# DRILLING POLYMERIC MATRIX COMPOSITES REINFORCED WITH GLASS FIBRES

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***Abstract.*** *Drilling of composite materials is a quite usual and important machining process employed in the aerospace and automotive industries in order to allow the assembly of various composite structures, despite the difficulties related to their heterogeneity and heat sensitivity. Nevertheless, drilling composite materials presents a number of drawbacks such as delamination and fibre pull-out associated with the characteristics of the material and with the cutting parameters employed. Among the defects caused by drilling, delamination appears to be the most critical. In order to minimize these problems, methods to appropriately select cutting parameters are required due to the fact that an inadequate choice can lead to unacceptable component degradation. This work is concerned with the effect of the composite reinforcement, machining parameters (cutting speed and feed rate) and tool geometry on the feed force and hole quality when drilling glass fibre reinforced plastic composites. In general, the results indicated that feed rate is the most critical factor affecting feed force and surface quality, followed by reinforcement mesh and tool geometry.*

***Keywords****: drilling, glass fibre reinforced plastics, delamination, feed force*

## 1. Introduction

Composite materials are widely employed especially in the aerospace industry. Among the composite materials available, those made of an epoxy resin reinforced with glass fibres are the most used owing to the fact that they possess satisfactory mechanical properties and low cost compared to other composite materials, such as polyester resins reinforced with carbon, boron or aramid fibres.

Due to the fact that a composite material has two insoluble phases with distinct properties, the machining of these materials presents particularities not observed when cutting metallic alloys. Of special interest for the present work is the drilling operation, which is usually used as a finishing process employed to produce cylindrical holes where bolts and rivets are fixed. Therefore, any damage impaired on the quality of the hole may negatively affect the performance of the component (Khashaba, 2004).

Together with glass fibres, carbon and aramid fibres are the most used synthetic reinforcement materials. Despite their superior mechanical resistance and lower specific weight, the cost of carbon and aramid fibres is a considerable factor limiting their widespread use, which is concentrated on the aeronautic and aero spatial industries (Smith, 1998).

The quality of the holes (surface roughness and dimensional tolerancing) produced when conventionally drilling composite materials is strongly dependent on the selected machining parameters, drill geometry, machining forces and torque. The inadequate choice of any parameter would inevitably lead to a machined component with unacceptable quality caused by fibres pull-out, cracks and delamination.

According to Capello (2004), delamination is the most serious damage that can be impaired to composite materials, due to the fact that it may reduce the fatigue resistance of the part and consequently its service life. This defect can be observed both at the entrance and exit surfaces of the component. Caprino and Tagliaferri (1995) and Davim *et al.* (2004) noticed that feed rate is the most important factor which significantly affects delamination, whereas an increase cutting speed contributes to the reduction of the roughness of the machined wall of polymeric composites. However, Lin and Chen (1996) reported that increasing cutting speed results in higher drill wear and consequently higher machining forces.

A relevant factor that must be taken into account when drilling composite materials is that the drills commercially available were designed for the machining of metals, therefore, their use results in defects frequently found in composites employed in aircrafts structure (Lachaud *et al.*, 2001). These authors classified the damages caused when drilling as defects at the entrance of the drill, circularity defects, temperature induced defects, defects on the hole wall and delamination at the drill exit.

The surface roughness of the drilled wall increase as cutting speed and feed rate are elevated, however, it is more sensitive to the latter (Ogawa *et al.*, 1997 and Aoyama *et al.*, 1995). Comparing drilling with trepanning of composite materials, Mathew *et al*. (1999) found that the former presents inferior performance when considering cutting pressure and torque. Capello (2004) reported that when drilling using lower feed rates delamination is minimized due to the fact that the cutting edge shears the material. Increasing feed rate the drill pushes the work material and delamination can be observed. According to Ionue (1997) the use of high feed rates is recommended when a large number of holes must be produced with an acceptable quality, however, in order to generate a small number of holes with high quality it is necessary to employ low feed rates.

## 2. Experimental procedure

The experimental work was carried out at the Machining and Automation Laboratory of the University of Minas Gerais, Brazil, as well as at the Technology Laboratory of the University of Aveiro, Portugal. During the drilling tests the effect of the cutting parameters (cutting speed and feed rate) on feed force and on the delamination factor was assessed.

In the first part of the experimental work (carried out at the University of Minas Gerais), the work material tested was a glass fibre reinforced composite produced by hand lay-up using 50% weight glass fibre and 50% weight epoxy resin. Three different fibre densities were tested: low (145 g/m$^2$), medium (200 g/m$^2$) and high density (330 g/m$^2$). Curing was conducted at room temperature. High speed steel twist drills (6 mm diameter) were used as tool material. The tests were carried out on a machining centre (9 kW spindle power and 7500 rpm maximum rotational speed). Figure 1 shows the experimental set-up (drill and workpiece mounted over the dynamometer). It can be seen that the work material was fixed between two aluminium plates previously drilled with a diameter of 8 mm in order to firmly support it. The cutting parameters tested were as follows: cutting speeds of 30, 60 and 90 m/min and feed rates from 0,1 to 1 mm/rot, thus resulting in 9 tests (10 holes were produced under each cutting condition).

Figure 1. Experimental set-up used in the first part of the work

The second part of the experimental procedure (conducted at the University of Aveiro, Portugal) employed, as work material, a polyester matrix reinforced with 65% of glass fibre (Viapal VUP 9731) manufactured by hand lay-up. The principal mechanical properties of this composite were: flexural strength of 98 N/mm², tensile modulus of 3500 N/mm², tensile strength of 52 N/mm² and thermal conductivity of 0.15 W/m ºC. A helical flute K10 carbide drill (stub length) and a Brad & Spur K10 carbide drill, both manufactured according to DIN 6539 by M.A. Ford® Company (see Fig. 2), were used as tool materials. The stub length drill has 118º point angle, 22º helix angle, 10% cobalt grade and 26 mm of flute length. The Brad & Spur drill has 10% cobalt grade and 25.5 mm flute length. A machining centre with 11 kW spindle power and a maximum spindle speed of 7500 rpm was used to perform the experiments. Nine tests were carried out under these conditions employing the following cutting parameters: cutting speeds of 55, 71 and 86 m/min and feed rates of 0,05 – 0,1 and 0,2 mm/rot.

Feed forces were measured with Kistler dynamometers (model 9257 at the University of Minas Gerais and model 9272 at the University of Aveiro) connected to charge amplifiers and data acquisition boards. The delamination factor was measured using Mitutoyo toolmaker’s microscopes (model TM 505 at the University of Minas Gerais and model

TM 500 at the University of Aveiro) equipped with digital micrometers (1 μm resolution). After measuring the maximum diameter ($D_{max}$) in the damaged zone, i.e., around each hole, the delamination factor ($F_d$) was calculated as the ratio between the maximum diameter ($D_{max}$) of the damaged zone and the hole diameter ($D_{hole}$).

(a) Brad & Spur drill

(b) Stub length drill

Figure 2. Cutting tools tested in the second part of the experimental work: (a) Brad & Spur K10 drill and (b) helical flute stub length K10 drill

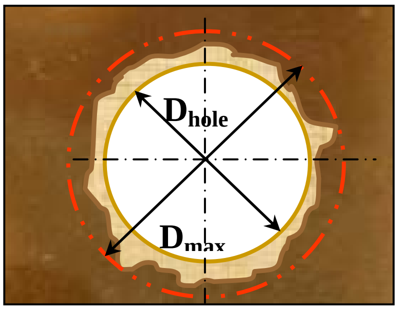


Figure 3. Scheme for calculating the delamination factor ($F_d$)

## 3. Results and discussion

Figures 4 to 9 show the results of the tests carried out at the University of Minas Gerais, where a epoxy resin reinforced with glass fibres with three distinct densities was machined using high speed steel twist drills. Figures 4 to 6 represents the influence of cutting speed and feed rate on the feed force for the three different fibre densities used in the reinforcement, respectively. Figure 4 shows that feed force increases with feed rate, however, when cutting speed is altered the effect on feed force is nearly negligible, except for the highest feed rate value (f=1 mm/rev), in which the feed force reduced slightly as cutting speed was elevated. When the density is increased, see Fig. 5, an elevation in the feed force is observed, particularly for feed rates values of f=0,75 and 1 mm/rev. In these cases it can be clearly seen that feed force also increased with cutting speed.

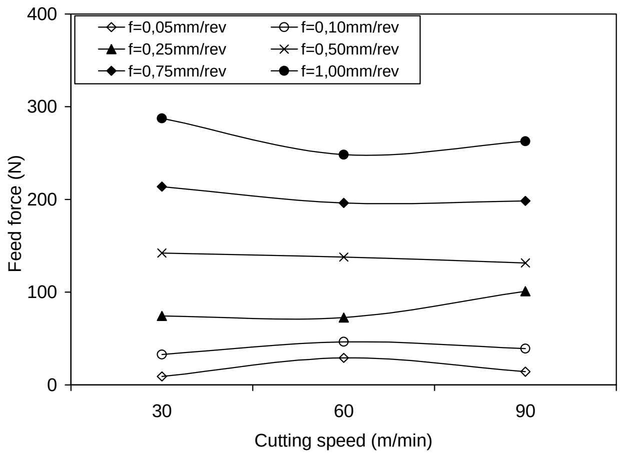


Figure 4. Effect of cutting parameters on feed force when drilling epoxy resin reinforced with glass fibres (low density)

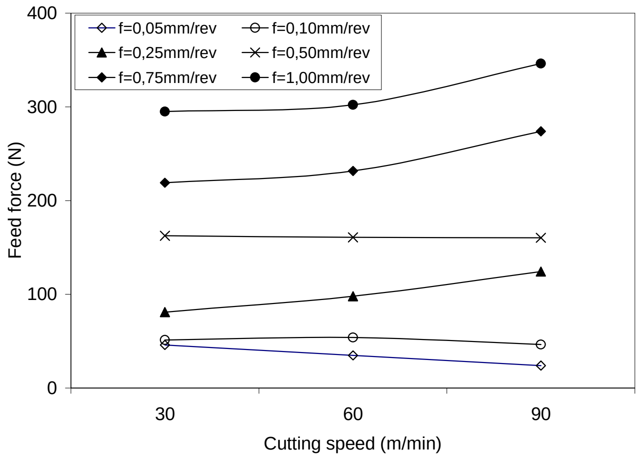


Figure 5. Effect of cutting parameters on feed force when drilling epoxy resin reinforced with glass fibres (medium density)

The effect of cutting speed and feed rate on the feed force when drilling the epoxy resin reinforced with glass fibre of high density is represented in Fig. 6. The same trend observed previously is again noted, i.e., the feed force increase is more accentuated when high feed rates are employed and the influence of cutting speed is negligible for low feed rate values. Comparing Figs. 4 to 6 it can be seen that as the reinforcement density is increased, the feed force is also elevated.

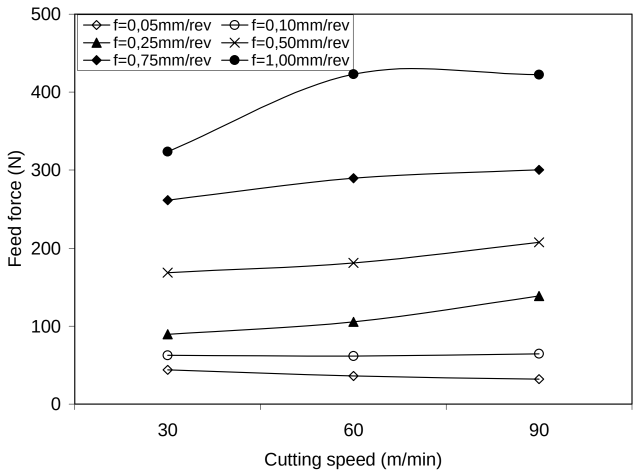


Figure 6. Effect of cutting parameters on feed force when drilling epoxy resin reinforced with glass fibres (high density)

The influence of the parameters cutting speed and feed rate on the delamination factor when drilling the epoxy resin reinforced with glass fibres is presented in Figs. 7 to 9 for the three fibre densities tested. Figure 7 suggests that for the low density, in general an increase in cutting speed results in higher delamination factor, however, the same does not apply when considering the feed rate results (the highest delamination factor was obtained for f=0,75 mm/rev and f=1,00 mm/rev gave results close to f=0,25 mm/rev). When a medium density glass fibre reinforced composite was tested, see Fig. 8, no consistency was noticed in the results, i.e., as cutting speed was increased best results (lowest delamination factor) were recorded at different feed rates. The results concerning the delamination factor for the high density material are presented in Fig. 9. Except for $v_c$=90 m/min and f=0,50 mm/rev, this mesh provided the least scattered results, although a clear trend could not be observed. In order to confirm the effect of cutting speed on the delamination factor, an analysis of variance (ANOVA) could be performed, thus indicating whether cutting speed significantly affects delamination within the range tested. This approach was not employed in the present case owing to the fact that the experimental planning would require a prohibitive amount of tests to be undertaken, since the number of factors and levels tested was relatively high.

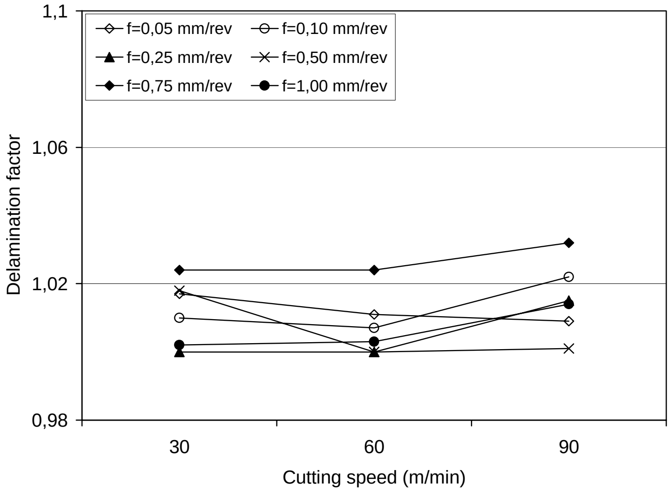


Figure 7. Effect of cutting parameters on delamination factor when drilling epoxy resin reinforced with glass fibres (low density)

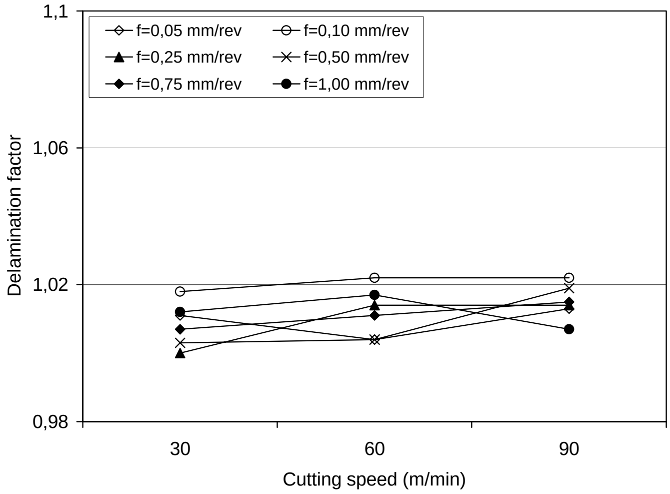


Figure 8. Effect of cutting parameters on delamination factor when drilling epoxy resin reinforced with glass fibres (medium density)

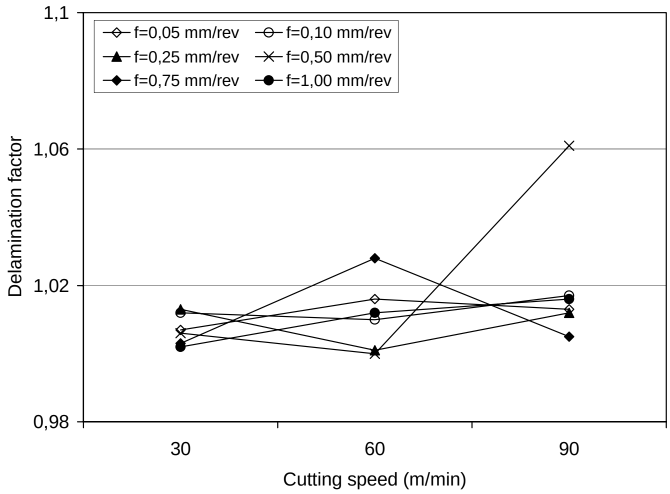


Figure 9. Effect of cutting parameters on delamination factor when drilling epoxy resin reinforced with glass fibres (high density)

The findings concerning the tests conducted at the University of Aveiro, in which a polyester resin reinforced with glass fibres was machining with two different drill geometries are presented in Figs. 10 to 13. Figures 10 and 11 show the effect of cutting speed and feed rate on feed force when using the stub length and Brad & Spur drills, respectively. Similarly to the results found for the reinforced epoxy resin, feed rate seems to possess a larger influence on feed force when compared to cutting speed. Additionally, the Brad & Spur drill provides lower feed forces and the force values recorded when testing the stub length drill were within the same range registered for the glass fibre reinforced epoxy resin (Figs. 4 to 6).

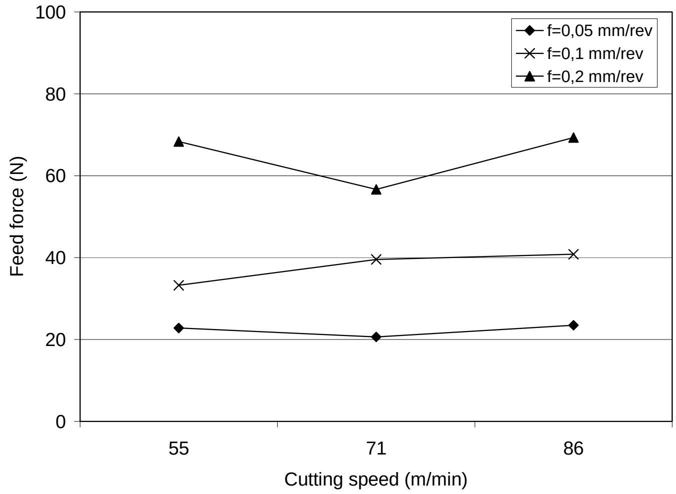


Figure 10. Effect of cutting parameters on feed force when drilling polyester resin reinforced with glass fibres using the stub length drill

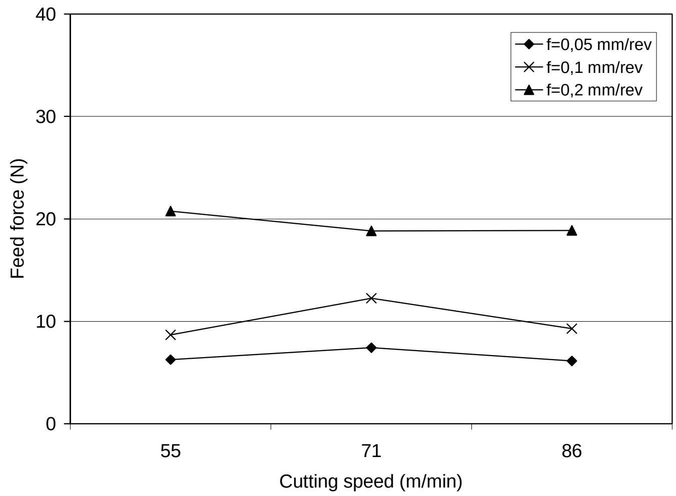


Figure 11. Effect of cutting parameters on feed force when drilling polyester resin reinforced with glass fibres using the Brad & Spurdrill

Figures 12 and 13 show the influence of the cutting parameters on the delamination factor for the two tool geometries tested. In contrast to the epoxy resin results, the delamination factor increases together with both cutting speed and feed rate. Moreover, the Brad & Spur drill presents a better performance than the stub length drill, i.e., the former produced lower delamination under the same cutting parameters. Comparing the delamination factor when drilling these two composites, it can be seen that the epoxy resin allows less delamination, especially when cutting the high density material. Again, an ANOVA could be employed in order to verify the influence of feed rate on delamination, however, this approach was not used for the same reasons previously indicated.

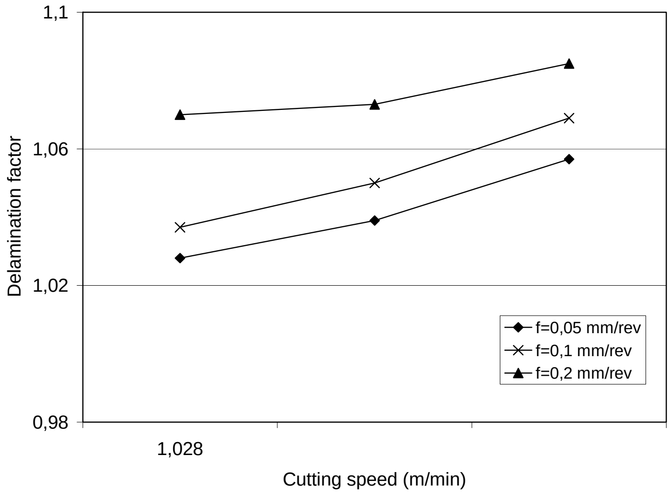


Figure 12. Effect of cutting parameters on delamination factor when drilling polyester resin reinforced with glass fibres using the stub length drill

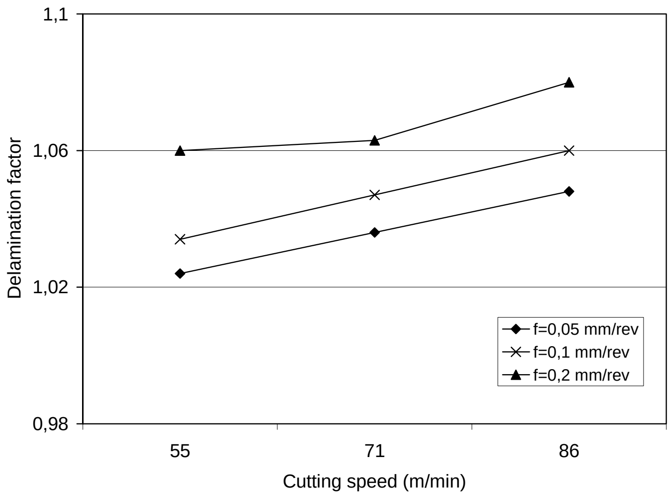


Figure 13. Effect of cutting parameters on delamination factor when drilling polyester resin reinforced with glass fibres using the Brad & Spur drill

## 4. Concluding remarks

After drilling an epoxy resin reinforced with glass fibres of different meshes with high speed twist drills the following conclusions can be drawn:

- The feed force increases with feed rate and reinforcement density, but it is not significantly affected by cutting speed;
- The relationship between the delamination factor and cutting speed or feed rate is not clear, however, lower values for the delamination factor were recorded after drilling the composite material with high density;

The findings related to the drilling of glass fibre reinforced polyester resin using two drills geometries allow the following conclusions:

- The feed force increases with feed rate and slightly with cutting speed;
- The Brad & Spur drill provides lower feed forces than the stub length drill under the same cutting parameters;
- The delamination increases with both cutting speed and feed rate and the Brad & Spur drill produces lower delamination factor compared to the stub length drill.

## 5. Acknowledgements

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## 6. References


Aoyama, E, Inoue, H., Hirogaki, T., Nobe, H., Kitahara, Y. and Katayama, T., 1995, "Study on Small Diameter Drilling in GFRP", Composite Structures, Vol. 32, pp.567-573.

Capello, E., 2004, "Workpiece Damping and its Effect on Delamination Damage in Drilling Thin Composite Laminates", Journal of Materials Processing Technology, Vol. 148, pp.186-195.

Caprino G. and Tagliaferri V., 1995, "Damage Development in Drilling Glass Fiber Reinforced Plastics", International Journal of Machine Tools and Manufacture, Vol.35, No.6, pp.817–829.

Davim, J.P., Reis, P. and Antônio, C.C., 2004, "Experimental Study of Drilling Glass Fiber Reinforced Plastics (GFRP), Manufactured by Hand Lay-up", Composites Science and Technology, Vol.64, pp.289-297.

Inoue, H., Aoyama, E., Hirogaki, T., Ogawa, K., Matushita, H., Kitahara, Y. and Katayama, T., 1997, "Influence of Tool Wear on Internal Damage in Small Diameter Drilling in GFRP", Composite Structures, Vol. 39, No. l-2, pp.55-62.

Khashaba, U.A., 2004, "Delamination in Drilling GFR-Thermoset Composites", Composite Structures, Vol. 63, pp.313-327.

Lachaud, F., Piquet, R., Collombet, F. and Surcin, L., 2001, "Drilling of Composite Structures", Composite Structures, Vol.52, pp.511-516.

Lin, S.C. and Chen, I.K. Drilling of Carbon Fiber-Reinforced Composite Material at High Speed. Wear 1996; 194(1-2):156–62

Mathew J., Ramakrishnan N. and Naik, N.K., 1999, "Investigations into the Effect of Geometry of a Trepanning Tool on Thrust and Torque During Drilling of GFRP Composites", Journal of Materials Processing Technology, Vol. 91, No. 1, pp. 1-11.

Ogawa, K., Aoyama, E., Inoue, H., Hirogaki, T., Nobe, H., Kitahara, Y., Katayama, T. and Gunjima, M., 1997, "Investigation on cutting mechanism in small diameter drilling for GFFW (thrust force and surface roughness at drilled hole wall)", Composite Structures, Vol. 38, No. 1-4, pp.343-350.

Smith, W.F., 1998, "Princípios de Ciência Engenharia de Materiais", McGraw-Hill, Lisboa, Portugal, 892p.


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