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# Diamond drilling of Carbon Fiber Reinforced Polymers: Influence of tool grit size and process parameters on workpiece delamination

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**Abstract**

The physical and mechanical properties of advanced composite materials promote their application in structural components for the aerospace and automotive sectors. However, limitations in their machinability are due to anisotropy/inhomogeneity, poor plastic deformation, and abrasive behavior. For CFRP drilling, the process efficiency is heavily influenced by cutting conditions and tool geometry. This paper reports the outcomes of experimental diamond drilling tests. A 4-mm thick carbon-epoxy composite laminate was machined. The plate was made of ten layers, in which the carbon fibers were intertwined at 90°. 6-mm diameter core drills were used. Core drills were characterized by an electroplated bond type and an AC32-H diamond grain type. Four different tool grit size ranges were tested: (1) 63/53 µm, (2) 125/106 µm, (3) 212/180 µm, and (4) 212/180 plus 63/53 µm. The results are reported in terms of workpiece delamination, thrust force, torque, and chip morphology. Overall, the results allow identifying the cutting conditions for the minimum drilling-induced delamination while retaining a satisfactory process productivity.


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*Keywords:* CFRP; Diamond drilling; Delamination; Cutting force

## 1. Introduction

Carbon Fiber Reinforced Polymers (CFRPs) are composite materials based on a polymer matrix reinforced with carbon fibers. These materials offer superior properties such as high strength-to-weight and stiffness-to-weight ratios, toughness, good corrosion-, creep-, fatigue-, and wear-resistance, low thermal expansion, and high vibration damping aptitude [1]. Such advantageous characteristics contributed to the wide diffusion of composite materials for structural components, especially in automotive, aeronautical, and aerospace industry [2]. Parts made of CFRPs are usually produced near-to-net shape, however additional machining operations are frequently required for assembly. The drilling of boreholes for rivets, bolts and screws represents one of the most common cutting operations. For instance, a single unit production of an Airbus A350 aircraft requires to drill up to 55,000 holes [3]. Therefore, the drilling process has to fulfill the requirements related with assembly needs and part quality specifications. Drilling is recognized as a complex process in which extrusion (by the drill chisel edge) and cutting (by the rotating cutting lips) coexist [4]. The inhomogeneity and anisotropy of composites cause the presence of damage in the region close to the drilled hole. The observed undesirable defects are fiber breakage, debonding, pull out, stress concentration, thermal damage, spalling, micro-cracking, and delamination [5]. Among these, drilling-induced delamination is a remarkable problem, which can imply the rejection (up to 60%) of aircraft components affected by such a defect [6]. As reviewed in [6, 7], in the last years, several papers aimed to understand the CFRP drilling mechanisms have been published. A particular focus was given on the effects of process parameter variation and tool material/geometry on the damaged area around the drilled holes, also by developing analytical and statistical models [5, 8]. In order to reduce delamination, lower values of feed rate have been suggested by many authors [4, 5, 9-12].


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Vice versa, conflicting results were given with respect to the cutting speed variation. When increasing the cutting speed, the delamination factor at the hole entrance was found to increase by Davim and Reis [11], to decrease by Phadnis [12], or it did not show any significant variation in the study by Abrão and co-authors [9]. In addition, when increasing the cutting speed, the delamination factor at the hole exit was found to increase by Davim and Reis [11], to decrease by Palanikumar [13], or to have a parabolic dependence on such variable (with a minimum point) by Marques et al. [4]. Many authors [3, 10, 14-16] investigated the influence of process parameters on thrust force and torque, since they are expected to directly affect the quality of the machined hole. According to Turki et al. [14], the reduction of the thrust force is one of the most effective ways to decrease the risk of damage. Feed has a greater influence than that of spindle speed on thrust force and torque. Therefore, a low feed rate is suggested during drilling of carbon/epoxy composites in order to lower thrust force and torque as well as to limit the presence of defects.

Several authors [5, 9, 10, 17-19] investigated the influence of tool geometry and/or material on drilling performance and delamination. Besides standard twist drills, tool geometries can vary among 'brad & spur' (or candle stick) drills, core drills, dagger drills, drills with multiple flutes, 'one shot' drills, saw drills, step drills, step-core- and core-special drills, and twist drills with double point angle [20]. The peculiar distribution of cutting forces exchanged with the workpiece can be identified as the main difference between the tools. In particular, core drills show advantages with respect to conventional twist drills due to the different application area and magnitude of the thrust force [21]. Twist drills are characterized by the chisel edge of the drill point that pushes aside the material during the tool penetration into the material. Moreover, the thrust force for core drills is approximable as a distributed circular load. This load distribution is expected to reduce the delamination risk, achieving a better hole quality.

Quan and Zhong [18] highlighted that core drills (with and without plated diamond coating) show advantages in terms of reduced tool costs, higher tool life, and better machined hole quality in comparison to High Speed Steel (HSS) drills. Low feed rates, high spindle speeds, and high pressure cooling conditions (applying water or air) were recommended in order to improve hole quality when drilling composites with core drills. Tsao and Chiu [19] developed compound core-special drills in order to minimize the problems related to the chip removal clog when using core drills. Such tools are composed of an outer tool (core drill) and an inner tool (twist drill, saw drill, or candlestick drill). Drilling of CFRP can be improved when using core-special drills with respect to standard core drills due to lower thrust force, delamination and chip clogging, as well as higher chip removal. Core drills are made with metal-bond polycrystalline diamond (PCD) particles, so that the cutting mechanism is similar to a grinding operation. Core drills are mainly characterized by the grit size of the particles and the thickness of the hollow tube. Tsao and Hocheng [22] compared the performance of core drills with grit sizes of 100, 200, and 400 sieve mesh, and thicknesses of 0.8, 1.0, and 2.0 mm, by varying the feed rate and the spindle speed in CFRP drilling. The grit size was found to be the most significant variable among the four control factors, while the drill thickness showed only a limited influence. Generally, the choice of grit size depends on the feed and the desired hole quality. In addition, Tsao [23] tested other core drills with grit sizes of 60, 80, and 100 sieve mesh, and thicknesses of 1.0, 1.5 and 2.0 mm. The experimental results indicated that (in those specific cases) the thickness had a significant impact on the overall drilling performance, so the lowest thickness was suggested to minimize thrust force and surface roughness. In this scenario, the present paper is focused on CFRP drilling by using diamond core drills with different tool grit sizes. The discussion of the results in terms of hole delamination at varying of the process parameters, such as cutting speed and feed rate, is supported by the measurements of thrust force and torque. The aim of the study is to identify the cutting conditions which can ensure the minimum drilling-induced delamination while retaining a satisfactory process productivity.

## 2. Experimental set-up

Drilling tests were performed on a 3-axis Cortini M500/F1 vertical CNC milling machine characterized by continuously variable spindle speed up to 8000 rpm and peak power of 3.7 kW. Details concerning the experimental setup as well as the measured outcomes are given in the following.

### *2.1. Workpiece material*

A 4-mm thick carbon-epoxy composite laminate was machined. The plate was made of ten 0.4-mm thick layers, in which the carbon fibers were intertwined at 90°. Table 1 lists the main properties of the CFRP plate (as provided by the material supplier).

Table 1. Workpiece material properties (from technical data sheet).

| | | |
|---|---|---|
| Matrix | Resin system | EPIKOTE™ Resin 04695-1 |
| | Density at 20°C | $1.17 \pm 0.02$ g/cm$^3$ |
| | Viscosity at 25°C | $9000 \pm 1000$ mPa·s |
| Hardener | Curing Agent | EPIKURE™ 05357 |
| | Density | $0.98 \pm 0.02$ g/cm$^3$ |
| | Viscosity at 25°C | $40 \pm 20$ mPa·s |
| Reinforcement | Type | Carbon Fiber |
| | Fabric weight | 400 g/m$^2$ |
| | Filaments/tow | 6K |
| | Weave type | Twill K2/2 (Style 402) |

### *2.2. Tool geometries*

For diamond drilling, 6-mm diameter core drills were used (Figure 1). Core drills are characterized by an electroplated bond type and an AC32-H diamond grain type. Four different tool grit size ranges were tested: (1) 63/53 μm, (2) 125/106 μm, (3) 212/180 μm, and (4) 212/180 plus 63/53 μm (according to the ISO 565 standard). The latter code (4) refers to core drills made of a 212/180 μm diamond substrate plus an external layer of 63/53 μm. Such peculiar tool design is expected to modify the cutting behaviour, since the main cutting work