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Duboust, N. orcid.org/0000-0001-7960-0196, Ghadbeigi, H. orcid.org/0000-0001-6507-2353, Pinna, C. orcid.org/0000-0002-9079-1381 et al. (4 more authors) (2016) An optical method for measuring surface roughness of machined Carbon Fibre Reinforced Plastic composites. Journal of Composite Materials. ISSN 0021-9983

https://doi.org/10.1177/0021998316644849

Article

An optical method for measuring surface roughness of machined carbon fibre reinforced plastic composites

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Abstract

Characterization of the damage induced by machining of fibre reinforced composites is usually performed by measuring surface roughness. Contact based surface profilometers are the most used equipment in industry; however it has been found that there are performance limitations which may result when used to measure machined heterogeneous composite surfaces. In this research, surface roughness is characterised using a commercial non-contact optical method, and compared with a conventional stylus profilometer. Unidirectional and multidirectional carbon fibre laminates were edge trimmed and slot milled. The variation in surface roughness was compared using different tool types, fibre orientations and cutting parameters. Surface damage and cutting mechanisms were assessed by using scanning electron microscope (SEM) images and the suitability of roughness parameters were also analysed including: Sa, skewness and kurtosis. Using the optical system allowed accurate roughness calculation of individual plies on a multidirectional laminate with different fibre orientations. The research has also shown that the optical system, including the use of areal roughness parameters, can increase accuracy of roughness values extracted from machined fibrous composite surfaces and is less sensitive to measurement position than the stylus.

Key words

Carbon fibre, composite machining, edge trimming, surface roughness, milling, surface defects, surface inspection, surface integrity

Introduction

Surface roughness measurement and damage characterisation of composite materials are necessary after machining in order to assess surface quality. However, accurate and reliable surface roughness measurement of composite materials can be challenging because of the non-homogeneous structure of composites and the variation in damage. Ramulu et al. [1], found difficulty while measuring parallel to the fibre direction with a stylus, this was because the stylus path may span over a few plies or pass over multiple fibre orientations.

Research has shown that the cutting mechanism and the surface roughness can vary depending upon fibre orientation and machining direction [2],[3],[4] and [5]. Wang et al. [5], reported that the surface damage and roughness on each fibre orientation of a multidirectional laminate was different. However, they were not able to reliably characterise roughness of each individual layer. Azmi et al. [6], reported that the Ra values may not always reflect the surface qualities of machined fibrous composite materials. Two problems were raised which relate to stylus-based roughness quantification: i) the presence of fibres on the machined surface can affect the movement of the stylus tip; and ii) that variation in the roughness reading is very dependent upon measurement position relative to ply configuration.

During machining the surface quality and/or integrity can be affected by multiple factors including: tool geometry and wear; workpiece material properties; workpiece manufacturing process, machine vibration and fixture rigidity [7]. In order to assess surface quality, surface texture measurement is often used and roughness parameters are calculated [1]. A high surface roughness height parameter value is often an indicator of poor machining parameters, or a high level of tool wear. This can also lead to an increased likelihood of other critical defects including un-cut fibres, fibre pull-out or delamination. Haddad et al. [8], has demonstrated that various damage types, which are characteristics of a machined composite surface, can be correlated to mechanical performance. It is therefore important to be able to accurately quantify surface roughness to achieve an understanding of machining induced surface defects. This in turn, allows for accurate quantification of the effects of these defects on the in-service performance of components.

Composites can suffer from a number of different types of damage due to the machining process including; fibre pull-out, inter-ply delamination, matrix cracking, matrix burning, un-cut fibres and fibre-matrix de-bonding [3]. The damage can affect the fatigue life and strength of a component and therefore should be represented reliably by a surface damage parameter. Haddad et al. [8] investigated the effects on fatigue life and mechanical properties due to surface quality. Machining by water jet, abrasive diamond cutter and a standard burr tool were compared using contact and non-contact texture measurement methods. It was shown that the surface roughness and type of machining process had a strong effect on mechanical performance for a fibre composite. The authors found that an increase in the average surface roughness of samples caused a decrease in the inter-laminar shear strength and compressive strength. However, the failure stress of the burr tool machined samples was less than that of the water jet, even when specimens had a similar Ra. Different machining processes could therefore result in the same value for surface roughness parameter Ra, even where different machining induced surface damage and mechanical properties were reported.

Research has also shown that the machining parameters feed rate and cutting speed will have a strong influence on the surface quality [6],[9],[10] and [11]. Azmi et al. [6], looked at the machinability of glass fibre by end milling with respect to surface roughness, tool life and machining forces. Increasing feed rate had the most dominant effect on increasing surface roughness, and was said to increase the uncut chip thickness. They found that increasing the spindle speed was shown to generally decrease the surface roughness.

U.C Nwaogu et al. [12] compared tactile and focus variation optical device for the texture measurement of casting surfaces, using areal and profile parameters. It was found that the areal (Sa) parameters had less variation in measurement than the profile parameters (Ra). See [13], for a description of areal and profile texture parameters. The Ra parameter is the arithmetic mean roughness and gives the centre line average or the deviation of the surface profile from the centre. The absolute value of the peak or valley is used, thus Ra does not distinguish between peaks or troughs. Similarly, the Sa parameter is described as the arithmetic mean of the absolute of the ordinary values over a definition area. The authors compared the Sa parameter from the focus variation system and the Ra from stylus measurement and found an agreement. It was recommended that the areal parameters (Sa) were more useful in measuring the surface of castings due to better repeatability and a more substantial surface section being measured. The similarity in terms of non-homogeneity and unreliability of measurement between composite and cast surfaces indicates that the Sa parameter has good potential for application in composite surface roughness quantification.

Ghidossi et al. [14] also looked at the effect of machining parameters on roughness and failure stresses in edge trimming of glass fibre reinforced plastic and carbon fibre reinforced plastic

(CFRP). It was found that increasing the cutting speed reduced the surface roughness. However a surprising result was found, that the lowest failure stresses were seen on specimens machined at the highest cutting speed. Therefore the surfaces with the highest Ra did not necessarily have the most likely failure, and the Ra parameter did not give a full indication of damage.

Another relevant issue is whether the surface roughness parameter - (Ra)-, alone can give an accurate representation of the damage from machining, or whether other surface roughness parameters such as maximum peak to valley height (Rt), skewness (Rsk) and kurtosis (Rku) also need to be considered. Herring et al. [15], studied the effect of manufacturing method on the surface texture of CFRP mould facing surfaces using a number of profile parameters recorded from tactile measurement device. The parameters identified in this investigation were Ra, Rt, skewness and kurtosis. The Skewness is a measure of the symmetry of the height distribution, and gives information about the amount of hills or valleys on the surface (Figure 1). Rku, demonstrated in Figure 1, explains the distribution sharpness and highlights whether the surface profile has peaks and valleys which are either steep or rounded. Their investigation indicated that the roughness parameters studied were capable of distinguishing the surfaces generated by different manufacturing techniques. However, Rt was more sensitive to individual scratches or particles on the surface. Interestingly the authors state that at minimum Ra, Rsk and Rku should be calculated to achieve a useful understanding of a composite surface.

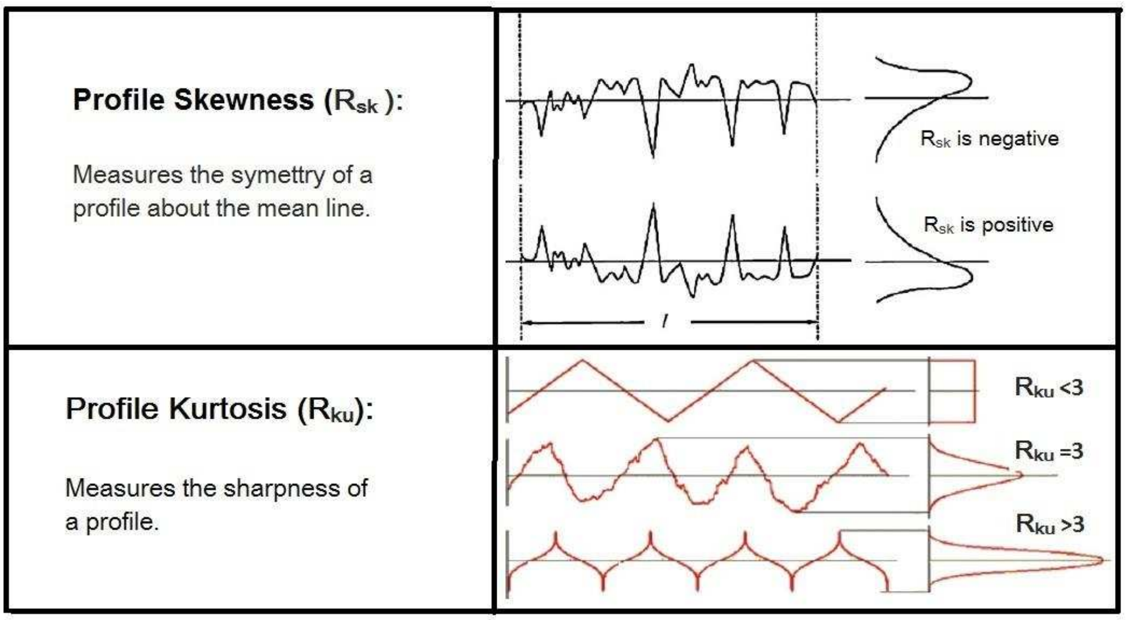


Figure 1.
Explanation of Skewness and Kurtosis surface profile parameters. Adapted from [15].

The literature has highlighted the potential problems with the use of a stylus for composite roughness quantification for the measurement of individual fibre orientations and overall layup of multidirectional laminate. In addition, the need for roughness parameters other than Ra has been identified. Therefore, the motivation for this work is to compare the advantages of roughness measurement of machined composite surfaces made using the new optical system, with a stylus profilometer. Following this there will be an assessment of the damage produced by an edge trimming experiment.

Experimental procedure

In the present study multidirectional and unidirectional CFRP laminates were machined by full slot-milling and edge trimming, respectively. The two tests are included in separate experiment and discussion sections. The surface quality was assessed using the non-contact optical method and with the stylus profilometer- in order to compare the advantages of each system.

Optical system for texture measurements

Typically profilometers are the most widely used equipment for assessing surface quality of components, by measuring surface texture and calculating the Ra roughness parameter. The profilometer works by trailing a diamond tipped stylus in a straight line along the specimen. A transducer then detects small deviations in profile height. In this study a stylus was compared with the commercial focus variation optical system manufactured by Alicona. The optical system is called an Infinite Focus SL shown in Figure 2, -where a schematic diagram is also illustrated.

The optical system can create three dimensional surface images which capture colour and topographical information, and used to analyse form and roughness parameters. It can also be used to find areal surface roughness parameters such as Sa. The optical system uses focus-variation of an optic, taking multiple images at varying vertical distances and using optical sharpness to create a full high resolution 3D surface image. R. Danzl et al. [16] and [17], details the system operation and demonstrates its capability to achieve similar results to a calibrated stylus device using a standard roughness specimen. This system has not been applied to the characterization of machined fibrous composite surfaces in any known literature.

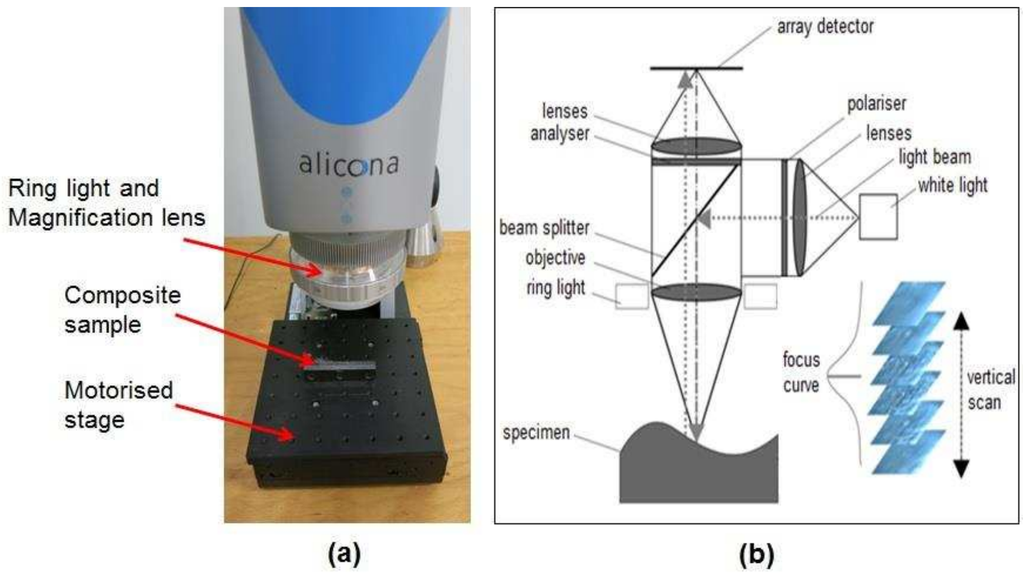
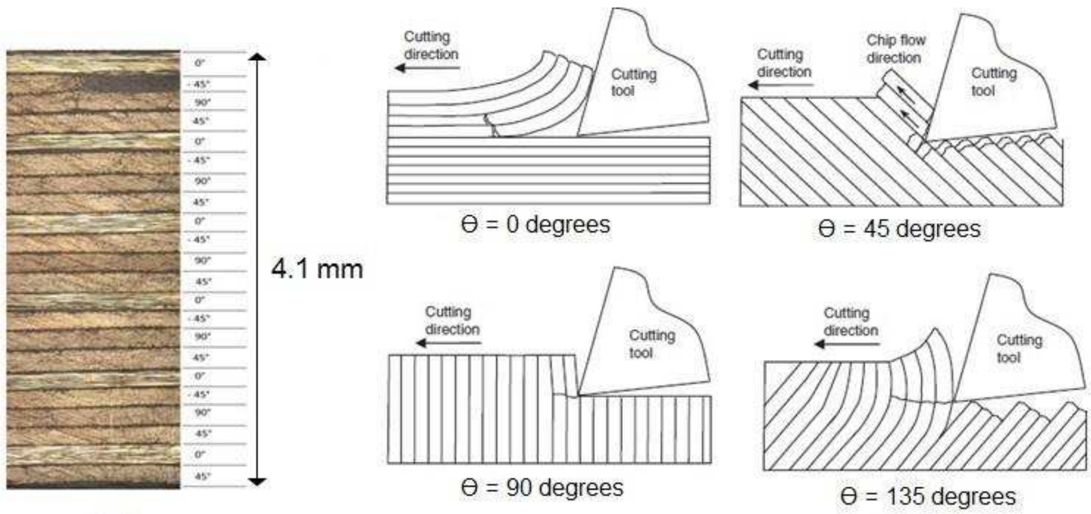


Figure 2.
(a) Optical focus variation surface measurement instrument (Alicona), with machined CFRP

sample.
(b) Schematic diagram of optical system. [16]

A multidirectional laminate made of carbon fibre in a 0/45/90/-45 stacking sequence was slot milled in this experiment using a CMS Ares 5-axis Machine Tool. The composite was manufactured from lay-up of pre-preg and autoclave cured. The laminate had a thickness of 4.1 mm and 22 plies in total, shown in Figure 3a. The fibre was of type T700GC and the matrix was an epoxy resin of type Hexply M21. In Figure 3b the fibre orientation definition is explained, and the relation between cutting direction of the tool and fibre axis is shown. The composite was slot milled with a 25 mm diameter tool holder and polycrystalline diamond (PCD) tipped insert as shown in Figure 4. Table 1 describes the parameters of the tool holder and insert used. PCD inserts were used due to their good surface quality performance and an excellent resistance to wear. The feed rate and cutting speed were both varied at four different levels and each test was repeated once to give a total of 32 tests as per Table 2. The cuts were performed with full tool holder diameter width of cut, i.e. ae= 25 mm, and axial depth of cut of ap= 4.1 mm. A 52 mm length of cut was used. All of the texture measurements were taken from the conventional side of the slot in each test. It is know that conventional or climb milling on either side of the slot result in a different cutting mechanism and therefore surface qualities. In order to be consistent all of the texture measurements were taken from the intended machined surface which would be left on the part- which was in conventional milling.



(a) (b)

Figure 3.

Multidirectional Laminate.

(a) Composite Stacking Sequence (SEM).

(b) Fibre orientation in relation to cutting direction. [3]

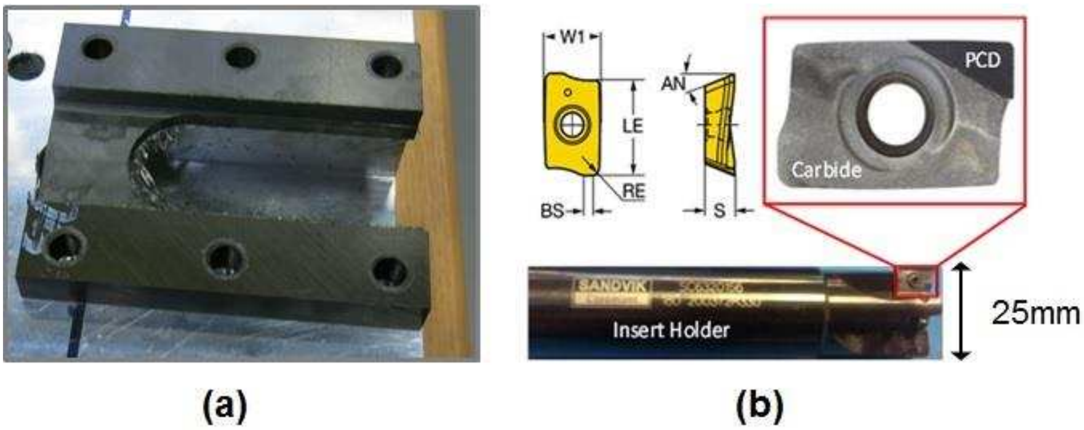


Figure 4.

(a) Multidirectional CFRP with milled slot and fixture.

(b) PCD insert with tool holder.

Table 1.

Insert and Tool Holder parameters.

Insert Holder	Make	Sandvik Coromant
	Serial no.	SC6320156
	Helix Angle	0°
	No. of Flutes	4
	Tool Diameter	25 mm
	Material	Solid Carbide
	Cutting Direction	Right Hand
Insert	Make	Sandvik Coromant
	Serial no.	R390-11T304E-P4-NL CD10
	Clearance Angle – AN	21°
	Rake Angle	21°
	Insert Width – W1	6.8 mm
	Cutting Edge Effective Length – LE	11 mm
	Major Cutting Edge Angle	90°
	No. of Inserts	1
	Cutting Material	PCD brazed to WC
	Corner Radius – RE	0.4 mm

	Weight	0.002 kg
	Max. Axial Depth of Cut	4.5 mm

Table 2.

Parameters used in Multidirectional laminate test (32 tests).

Feed per Tooth (mm)	Feed (mm/min)	Cutting Speed (mm/min)	ap (mm)	ae (mm)
0.025	17.75	85	4.1	25
0.04	28.41	175	4.1	25
0.06	42.61	225	4.1	25
0.075	53.26	285	4.1	25

Experiment – milling of unidirectional laminate (Test 2)

In test number two, a unidirectional carbon fibre laminate was edge trimmed in the Ares CMS 5-Axis Machine Tool, using two different tool types and varying feed per tooth. The 9.5 mm diameter 4 flute milling cutter is shown, and the 10mm diameter, 12 flute burr-tool are shown in Figure 5. Both tools are diamond coated, while the burr tool has an ultra-fine diamond coating which has a very small grain size. The 12 flute tool is a burr style router which has a segmented helical cutting edge. This tool has a primary helix which is intersected by a secondary helix to create a number of cutting teeth. Each tooth has two edges which cut the material, and two non-cutting edges; which allow the removal of chips and machined material. The 4 flute tool tool has a single helix with slightly positive rake angle. The tool information is shown in Table 3 and Table 4 shows the machining parameters used in the test. Samples of the unidirectional laminate were edge trimmed at three different fibre orientations: 0, 45 and 90 degrees. The tools were compared at a constant r/min and the feed per tooth was varied at three different levels. The slotting operation was performed at full tool diameter width of engagement of: a_e= 9.5 mm and a_e= 10 mm, for tool one and tool two respectively. The whole thickness of the workpiece (7 mm) was selected for the axial depth of cut a_p, and an 80 mm length of cut was used for each test. Each tool was replaced after making seven cuts in order to reduce any effects of tool wear.

Figure 5.
(a) Tool 1, helical with 4 flutes and 9.5mm diameter.
(b) Tool 2, burr tool with 12 flutes and 10mm diameter.

Table 3.
Milling tool properties. For test two on unidirectional laminate.

	Tool 1- Helical End Mill	Tool 2- Burr Tool
Manufacturer	Sandvik	OSG
Serial no.	2P210-1000-NC N20C	
Tool Diameter (mm)	9.5	10
No of flutes	4	12
Coating	Diamond like coating (Average thickness 7.5 μm)	Ultra-fine Diamond Coating

Rake angle	1.5 deg	8 deg
Clearance Angle	Primary - 11.5 deg Secondary - 9 deg	16 deg
Helix Angle	30 deg	15 deg

Table 4.

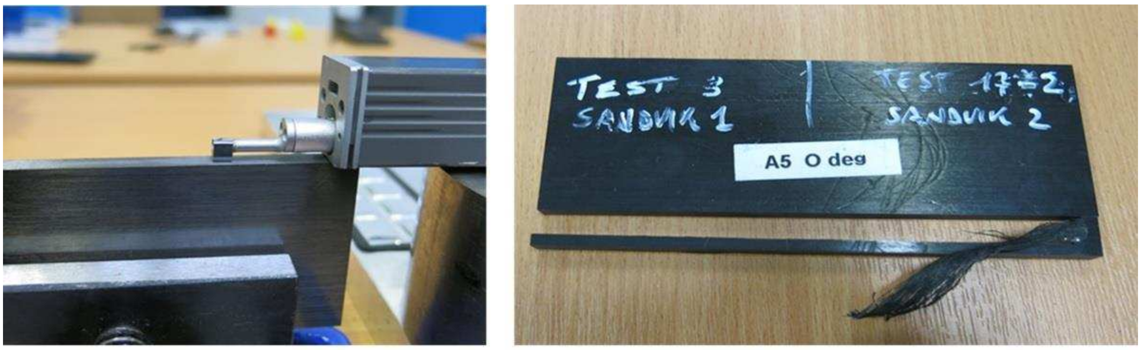
Cutting parameters in unidirectional test two.

Feed per tooth (mm)	r/min	Fibre orientation	Feed rate (mm/min) Tool 1	Feed rate (mm/min) Tool 2	a_p (mm)	a_e (mm)
0.005	4775	0	95.5	286.5	7	Tool 1- 9.5
0.0095	4775	45	181.4	544.3	7	Tool 2- 10
0.014	4775	90	267.4	802.1	7	

Roughness measurement methods

The surface roughness was measured after machining using both the Mitutoyo profilometer and optical systems on the unidirectional laminate. Figure 6 shows the unidirectional sample and stylus profilometer device. While using the stylus, repeat roughness measurements were taken in three different positions of the sample in order to increase reliability. The three measurements were taken in the feed direction with stylus in the same position of each sample at the top, middle and bottom in order to obtain an average result. A λ_c cut-off wavelength of 800 µm was used with a 4 mm evaluation length and 5 µm probe diameter.

For the optical system the Sa areal roughness parameter was used which takes the roughness over a scan area rather than across a profile line. This parameter calculates the arithmetic mean roughness of the surface deviation, similarly to the Ra parameter, but it is useful for composite surfaces that are heterogeneous, due to characterisation over a larger area of the surface. An evaluation area of 4 mm by 4 mm was used in order to calculate the Sa parameter. A cut-off wavelength of 800 µm was used in all measurements made with the optical system according to ISO 4288. The cut-off wavelength determines the amount of low spatial frequency components or waviness of the surface profile which is removed. This allows for the desired high spatial frequency roughness parameters to be measured. A vertical resolution of 100 nm and a lateral resolution of 2 µm were applied using the optical system which is suitable for the composite which has a fibre diameter of approximately 5 µm. Levelling of the surface is first performed before filtering by setting a reference plane which removes any profile or form deviation on the surface scans.



(a) (b)

Figure 6.
(a) Mitutoyo profilometer on unidirectional laminate,
(b) Unidirectional edge trimmed laminate, test two.

Results and Discussion

Roughness of multidirectional laminate (Test 1)

The optical system works by taking a three dimensional surface image in order to calculate roughness parameters; these are shown in Figure 7. The advantage of the optical system is that it is possible to measure the surface texture along a defined path of the material; it therefore allows the measurement of individual ply layers and different fibre orientations- as highlighted by the red line in Figure 7. The profile path taken for the roughness measurement is shown in Figure 7a, for the 0 degree fibre orientation, and for the transverse to feed direction shown in Figure 7b. It can be seen that there is a large difference in maximum profile height between the transverse measurement and 0 degree fibre orientation.

Some problems were found when using the stylus profilometer. There is a large variation in the roughness value measured depending upon the position or angle of the stylus, especially when measuring parallel to the fibres. It was also found that the stylus path may not lie directly parallel with the fibres, or pass over multiple laminate layers. Similarly, it is difficult to know which laminate layer or fibre orientation is being measured; as each layer has a slightly varying thickness and cannot be seen with the naked eye. Therefore, it was preferred to use the optical system for measurements. It was found that it can accurately measure individual ply layers, unlike the profilometer which proved to be unreliable for measuring roughness parallel to the fibres direction. Importantly, the roughness measurements made with a stylus were therefore not considered fully dependable for a multidirectional laminate.

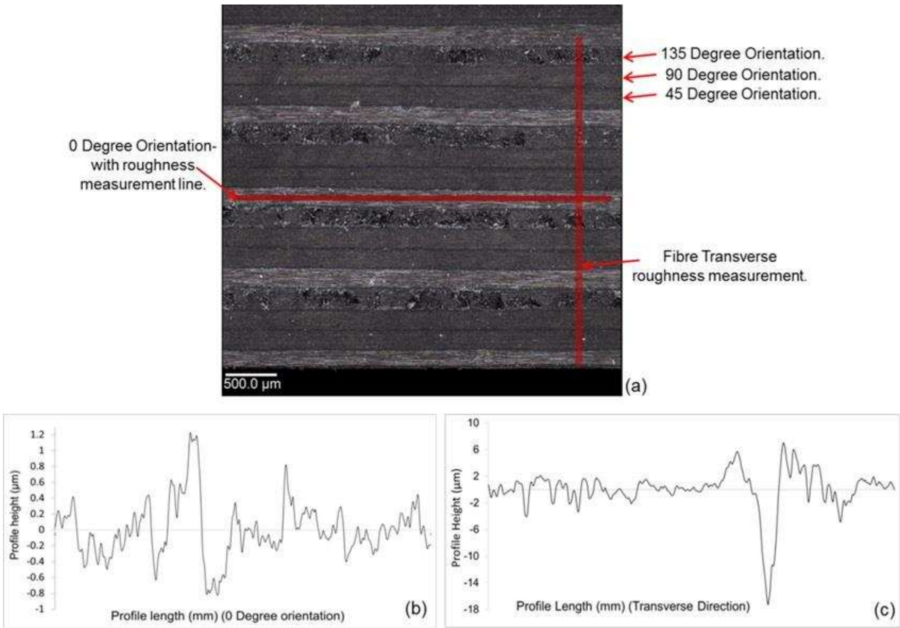


Figure 7.

(a) 3D surface structure images of multidirectional laminate measured by optical system. Red line shows the user selected roughness measurement path in transverse direction and a 0 degree laminate.

(b) Profile path for 0 degree fibre orientation,

(c) Profile path for transverse direction.

Figure 8 shows the average roughness on each of the fibre orientations taken by the optical method. It was found that there is a large variation in roughness across the surface of one laminate, and that the 135 degree fibre orientation had the greatest roughness while the 45 degree had the lowest. This effect can be explained by the different cutting mechanism across each of the fibre orientations which will be explained further in the SEM section. The 135 degree fibre orientation was found to have an average roughness nearly a factor of 10 greater than the 45 degree fibre orientation. It can therefore be realised that the 135 degree fibre orientation is critical for determining the highest roughness and most prominent damage.

In order to assess the suitability of using the stylus for measurement it was compared with optical approach: it was found that when using the stylus for measurement; that the roughness has a high probability of being under-represented, if the stylus path does not fall across the 135 fibre orientation. Consequently there is an expected uncertainty in using the stylus for roughness measurement of a multidirectional laminate due to the variation in structure at different areas on the surface.

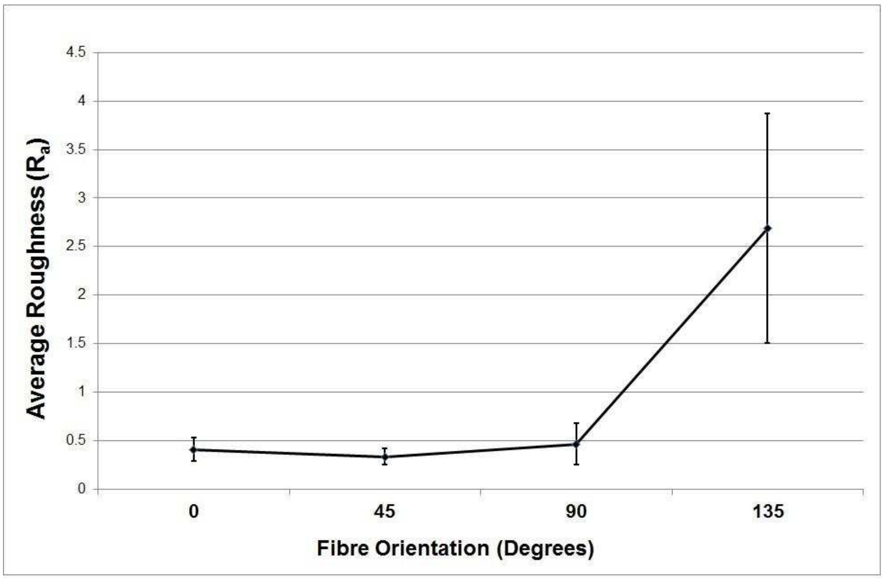


Figure 8.

Average roughness vs fibre orientation on multidirectional laminate, with error bars shown as standard deviation using optical technique.

In Figure 9 the roughness across the 90 degree fibre orientation is plotted against feed rate grouped by all of the applied cutting speeds. Similar trends in the data were seen across the 0, 45 and 90 degree orientations. However, for the 135 degree orientations there was a higher magnitude and standard deviation or scatter in the roughness measurements. The obtained data for the latter orientation; showed slightly different trends across the range of cutting speeds. This can be explained by the different cutting mechanism and large variation of the structure due to pits and torn chunks. It can be concluded from Figure 9 that increasing the feed rate caused an increase in the surface roughness across all of the cutting speeds used.

A component of this increase in roughness will be due to the increase in ideal roughness- which is a function of the square of the feed and tool geometry [18]. Ideal roughness represents the best surface finish which will be possible for a given feed and tool geometry.

Figure 10 shows a main effects plot for the feed rate and cutting speed which was produced using Minitab software [19]. A main effects plot works by creating a mean response from each factor using all of the test data. In this case the two factors were feed rate and cutting speed and their corresponding output effect on Ra. Figure 10 shows that there was a mean increase in the surface roughness due to a higher feed rate. Statistical methods were applied using regression modelling and it was found that the feed rate had a stronger contribution to increasing the roughness than cutting speed. The feed rate had a P value of 0.03 which indicates a statistically significant effect on the results. It was also found that the feed rate had a more significant effect on the 135 degree orientation. This increase in roughness with feed can be explained by the change in the effective chip thickness of material which is removed. Research by Ahmad and Shahid., [20] has shown that the lowest surface roughness is strongly correlated with decreasing the equivalent chip thickness, which is a geometric function of the feed speed and cutting speed. Therefore in order to get the best surface quality, both the feed rate and cutting speed parameters must be optimised together.

Figure 10 illustrates the effect of increasing the cutting speed from 85 to 225 (m/s) showing that this caused a mean increase in the roughness, however at the highest speed of 285 (m/s) there was a mean decrease. The cutting mechanism and the temperature of tool-workpiece interface will be affected by changes in cutting speed. An effect of increasing the cutting speed is that during each pass of the cutting edge, there will be less time for energy dissipation. This will lead to an increased cutting temperature, as the tool heats due to friction, and can cause thermal softening of the matrix and a reduction in its stiffness. As a result, the matrix would hold the fibres together less strongly and there would be a reduction in cutting forces. Smeared matrix on the surface could also be a by-product of an increase in the cutting temperature and show a reduction in the surface roughness. It has also been reported that the cutting mechanism can be changed to a "mechanical wrenching" due to increases in the cutting speed [21].

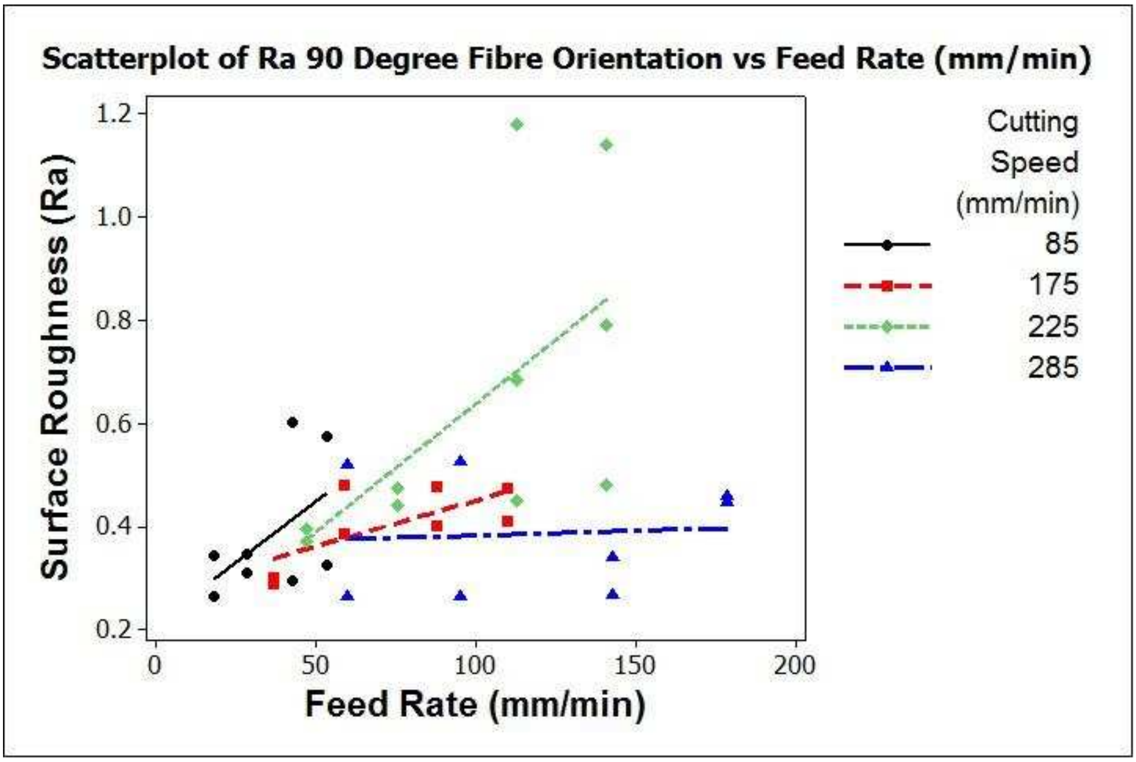


Figure 9.

Roughness of 90 degree fibre orientation, vs feed rate at each cutting speed. Shown for multidirectional laminate and optical technique.

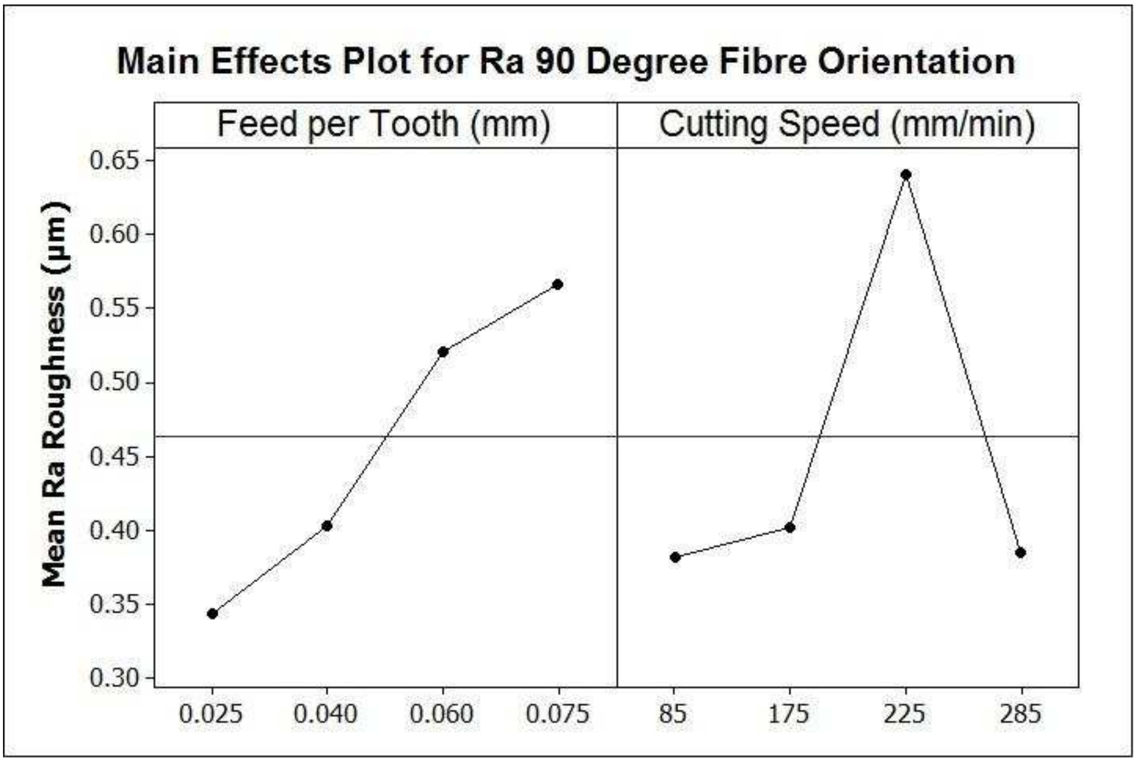


Figure 10.
Roughness of 90 degree fibre orientation, against feed rate at each cutting speed. Shown for multidirectional laminate and optical technique.

Roughness measurements for unidirectional laminate (Test 2)

For the unidirectional test, the main effects plot for roughness with increasing feed per tooth for each of the different tools types is shown in Figure 11. Texture measurements were taken using the optical system which enabled calculation of the Sa areal roughness parameter. Overall results showed that the minimum average roughness was again found on the 45 degree fibre orientation laminates and that roughness increased with feed rate. An average roughness of 2.1

μm was seen on the 0 degree fibre orientation, 1.85 μm on the 45, and 2.0 μm on the 90 degree fibre orientation. These trends compare well with the results from Test 1 on the multidirectional laminate. When the optical system was compared against the stylus profilometer measurement method in this test, the results showed the same trends. The use of areal parameters (Sa) was found to be advantageous when using the optical device because it will take into account damage across a larger measurement region and therefore the roughness was found to be less sensitive to measurement position than by stylus. For this reason the optical measurements were presented.

Using regression methods the tool type had the strongest effect on the surface roughness followed by feed rate, while both had a P-value which showed a statistically significant effect on the roughness. In Figure 12 a comparison of the tools is shown; the 12-flute burr tool was found to leave a higher Sa surface roughness than the 4 flute single helix tool- while running at the same feed per tooth. However, the 12-flute burr tool was also removing the material at faster rate. The burr style tool had a maximum material removal rate of 56.2 cm^3/min, compared to- 17.8 cm^3/min for the 4-flute helical tool. Haddad et al. [21], also found that a burr style tool produced a higher surface roughness than a fluted tool. They reported a different cutting mechanism between the two tools and that the burr style tool was more similar to an abrasive machining process; closely spaced grooves were left on the surface which were dependent on feed rate. In agreement with our findings- (Figure 11), the authors found a larger increase in the roughness due to feed rate in the burr style tool, which was attributed to an increase in temperature with feed.

The benefits of the optical system were found to be strongest when used to measure a multidirectional laminate (Test 1). This is because the unidirectional laminate has a lower variation in surface texture and therefore the measurement is less sensitive to stylus path. It was found that the variation or scatter in measurements made using the profilometer on the unidirectional laminate was less than that seen on the multidirectional. Therefore, the use of the optical device will be beneficial on a multidirectional composite surface as it provides the ability to take into account the different degrees of damage across all of the fibre orientations; in any fibrous composite material. The optical device and areal parameters have been found to be less sensitive to measurement position, or path, than the stylus and therefore provide a more accurate metric with which to assess machined composite surfaces.

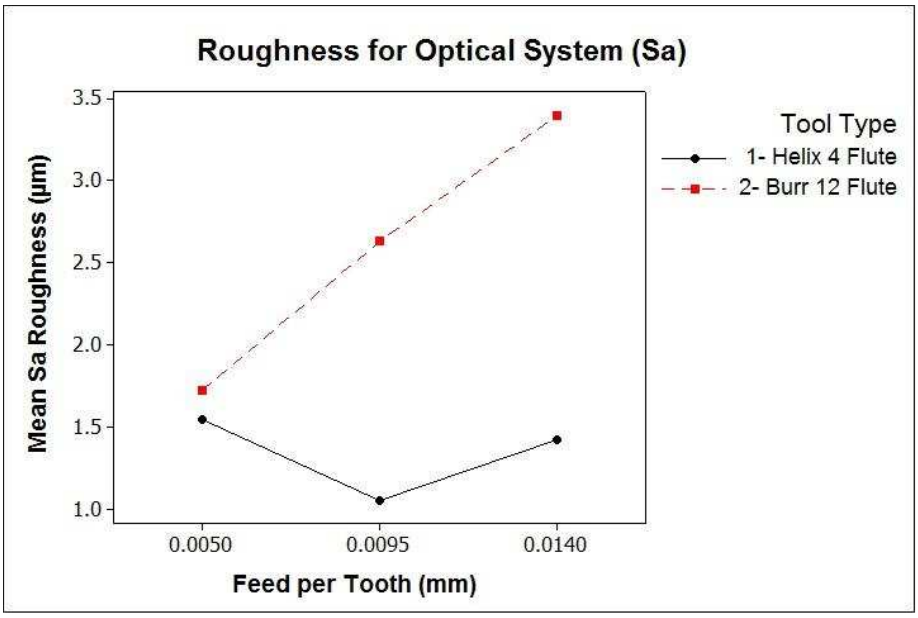


Figure 11.
Plot of the mean roughness (Sa) versus feed per tooth by optical technique for each of the two tool types on the unidirectional laminate.
Tool 1, 4 flute helical fluted tool.
Tool 2, burr-style with 12 flutes.

Skewness & kurtosis measurements (Test 1)

The kurtosis and skewness are not represented in the Ra parameter; and it is known that two different surfaces can have the same Ra [7]. Therefore these additional parameters were investigated to see if they can be used to more thoroughly characterise the machined surface and damage from machining. Histograms of the profile at varying fibre orientations were also taken. These show the percentage of all the values at each height above the mean profile line.

The average skewness and kurtosis across each of the fibre orientations was analysed as shown in Table 5. It was found that the average Skewness for the 135 orientation was negative, and that in the histogram in Figure 12 there is a longer tail in the negative direction. A negative skewness characterises a surface with deep cracks or voids, and this can be explained by the chunks of torn material and fibre pull-out removed from the material, which results in pitting. On the other hand the 45 and 90 fibre orientations typically had a positive skewness. This could be explained by the lack of sub-surface damage and fibres which protrude from the surface. The 0 degree fibre orientation also had a positive skewness due to the lack of cracks propagating below the surface. The skewness can therefore be a useful indicator of the damage in machined composites, indicating whether the surface is characterised by protruding fibres (positive skewness) or by fibre pull-out and voids (negative skewness). The Rt parameter was analysed along with the Sa and Ra parameters, and the mean Rt across each fibre orientation is shown in Table 5. However, the Rt parameter was not found to distinguish between damage on the 0,45 and 90 plies more effectively than the Sa or Ra parameter. The skewness and kurtosis parameters values were therefore analysed in more detail due to their ability to give unique information about the surface structure on each fibre orientation.

Table 5.

Skewness and kurtosis at each fibre orientation within multidirectional laminate.

Fibre orientation (^{0})	Average skewness (Sku)	Average kurtosis	Multidirectional laminate. Mean Ra (μm)	Multidirectional Laminate. Mean Rt (μm)
0	1.55	13.73	0.4	4.7
45	1.68	13.01	0.3	2.9
90	1.48	15	0.5	4.9
135	(-)1.25	9.25	2.7	38.4

The highest kurtosis was found for the 90 degree fibre orientation. This describes a surface with steep or sharp peaks and can be explained by uncut fibres protruding perpendicularly from the surface. The histogram shows a lack of tails in the positive or negative direction – Figure 13. All of the fibre orientations have a relatively high kurtosis suggesting there are quite sharp peaks and valleys. The 135 degree orientation had the lowest kurtosis which can be explained by the torn chunks of material and pits rather than the sharp protruding fibres on the 90 degree orientation. These parameters were analysed using the optical system, this would not have been possible using the stylus profilometer due to the difficulty in measuring one layer of the multidirectional laminate. The skewness was found to be the most useful parameter due to its ability to distinguish surfaces with cracks and pits versus protruding or un-cut fibres.

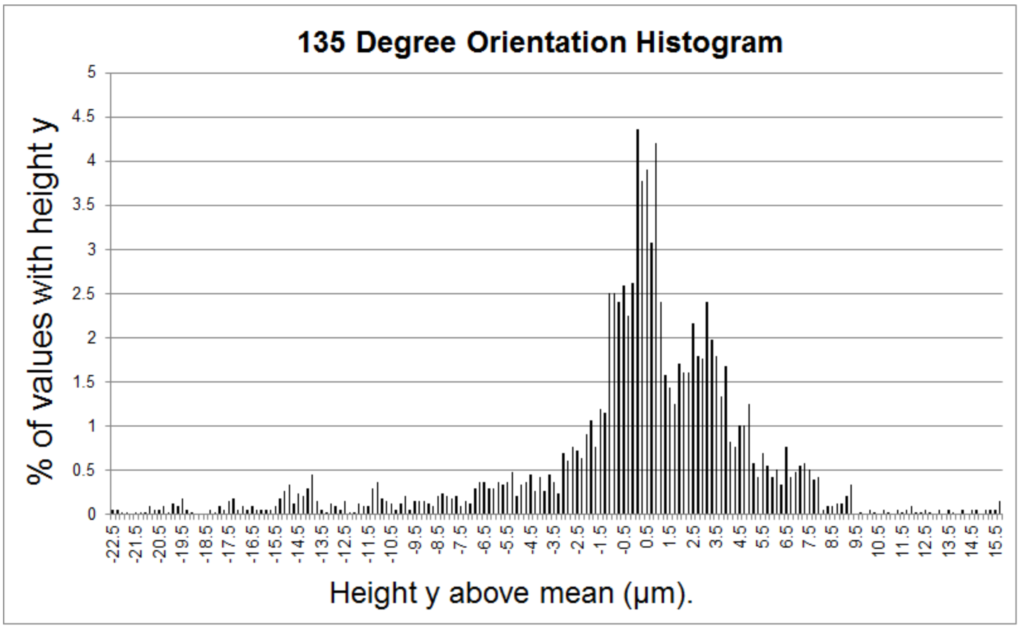


Figure 12.

135 Degree fibre orientation histogram on multidirectional laminate using optical system.

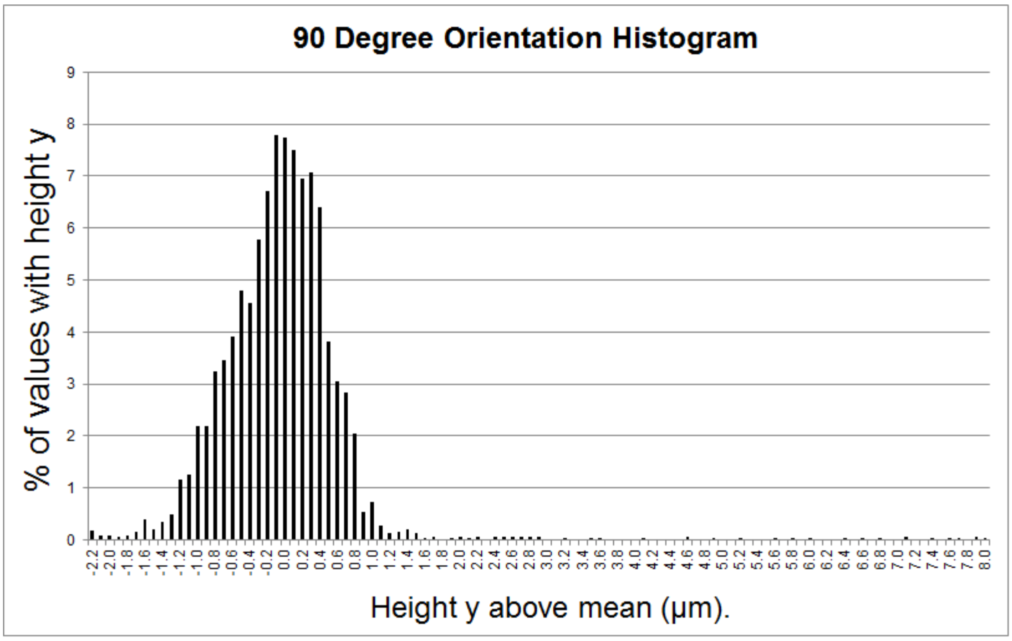


Figure 13.
90 Degree fibre orientation histogram on multidirectional laminate using optical system.

Scanning electron microscope images (multidirectional laminate)

Scanning electron microscope (SEM) images were used to take micrographs of the surface of the machined samples from the multidirectional laminate (Test 1). These were used to identify the extent of the damage from machining. As depicted in the SEM images shown in Figure 14 and at a higher magnification in Figure 15, the fibre orientation had a strong effect on the machining damage and quality of the surface. The 0 and 45 degree fibre orientations were seen to be relatively smooth. While for the 135 degree fibre orientation the surface quality was significantly worse; with large pits and torn fibres on the surface, as indicated in Figure 14 and Figure 15b.

The explanation for the worse surface quality for the 135 degree fibre orientation is due to the cutting mechanism: the fibres are bent and subsequently a primary fracture will propagate below the surface along the fibre matrix boundary. Finally, the fibres break in a combination of bending and fibre shearing [22]. This effect can be seen by the large pits and fibres which have been bent out of plane on the surface. A bouncing back effect has been suggested by Wang and Zang [2]. This happens after the cutting tool has passed and the fibres spring back. This effect would be expected to be greater in cutting the 135 degree orientation due to the large amount of bending and buckling of the fibres.

Machining of the 0 degree fibre orientation causes a bending and fracture type chip removal mechanism. From the SEM micrographs it can be seen that the damage does not propagate below the surface to the same extent as in the 135 degree fibre orientation. Most of the fibres can be seen lying on the surface in their original orientation without damage – Figure 14a and Figure 15a. Here the fibres are removed in a bending and crushing mechanism which causes the fibre to de-bond from the matrix and then fracture. This effect is was also found in the work by Wang and Zang. [2], and Wang et al. [5].

The 90 degree fibre orientation shown in Figure 14b is smoother than the 135 degree fibre orientation but was generally found to have a slightly higher roughness than the 0 degree and 45 degree orientations. However, Figure 14a indicates that the surface is different to that of the 0 degree fibre orientation. Much of the surface is covered in smeared matrix, but some fibre ends can be seen on the surface, which lie in their original orientation. Any variation in the surface height appears to be caused by fibres which have been sheared at different lengths. A fibre shearing cutting mechanism is suggested in accordance with reports from the literature [3].

The 45 degree fibre orientation is most similar to the 90 degree fibre orientation in appearance and again much of the surface is covered with smeared matrix and some sheared fibre ends as indicated in Figure 15c. In this image it is hard to distinguish any individual fibres and the surface looks very smooth. The machined surface for the 45 degree fibre orientation was found to be the least rough and there appears to be very little damage or cracks propagating below the surface. This suggests that most of the fibres are being sheared through their cross section, without being bent out of plane. A fibre crushing and cutting mechanism has been suggested in the literature for machining of the 45 degree fibre orientation [5]. Pecat et al. [23], found that the resultant cutting force was highest while machining the 45 degree fibre orientation. This was explained due to a strong fibre tension dominated failure mode; in contrast to a weak matrix dominated failure mode in the 135 orientation.

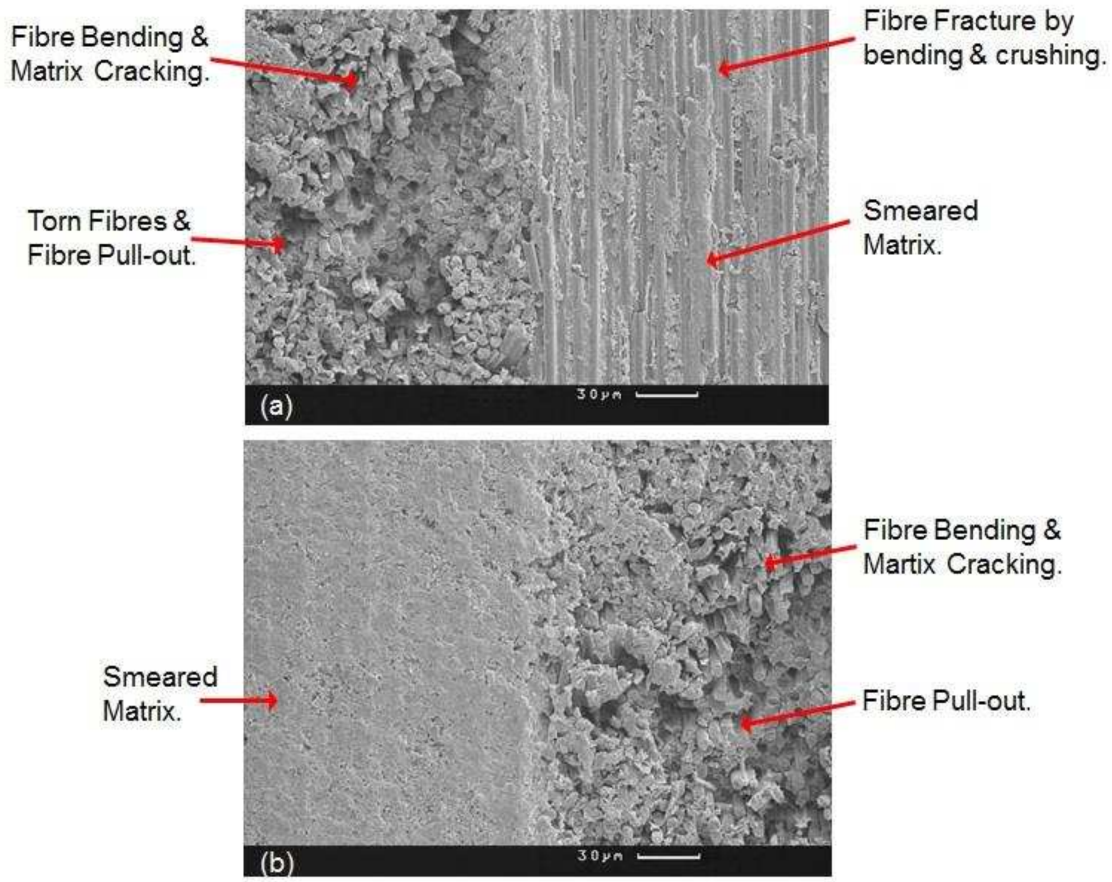


Figure 14.

(a) SEM image of 135 and 0 degree ply comparison.

(b) SEM image of 90 and 135 degree ply.

(These tests were performed at a cutting speed of 175 mm/min and feed of 0.075 mm/rev on multidirectional laminate.)

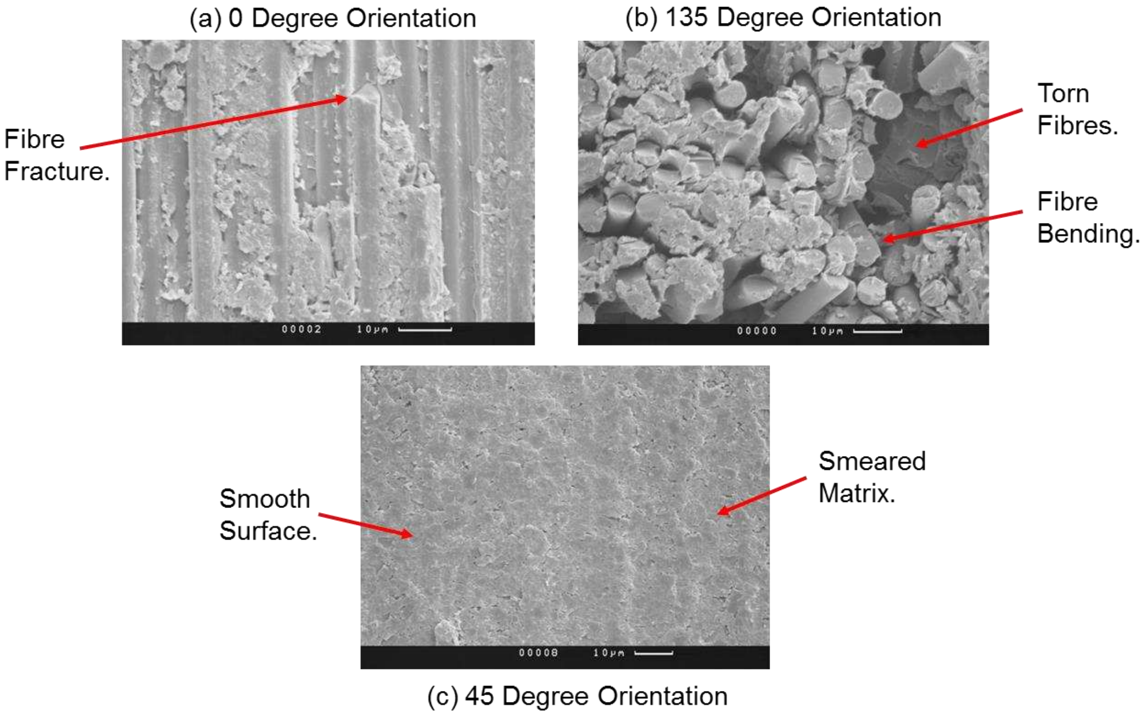


Figure 15.

(a) 0 Degree fibre orientation SEM image. (b) 135 Degree fibre orientation SEM image.

(c) 45 Degree fibre orientation SEM image.

(These tests were performed at a cutting speed of 175 mm/min and feed of 0.075 mm/rev on multidirectional laminate.)

Conclusions

This research used a new optical method to measure surface roughness and damage of machined composite surfaces. The results have confirmed that the fibre orientation plays an important role in the chip removal mechanism and surface damage. The 135 degree fibre orientation was found to be the critical fibre orientation for surface damage and roughness measurement. The kurtosis and skewness roughness parameters were found to be useful and give a more thorough representation of the surface quality and damage, including showing the presence of cracks or pits and protruding fibres. Statistical methods showed that the feed rate and tool type had the most significant effect on the surface quality; and that the 135 degree fibre orientation was the most strongly affected by changes in feed.

The non-contact optical method has been shown to be a useful research tool for measuring surface roughness of machined composites. Importantly, it allows the characterisation of roughness or damage on individual ply layers of a machined multidirectional laminate which is not possible with a stylus. The technique avoids the unreliability issues that were found to be associated with the quantification of surface roughness using a stylus; and thus enables a more thorough characterization of the profile and the complex damage mechanisms seen in machined fibrous composite laminates. It is suggested that the use of areal surface parameters like Sa should be further adopted in roughness measurement of fibrous composite surfaces; and will increase reliability of roughness measurement for multidirectional laminates.

However there were some limitations found with the device; which is constrained by the distance between the stage and lens, and is therefore unsuitable for measuring large parts. It is also less portable and more expensive than the stylus, and it is thought that the device will become more appropriate to an industrial machining application when combined with the use of robotic arms to make automated or in machine roughness measurements. The results from this work can be used to demonstrate new opportunities for academia and industry in understanding roughness measurement and optimising the machining of fibrous composite materials.

Acknowledgements

This work was co-funded through the EPSRC Industrial Doctorate Centre in Machining Science (EP/I01800X/1) and by Rolls-Royce whom the authors would like to thank.

The authors would also like to thank the staff of the Knowledge Transfer Centre at the AMRC and Professor Leach of the University of Nottingham for the support provided during this work.

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