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Machining of carbon fibre: optical surface damage characterisation and tool wear study

N.Duboust[a*], D.Melis[b], C.Pinna[a], H.Ghadbeigi[a], A.Collis[c], S.Ayvar-Soberanis[b], K.Kerrigan[b]

[a] *Department of Mechanical Engineering, University of Sheffield, UK*
[b] *AMRC with Boeing, Advanced Manufacturing Park, Wallis Way, Catcliffe, Rotherham, S60 5TZ*
[c] *Rolls-Royce, 62 Buckingham Gate, London,UK*

* Corresponding author. *E-mail address:* n.duboust@sheffield.ac.uk

Abstract

Better control of fibre composites machining requires reliable surface roughness and damage characterisation measurements. The performance and tool wear rate of three different state of the art CVD and PCD cutting tools manufactured for carbon fibre machining were compared in wet and dry conditions. Machined surfaces were characterised by areal surface roughness parameters using a novel focus variation optical system. The tool wear and cutting forces were recorded up to 50 linear meters of machining or until tool failure. Results showed that wet machining conditions reduced tool failure; and that the CVD tool in wet conditions machined the greatest distance of 26m before reaching an average roughness limit of 3µm. The tool type was found to be the most significant parameter on the surface quality. The optical system was found to be a useful tool for measuring roughness of individual plies and characterising machining induced surface damage.

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Keywords: carbon fibre; surface analysis; surface roughness; composite machining; edge trimming; tool wear; PCD; CVD

1. Introduction

In machining of composite materials, reducing damage and reliable surface roughness characterization is necessary. The fibres in CFRP are highly abrasive and can lead to rapid tool wear. Also, surface defects including delamination, fibre pull-out, un-cut fibres and matrix burning can be a problematic. Studies have shown that standard cutting tools like; high speed steel, cemented carbide and existing nitrogen and carbon based coatings have insufficient wear resistance for composite machining [1,2]. It has also been shown that they produced a surface with poor quality and damage [3,4]. The superior wear resistance of polycrystalline diamond (PCD) and diamond coated tools has led to their increasing use in composite machining. Due to their high hardness these tools can maintain a sharp cutting edge and reduce surface defects.

Typically, roughness measurements made with a stylus have been used to identify machining damage, but previous research shows that this is unreliable for composite surfaces [5,6]. The variation in roughness reading can be dependent upon measurement position; because the stylus path may pass over multiple fibre orientations, or deviate due to protruding fibres [6]. It has been shown that fibre orientation will affect the cutting mechanism and surface roughness [7,8,9]. The motivation for this work was therefore to research machining damage and tool wear rate using new diamond coated and PCD cutting tools. An optical focus variation system was used to characterise surface roughness according to ISO 4287. The surface roughness was analyzed using this new non-contact optical system to take areal parameters and it is believed this method has some advantages over tactile methods.

2. Experiment

In this research, machining experiments by edge trimming were conducted with three different milling tools. The effects

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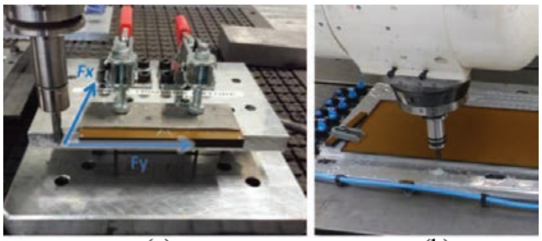
of tool wear, machining forces and surface quality under wet and dry machining conditions were compared. In the dry conditions air extraction was used to remove cut particles. In the wet machining, flood coolant and a filtration system was used- which can achieve 1μm particle filtration level. The tools were worn by machining until tool failure or a maximum of 54 linear meters. Fig. 1 shows the dynamometer used for cutting force measurement and the composite panel and vacuum fixture. The carbon fibre workpiece is 10mm thick made of an M21 epoxy resin and T700 fibre type.



(a) (b)

Fig. 1. (a) Dyno and machining force direction
(b) Wear panels and vacuum fixture- edge trimming

Two PCD and one diamond coated tool were compared- shown in Fig. 2. These will be referred to as tool (a), (b) and (c). Tool (b) is a solid carbide diamond coated tool, with nanocrystaline CVD coating. It is a burr style tool with a segmented helix and 12 flutes. Multiple cutting teeth are created when the primary helix is intersected. There are two cutting edges on each tooth, and a third edge which allows material removal. Tools (a) and (c) are both PCD with three flutes. The PCD Tool (a) has variable helix angle flutes with one negative one positive and one zero to minimise delamination. Tool (c) has 3 positive helix angle flutes. The cutting conditions and tool machining distance reached before catastrophic tool failure are shown in Table 1, and each test was repeated once. Cutting feeds and speeds were chosen according to manufacturer's recommended cutting parameters, and a similar feed per tooth was used across the three tools. In industry machining time needs to be optimised while maintaining surface quality. Therefore, a relatively high feed was chosen to challenge the capability of the milling tools.

Table 1. Machining parameters and meters Machined by tool before failure.

	Feed Rate, Cutting Speed and Feed per Tooth	Meters Machined	Sa at 30m Machined	Distance machined to reach minimum Sa of 3μm
Tool (a) PCD (DRY)	1.2m/min, 10000 RPM, feed/tooth- 0.04mm	**54m**	**5.99**	**7.4m**
Tool (b) CVD (DRY)	6.1m/min, 12,739 RPM, feed/tooth- 0.04mm	**22m** (Failure)	**22m** (**Failure**)	**0.16m**
Tool (c) PCD (DRY)	1.5m/min, 10,000 RPM, feed/tooth- 0.05mm	**30m** (Failure)	**5.33**	**0.16m**
Tool (a) PCD (WET)	1.2m/min, 10000 RPM, feed/tooth- 0.04mm	**54m**	**6.41**	**7.4m**
Tool (b) CVD (WET)	6.1m/min, 12,739 RPM, feed/tooth- 0.04mm	**54m**	**3.13**	**26.2m**
Tool (c) PCD (WET)	1.5m/min, 10,000 RPM, feed/tooth- 0.05mm	**40m**	**5.64**	**7.4m**

Optical microscope images were used in order to take tool edge wear measurements. These were performed by setting the tool in a reference position. The increase in tool edge wear was measured using edge recessions between a new and set point, where the initial wear was taken as zero for an unworn tool. These measurements were verified with edge radius

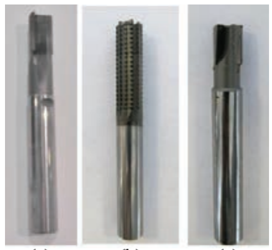

(a) (b) (c)

Fig. 2. Cutting tools used in the experiment.
(a) PCD Tool- 3 flutes, 9.53mm Diameter
(b) CVD Burr Tool- 12 flutes, 10mm Diameter
(c) PCD- 3 flutes, 10mm Diameter

measurements using the Alicona optical system which can take 3D scans of the cutting edge. The edge radius measurements were found to show a similar trend with machining distance to the edge recession measurements. It was chosen to use the results from optical microscope because the edge radius of the complex CVD burr tool geometry could not be reliably measured using the optical system. The cutting forces were measured by Kistler dynamometer in the feed and radial directions. F_y and F_x are in the direction shown in Fig. 1(a), with F_y in the feed direction and F_x perpendicular to the feed. For the force measurements a sampling frequency of 20,000 Hz was used to convert analogue to digital for the charge signal taken from dynamometer. The cutting forces were averaged across the cutting period removing a section at the beginning and end of cut. Surface roughness measurements were made using an optical system manufactured by Alicona [10]. This instrument can generate 3D surface images and works by focus variation. Roughness measurements were taken in three positions on the sample with a cut-off wavelength of 800μm; a vertical resolution of 100nm and lateral resolution of 2μm. A sample 2mm wide by 10mm high was used. Roughness parameters S_a, and Skewness and Kurtosis were taken. The laminate has a quasi-isotropic stacking sequence with fibre orientations of 0, 45, 90 and 135 degrees. In order to see the effects of fibre orientation on surface damage, the average roughness was measured across the individual fibre orientations. The stacking sequence of each ply of the layup was known; therefore each fibre orientation could be measured by using the top and centre plies as a reference. The optical system allows individual laminate layers to be viewed and then selected for roughness measurement as shown in Fig. 3.

3. Results

Optical surface scans in Fig. 4. show the machined surface for the PCD tool (Fig. 2(a)), in wet conditions. Fig. 4(a) shows the machined surface profile with a new tool, while Fig. 4(b) shows the surface after the tool has machined 54m of material. It can be seen that there is a variation in surface damage and structure across the different layers of the laminate which have different fibre orientations, and that the surface appears rougher in Fig. 4(b) with more damage on the top and bottom plies. Fig. 5. shows the average surface roughness (S_a) as a function of meters machined in wet and dry conditions. It is seen that there is an increase in roughness as tool wear increases with meters machined, across each of the tool conditions. The PCD tool (a) reached the maximum of 54m of machining in both the wet and dry conditions. While, the CVD tool (b) and PCD tool (c) both failed catastrophically in the