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A study on the grindability of multidirectional carbon fibre-reinforced plastics

N.S. Hu*, L.C. Zhang

School of Aerospace, Mechanical and Mechatronic Engineering, The University of Sydney, Sydney 2006, NSW, Australia

Abstract

This work studied the grindability of the multidirectional carbon fibre-reinforced plastic (CFRP) composites with the panel layup of $[(0°/90°/45°/-45°)_3]_s$. Focuses were on the chip formation, material removal mechanism, ground surface features and grinding force characteristics. The results were systematically compared with the unidirectional CFRP composites. It was found that the grinding forces for the multidirectional composites increase nearly linearly with raising the grinding depth. The chips produced showed a mixture of fine powder and broken fibres of various lengths. This is different from grinding the unidirectional fibre-reinforced composites, where the geometry of chips was mainly dependent on the fibre orientations. The longitudinal surface roughness of ground multidirectional composites varied strongly with the local fibre orientations. Severe damages, such as fibre pullout, were observed with the plies of [−45°].

Keywords: Grinding; Multidirectional CFRP composites; Grinding force; Surface roughness; Subsurface damage

1. Introduction

Along with the increasing applications of carbon fibre-reinforced plastics (CFRPs) in a wide range of industries, the machinability of this type of composites has been studied considerably to try to achieve the required geometry, tolerance and surface finish, focusing on cutting, trimming, turning and drilling of unidirectional FRP composites [1–7]. Little work has been done on the materials' grindability [8–13], which is particularly true in the case of multidirectional FRP composites [14,15].

The purpose of this investigation is to study experimentally the performance of the multidirectional CFRP composites under surface grinding, with a focus on the chip formation, material removal mechanism, ground surface features and grinding force characteristics.

2. Experimental

2.1. Material preparation

The CFRP composites were fabricated from MTM 56 prepregs with carbon fibres of 7–8 μm in diameter. The panel layup of the multidirectional CFRP composites was $[(0°/90°/45°/-45°)_3]_s$. Each panel had 24 plies. The geometry of the laminates was about length × width × thickness = 150 mm × 150 mm × 5 mm. The plies with the fibre orientation of [−45°] are equivalent to the fibre orientation of 135° in grinding the unidirectional composites as discussed by Hu and Zhang [12,13], where the fibre orientation was defined clockwise from the ground surface to the direction of the fibres as illustrated in Fig. 1. The multidirectional composite laminates were fabricated using hot press machine as recommended by product handbook. They were cured under the constant pressure of 0.8 MPa at the temperature of 120 ± 5 °C for 10 min. The heating and cooling rates were controlled at about 8–10 °C/min, with a demolding temperature below 80 °C.

2.2. Grinding

The specimens used had the geometry of length × height × thickness = 45 mm × 15 mm × 5 mm. The grinding was carried out on a surface grinder MININI M286 CN, using an aluminum oxide grinding wheel BWA36HVAA, which were the same as in the experiment with the unidirectional CFRP composites [11–13]. The wheel was dressed regularly with a single point diamond dresser at the dressing depth of 50 μm each time and dressing feed of 200 mm/min at the wheel peripheral speed of 20 m/s. The down grinding mode was employed. The wheel and table speed used were 25 m/s and 4 m/min, respectively. The grinding forces were measured with a three-dimensional piezo-electric dynamometer

* Corresponding author. Tel.: +61-2-9351-7158; fax: +61-2-9351-7060.
E-mail address: nhu@aeromech.usyd.edu.au (N.S. Hu).

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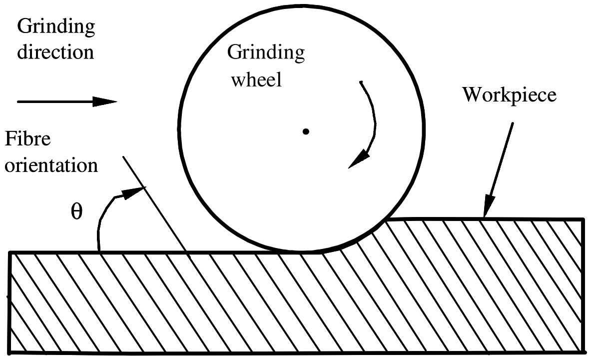


Fig. 1. Schematic diagram of surface grinding.

(Kistler-5011) which was mounted on the hydraulic table of the machine.

2.3. Surface characterization

The topography of the ground specimens was examined by both optical microscope (Leica LEITZ DMRXE) and scanning electronic microscope (SEM) Philips XL-30. The surface roughness was measured using a surface roughness tester, Surftest-402 of Mitutoyo company.

3. Results and discussion

3.1. Grinding force

Two orthogonal components of grinding forces were measured, i.e., the horizontal force parallel to the grinding direction and the vertical force perpendicular to the grinding surface. Both the vertical and horizontal grinding forces per unit width (i.e. specific grinding forces) of the multidirectional CFRP composites were measured against the grinding depth and compared with the relevant ones with unidirectional fibres, as shown in Fig. 2. It can be seen that the grinding forces of the former increase nearly linearly with raising the grinding depth, which is quite different from those of the latter. The comparison manifests that in general the specific grinding forces in grinding the multidirectional composites are larger. The reason may be that the plies with different fibre orientations support each other more strongly. However, Fig. 2 also shows that under relatively large grinding depth (e.g. 300 μm), grinding the unidirectional composites with fibre orientations of 0° and 60° as well as 90° requires larger specific grinding forces than those for the multidirectional. This may be due to the severe smearing of resin loaded to the grinding wheel in grinding the unidirectional composites with these fibre orientations.

3.2. Surface roughness

In a ground multidirectional CFRP specimen, each ply with a specific fibre orientation occupies only a narrow band with a width around 0.21 mm on the specimen surface. Thus measurements of surface roughness on different bands corresponding to different fibre orientations were carried out under an optical microscope. The typical results of surface roughness along the grinding direction in one of six periodical ply groups (i.e. 0°/90°/45°/−45°) are shown in Fig. 3. It can be seen that a larger grinding depth generates higher surface roughness, and the ply of [−45°] fibre orientation has the roughest surface. In addition, if the results in Fig. 3 are re-plotted in terms of the fibre orientations and compared with the measurements on the ground composites reinforced by unidirectional fibres, as shown in Fig. 4, it becomes clear that the surface roughness of both the multidirectional and the unidirectional composites varies in the same way. However, the mutual constraint between the plies in a multidirectional specimen makes the composite more suitable for grinding to result in lower surface roughness.

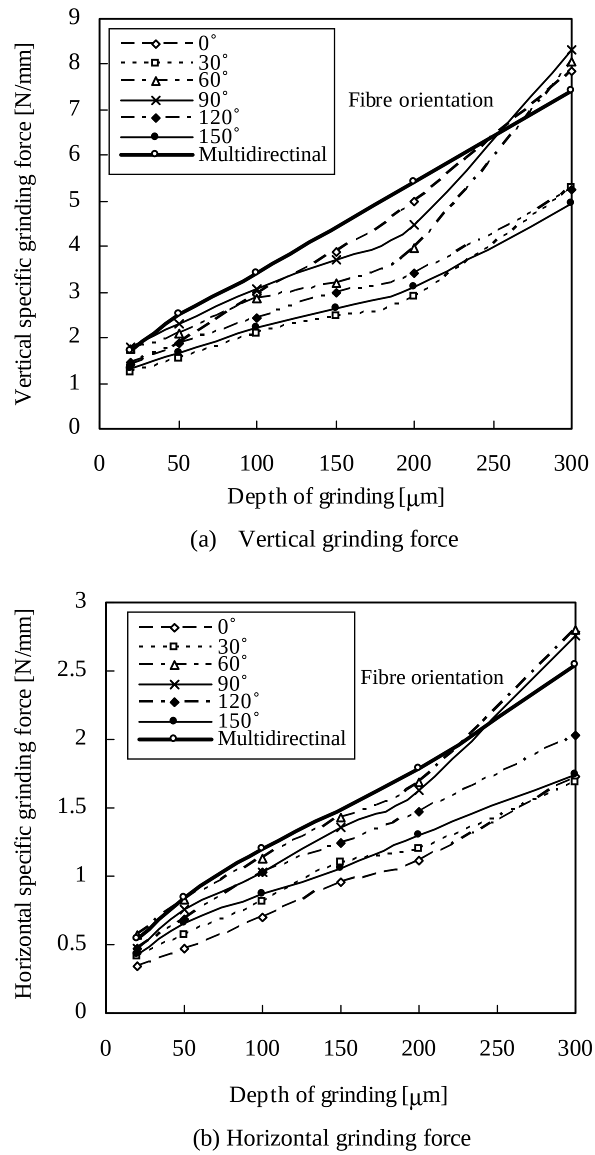


Fig. 2. Specific grinding forces versus grinding depth.

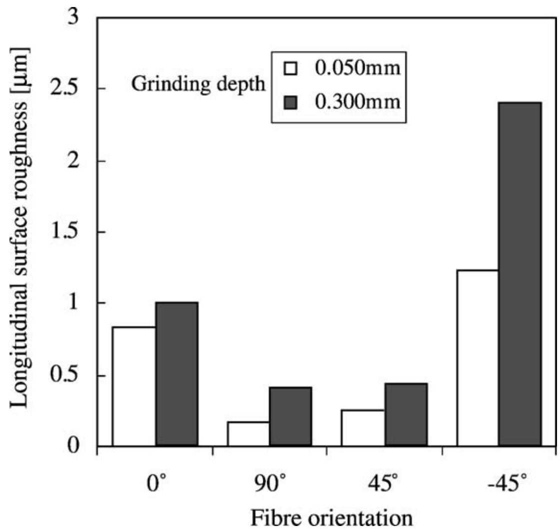
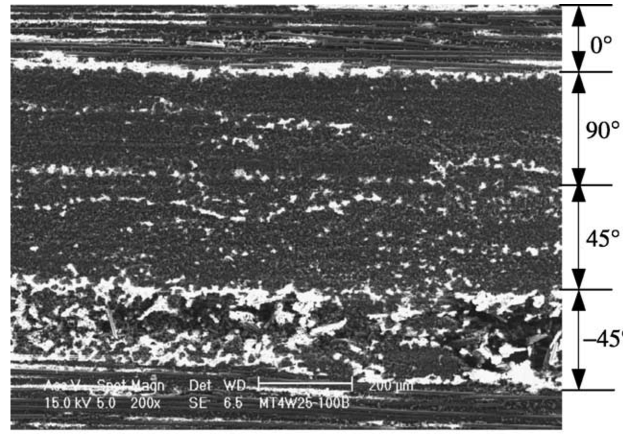


Fig. 3. Longitudinal surface roughness of the multidirectional specimens.

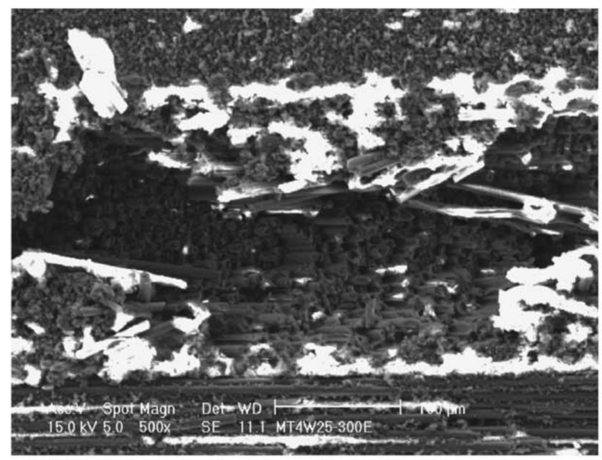
3.3. Surface topography and integrity

Under the present composite panel layup of [(0°/90°/45°/−45°)$_3$]$_s$, the surface of a ground specimen has four types of surface morphology periodically, as shown in Fig. 5(a). Compared with the typical monotonic surface feature on a ground specimen of the unidirectional composites shown in Fig. 6, it can be seen that the 90° and 45° ply bands have flat surfaces corresponding to the lowest surface roughness values in Fig. 4. The [−45°] ply band, however, possesses severely damaged surface and subsurface, see Fig. 5(b), which correspondingly gives rise to the largest surface roughness.

It was shown in a previous investigation [12] that a rougher ground surface often means a deeper subsurface damage. The lower surface roughness of the multidirectional composites suggests that the suppression among the plies with different fibre orientations plays an important role.



(a) 0°, 90°, 45° and [-45°] plies



(b) Severe digging occurring in [-45°] ply

Fig. 5. Surface morphology of a ground multidirectional composite specimen.

3.4. Chip formation and material removal

A deeper understanding of the chip formation and material removal mechanism will help the control of grinding

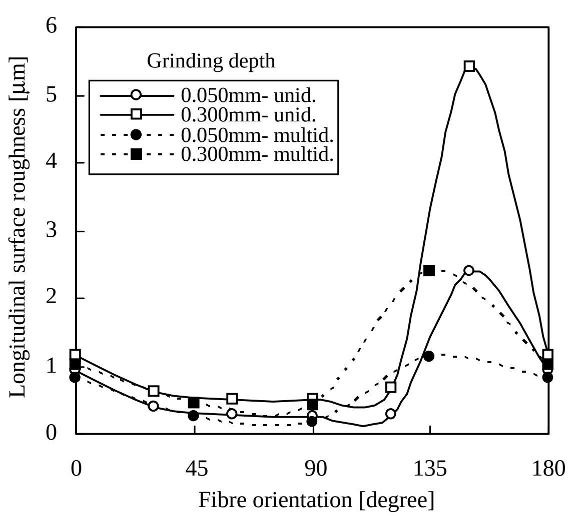


Fig. 4. Surface roughness along the grinding direction.

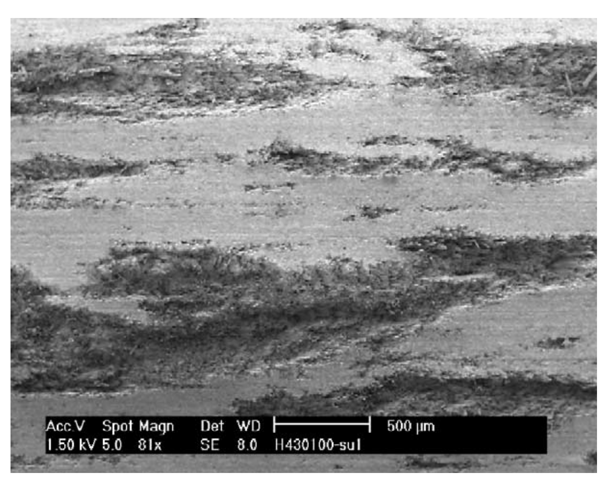
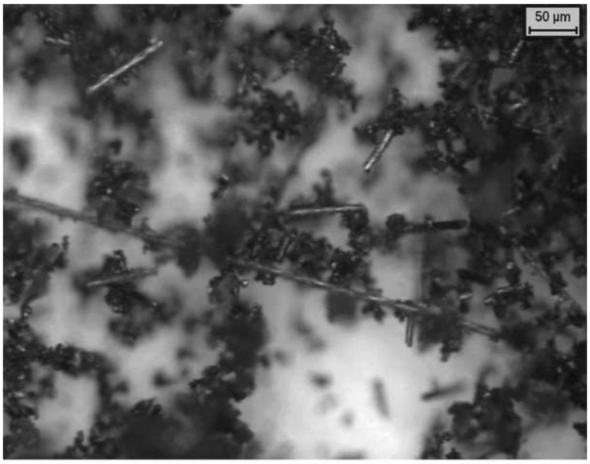
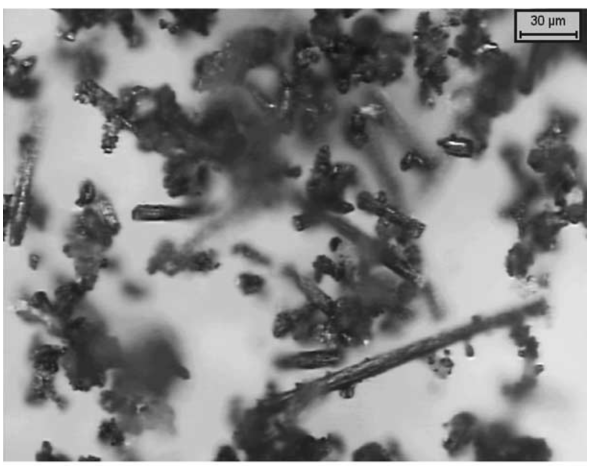


Fig. 6. Surface morphology of a ground unidirectional composite specimen (with the fibre orientation of 150°).

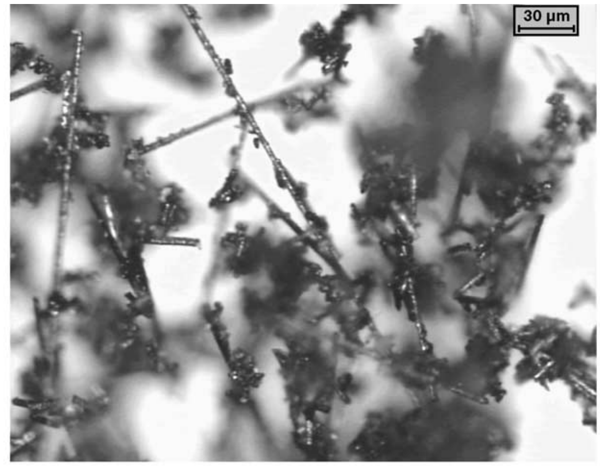


(a) Low magnification

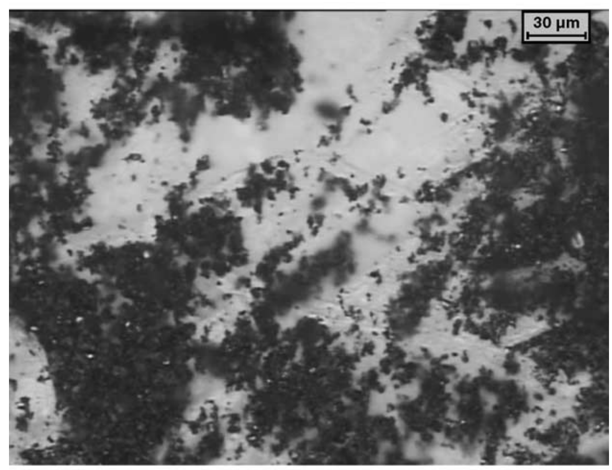


(b) High magnification

Fig. 7. Chips in grinding the multidirectional composites.



(a) Pullout fibres at 0° fibre orientation



(b) Powder at 90° fibre orientation

Fig. 8. Chips in grinding the unidirectional composites.

quality. The observations of the chip characteristics, as shown in Fig. 7, show that the chips are composed of fine powder, broken fibres, and some small pieces of broken composite. The relatively long broken fibres were from the 0°-plies where the material removal was mainly caused by mode II shearing fracture of the matrix resin and mode I opening cracking along the fibre/matrix interfaces. The very short broken fibres might attribute to the 45°-plies where pullout and shearing cutting mechanism were dominant. The powder chips could be from the 90°-plies, produced by orthogonal shearing cutting and squeezing of both the fibres and matrix resin. The small broken composite pieces were due to the cracking into the substrate in the [−45°]-plies. These mechanisms are different from grinding the composites with unidirectional fibres where the shapes of the chips were dependent on the fibre orientations. Generally, when grinding the unidirectional composites, chips show dominantly pullout broken fibres in 0° fibre orientation specimens and fine powder in 90° as shown in Fig. 8. Comparing Figs. 7 and 8(a), it can be seen that the average length of broken fibres in grinding the unidirectional composites is longer than that of the multidirectional ones under the same grinding conditions.

The above results seem to suggest that the material removal mechanisms of the multidirectional composites differ in different fibre orientation plies.

4. Conclusions

(1) The grinding forces for the multidirectional CFRP composites increase nearly linearly with raising the grinding depth and are generally larger than those for the unidirectional ones under the same grinding conditions.
(2) The longitudinal surface roughness of ground multidirectional specimens varies strongly with the measuring location at which the local fibre orientations differed. The surface roughness in 0°, 45° and 90° plies is very close to that of the unidirectional ones with the same fibre orientations. The big improvement in [−45°] plies

means that the suppression among the plies plays an important role.

(3) With the multidirectional CFRP composites, a ground surface can have several morphologies compared with the monotonic surface feature of the unidirectional ones.

(4) Several forms of chips appeared. The typical chip shapes in grinding the multidirectional CFRP composites are a mixture of fine powder, broken fibres and pieces of broken composite bulks.

Acknowledgements

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