wear rate as in Fig. 17, the measurement of the wear was taken after CFC plate was drilled and before titanium plate was drilled as in Fig. 23. The tungsten carbide grains underwent grounding and smoothening by rough carbon fibres as shown in Fig. 24. The observation was done on the edge rounding, in which abrasive tool wear characteristic was evident, as a result of abrasive carbon fibres that rub against the cutting edges.

3.2.2 Effects of UAD Machining Condition on CFC Delamination and Ti-Alloy Exit Burr

An analysis was conducted on delamination factor that is a ratio of CFC delamination extent at the hole entrance to the hole diameter. Figure 25a, b demonstrate the comparison between conventional drilling and UAD, in terms of CFC delamination at the hole entrance after 40 holes were drilled. The result showed that for UAD, the delamination length at the hole entry for the 40th hole was 3 mm, while for conventional drilling was 1.5 μm; hence UAD produced further length of hole

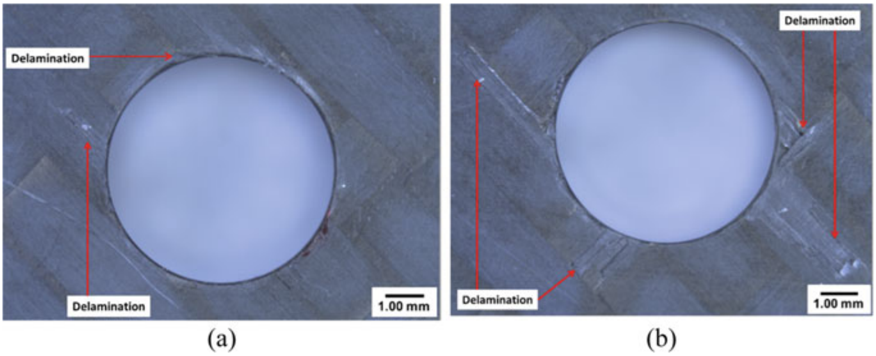


Fig. 25 CFC entry delamination at hole 40 produced by **a** conventional drilling, and **b** UAD

delamination. Moreover, there were more CFC delamination during UAD because of the cutting tool which experienced more vibration energy effects. When the drilling penetrated Ti6Al4V, the back and forth oscillation of the drill flutes against CFC surface, combining with tool wear and high thrust forces, exerted more pressure on the CFC layers which then pulled the layers, hence causing the CFC to separate or delaminate.

Figure 26a, b illustrate the burr size comparison between conventional drilling and UAD, around the 40th hole. It was found that the burr produced at the 40th hole after drilled conventionally had 111 μm of thickness and 162 μm height, each. Meanwhile, the burr of the 40th hole drilled by UAD had 68 μm of thickness and 128 μm height which meant, the burr thickness was smaller by 39% and its height was smaller by 21%. Minimization or elimination of the burr formation is highly desired in industry especially in securing assembly of parts. UAD application in

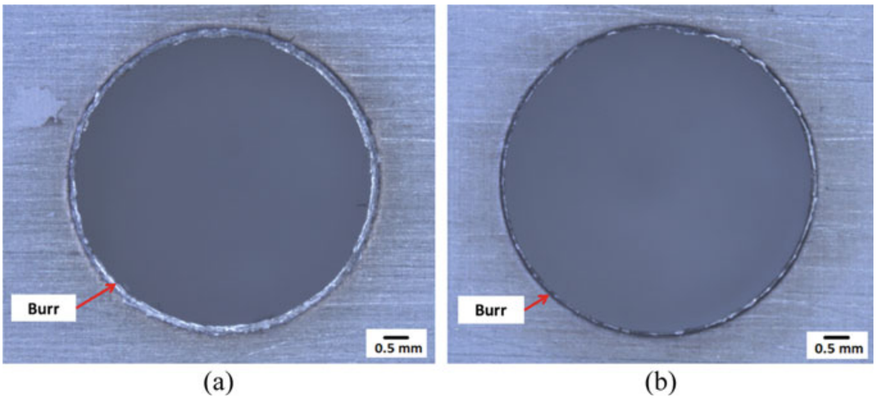


Fig. 26 Titanium exit burr at hole 40 produced by **a** conventional drilling, and **b** UAD

this study has shown its potentials for hole production with fewer or smaller burr as compared to conventional drilling.

4 Concluding Remarks and Future Perspective

The chapter presents a comprehensive investigation on tribological behaviors of tools that were involved in manufacturing processes of various engineering materials. In the field of metal stamping, the use of multilayer DLC composite coating on a tool has shown to be effective to prolong the tool life. This could relate with high hardness, high young modulus and also low residual stress of DLC composite, which lead to improved adhesion strength amidst the DLC and tool substrate. For machining application, alternative techniques which involve cryogenic cutting fluid and ultrasonic assisted cutting tool are recommended in order to enhance the tool life and machined surface quality. The application of Liquid Nitrogen (LN) as cryogenic cutting fluid to turn AISI 4340 alloy steel has demonstrated improvement in reducing cutting temperature by 35–55%. This could lead to a reduction in both tool wear and the alteration of machined surface. Whereas, the utilization of ultrasonic assisted cutting tool for drilling Carbon Fibre Composite and Titanium stacks has prolonged the tool life and enhanced the hole quality as a result of reduction in titanium adhesion, tool wear and improved titanium chip evacuation. The alternative techniques proposed in this chapter are seen as feasible solutions to environmental-friendly manufacturing operations. On another note, more scientific research are needed to develop advanced composite hard coatings and environmentally benign manufacturing techniques in order to realize the requirements of industry to achieve sustainable manufacturing environments, higher productivity and lower production costs. For metal forming, the development of advanced composite hard coatings, ie. nano-multilayer composite coatings, with super hardness, good thermal stability, high oxidation resistance and high wear resistance are a necessity for lubricant-free formation. In machining operations, the cryogenic cooling coupled with ultrasonic assisted machining technique could be a feasible solution in overcoming severe tribological loads at the tool/workpiece interface, and is a future challenge in making manufacturing attractive.

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