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# COMPARATIVE ANALYSIS OF BURRS IN UD-CFRP COMPOSITES USING ADVANCED HOLE MACHINING TECHNOLOGIES

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Machining of carbon fibre reinforced polymer (CFRP) composites is challenging due to their inhomogeneous and anisotropic structure as well as the strong effect of the carbon fibres on wear. Burrs are critical machining-induced macro-geometrical defects in the case of the machining of CFRP composites, which may lead to assembly difficulties. Nowadays, although novel hole-machining technologies reduce the likelihood of burrs occurring, these technologies are often more costly and require longer machining times. The current experimental study focuses on the analysis of burrs induced by advanced hole machining technologies (helical milling, tilted helical milling and wobble milling) and comparison with a conventional one (conventional drilling). A total of 32 experiments were carried out in a VHTC 5-axis machining centre using uncoated solid carbide end mills. Furthermore, these technologies are compared and discussed based on the burrs experienced and average material removal rate (AMRR). Experimental results show that conventional drilling caused the lowest amount of burrs, followed by wobble milling, tilted helical milling and helical milling. Even though wobble milling is one of the most advantageous technologies in terms of burrs, the AMRR of conventional drilling is twenty times larger than that of wobble milling, therefore, the further development of wobble milling is recommended.

**Keywords:** carbon fibre reinforced polymer, exit burr, drilling, digital image processing

## 1. Introduction

Nowadays, the demand for fibre reinforced polymer composites is increasing and their key role in industry is undeniable. Carbon fibre reinforced polymer (CFRP) composites are no exception. According to a market report made in 2018 by M. Sauer and M. Kühnel [1], their demand by 2017 has more than doubled (114k tons) compared to that of 2010 (51k tons). The reason for this increasing trend lies behind the outstanding material and specific mechanical properties of these composites. CFRPs possess larger strength-to-weight ratios compared to metals, making them exceptionally suitable for parts built into assemblies connected to the aviation, aerospace and automotive industries, reducing fuel consumption [2, 3]. They also exhibit good levels of corrosion resistance and are very strong as well as stiff. However, to be a part of an assembly, these composites must be machinable, that is, can be drilled or milled. CFRPs are difficult to machine, since the carbon fibres significantly contribute to tool wear as well as make the material anisotropic and inhomogeneous. These aspects lead to several difficulties such as delamination, burrs, matrix degradation, microcracks or fibre pullouts [3, 4]. Since the present of burrs renders post-machining almost inevitable, in order to reduce the resources necessary for further manufacturing and achieve the quality that the aviation and automotive industries require, novel technologies have been introduced. In the current study, the most frequently used and promising novel UD-CFRP machining technologies are compared, namely conventional drilling, helical milling, tilted helical milling and wobble milling. The kinematics of these technologies are illustrated in Fig. 1.

The kinematics of conventional drilling (Fig. 1a) is the simplest of the four technologies investigated: the axis of the tool is coincident to the axis of the hole along which the tool is moving downwards while rotating around this axis. Therefore, the diameter of the hole is determined by the diameter of the tool [2, 5]. This simplicity renders machining the least time-consuming and results in a large material removal rate (MRR), however, in the case of drilling, it is highly likely that the surface will be damaged when the tool enters and exits the composite, leading to separation of the laminated layers. This phenomenon is referred to as delamination, which can render parts unsuitable for further assemblies.

To prevent such outcomes, a novel technology, namely helical milling (Fig. 1b) has been introduced. This technology is also known as orbital drilling [6], since the tool is moving on a helical path while rotating around its own axis, which is shifted from the axis of the hole. The kinematics can be carried out by circular inter-

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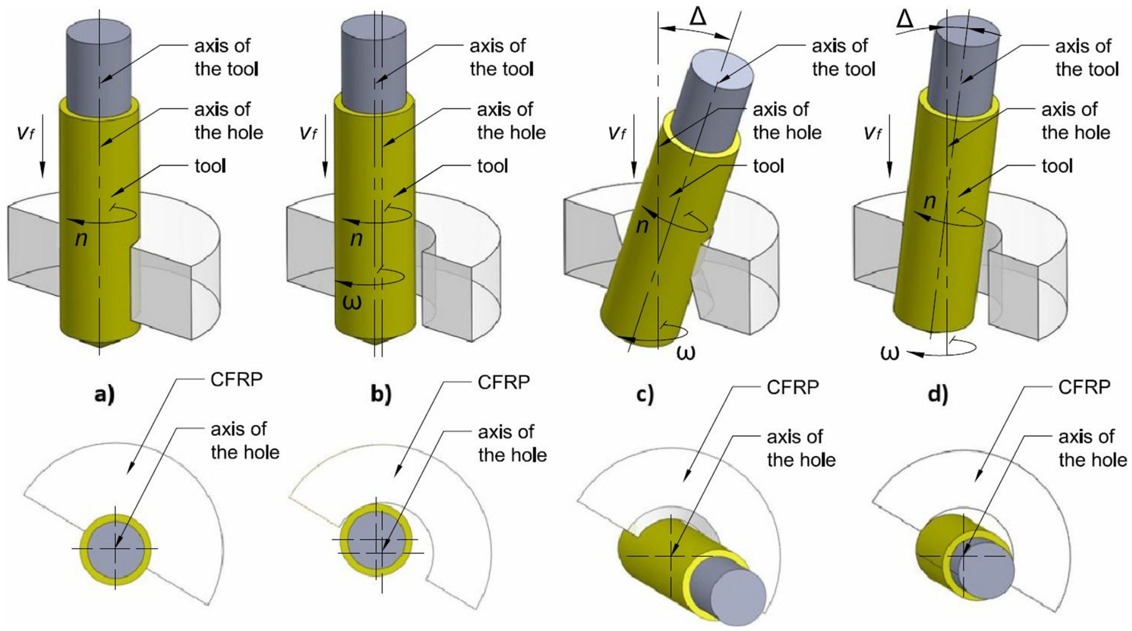


*Figure 1:* The examined technologies: a) conventional drilling, b) helical milling, c) wobble milling, d) tilted helical milling [3]

polation even with a tool with a smaller diameter to the hole being machined. According to Denkena et al. [5], although smaller forces and tool wear occur during machining, the drawback of this technology is that the effective cutting speed can reduce to zero [7].

To avoid an effective cutting speed of zero, further novel technologies have been introduced, which require a 5-axis machining centre or an industrial robot to be executed. One of them is tilted helical milling (Fig. 1d), during which the tool moves along a helical path while being tilted to the axis of the hole with an angle of $\Delta$ [7]. The surface of the hole becomes threaded, which leads to a high incremental increase of surface roughness compared to the other technologies.

The novel technology, wobble milling (Fig. 1c), is also based on the principle of tilted axes. The tool chamfers the top and bottom sides of the composite while the axes of both the hole and the tool enclose an angle of $\Delta$. This tilted motion compresses the layers of the composite, before the material is eliminated between the chamfers. The advantage of this process is that the surface is less likely to delaminate.

In the case of technologies that can only be executed on the 5-axis machining centres or using industrial robots, since the time required for machining is higher than needed for drilling, a novel characteristic factor shall be introduced for their comparison, namely the average material removal rate (AMRR), which gives the average amount of material that is removed over a unit of time [3].

## 2. Experimental and theoretical methods

This chapter is comprised of three subchapters. The first summarizes the information about the workpieces, tools and machines required for the experiments. In the second, details regarding the methods applied during the experiment and analysis are provided such as the experimental design, measurements of burrs, AMRR and analysis of variance (ANOVA).

### 2.1 Experimental setup

The workpieces of the present study were composed of UD-CFRP composite plates containing a vinyl ester matrix and long carbon fibres to provide reinforcement. The plates were cut by a water-jet cutting machine into cylindrical parts with a diameter of $d = 40$ mm and thickness of $h = 5$ mm.

The experiments were executed on a VHTC-130M-5HT 5-axis CNC machining centre with a tilting head. Two cutting tools were used for the machining: both tools were uncoated solid carbide end mills with only one cutting edge and a helix angle of $\lambda = 25°$. For conventional drilling and milling technologies, a tool with a diameter of $D_1 = 6$ mm (TIVOLY 82329710600) and of $D_2 = 4$ mm (TIVOLY 82329710400) were used, respectively.

A Nilfisk GB733 industrial vacuum cleaner was used to eliminate chips from the working environment. No coolant was applied during the experiment.

### 2.2 Methods

**Full factorial experimental design**

By focusing on the impact of the technologies (category factor) and feed rate (continuous factor) on the burrs and AMRR, an experimental design was needed that can be applied in the case of category factors as well. In this study, a full factorial experimental design [8] was applied,

*Table 1:* Parameters and their levels

| | Feed rate (mm/min) | | | Technologies (-) | | | |
|---|---|---|---|---|---|---|---|
| Levels | 50 | 100 | 150 | *T*1 | *T*2 | *T*3 | *T*4 |

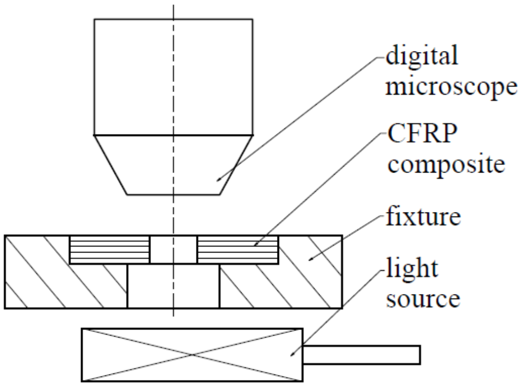


*Figure 2:* Digital photo capturing

moreover, the impact of the feed rate on the burrs and AMRR was examined in the case of the following technologies: conventional drilling ($T1$), helical milling ($T2$), tilted helical milling ($T3$) and wobble milling *(T4)*. During the experiment, a constant cutting speed of $v_\mathrm{c} = 120$ m/min was set, thus the spindle speeds of the tools with diameters of $D_1 = 6$ mm and $D_2 = 4$ mm were $n_1 =$ 6,366 RPM and $n_2 =$ 9,549 RPM, respectively. The feed rate was set at the following three levels: $v_{\mathrm{f},1} = 50$ mm/min, $v_{\mathrm{f},2} = 100$ mm/mi and $v_{\mathrm{f},3} = 150$ mm/min. At least one of the settings was repeated five times for each technology to ensure the experiment was reproducible. In order to eliminate the hidden errors, the 32 experimental settings were randomized. The parameters and their levels are summarized in Table 1.

### Evaluating burrs

A Dino-Lite AM0413MT digital microscope was used with a 50x magnification and DinoCapture 2.0 software installed to examine the burrs. The photos were taken from the top and bottom sides of the composites which, being denoted by their individual numbers written on top, were identified with ease. A light source was placed beneath the composites to illuminate them, thereby enhancing the view of the uncut fibres as presented in Fig. 2.

In order to create as clear photos as possible, the distance between the composites and the microscope varied at each setting. As a result, since the holes in the photos were of different sizes, a universal evaluation method was needed to eliminate any errors when compared. This was achieved by creating an image of an ideal hole (not containing any black pixels where the white circle and black square meet) before segmenting it and calculating the number of black and white pixels found.

The photos of the machined holes, after being segmented, were cropped given the absence of any black pixels at each side of the square and circular meeting point, as is shown in Fig. 3. Then the number of pixels was determined using the program Wolfram Mathematica, before being listed in Microsoft Excel and used for further calculations in Minitab. The burrs resulting from different technologies were compared based on a burr ratio factor ($F_\mathrm{br}$) and the length of the longest burr of the holes ($L_\mathrm{B}$).

The burr ratio factor

$$F_\mathrm{br} = 100\left(1 - \frac{\frac{W_i}{T_i}}{\frac{W_\mathrm{id}}{T_\mathrm{id}}}\right) \tag{1}$$

is based on the quotient of the ratio $W_i$ (the number of white pixels of the given hole) to $T_i$ (total number of pixels of the given hole) and the ratio of $W_\mathrm{id}$ (the number of white pixels of the ideal hole) to $T_\mathrm{id}$ (total number of pixels of the ideal hole). The larger $F_\mathrm{br}$ is, the more burrs found in the hole. By following this method, since the difference in the size of the photos does not affect the results, the comparison of holes does not depend on the distance set between the microscope and the composites.

The length of the longest burr in the case of each setting examined was determined using AutoCAD 2022 by measuring their lengths based on the photos created by DinoCapture 2.0 (Fig. 3a). On the one hand, measurements were made by connecting the endpoint of the longest uncut fibre to the edge of the hole with a straight line and determining the distance between them three times before calculating their mean according to

$$L_\mathrm{B} = \frac{1}{3}\sum_{j=1}^{3} l_j \tag{2}$$

where $l_j$ ($\mu$m) denotes the measured length of the longest burr and $L_\mathrm{B}$ ($\mu$m) represents the average length of a given burr used for comparison.

On the other hand, a corrected burr length ($L_\mathrm{B,corr}$) was calculated by measuring the length of the burr via the creation of a polyline: the five break points of these polylines were nearly equidistant from each other and each hole was measured three times. The lengths of the polylines were calculated by

$$L_\mathrm{B,corr} = \frac{1}{3}\frac{1}{5}\sum_{j=1}^{3}\sum_{i=1}^{5} l_{ij} \tag{3}$$

where $l_{ij}$ ($\mu$m) denotes a segment of the polyline of the longest burr and $L_\mathrm{B,corr}$ ($\mu$m) represents the length of the burr used for comparison.

### Average material removal rate

The AMRR (mm$^3$/min), which gives the average amount of material removed, was calculated using

$$\mathrm{AMRR} = \frac{hd^2\pi}{\Delta t} \tag{4}$$


*Figure 3:* Digital image processing: a) photo captured by the digital microscope, b) segmented image, c) cropping the image, d) image used for the analysis

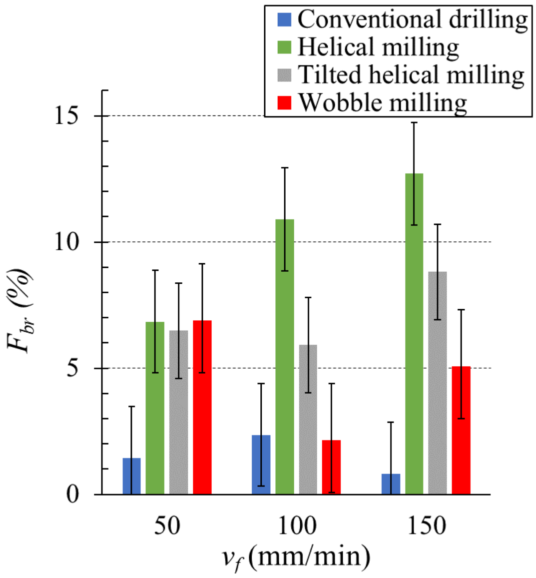


*Figure 4:* Burr ratio factor – feed rate diagram

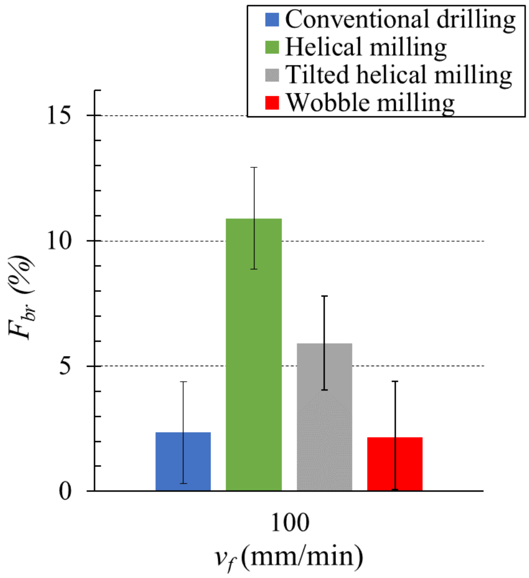


*Figure 5:* Main effect of the technologies on the burr ratio factor at $v_f = 100$ mm/min.

by measuring the required time for machining. In Eq. 4, $h = 5$ mm is the height of the composite, $d = 6$ mm is the diameter of the holes, and $\Delta t$ (min) denotes the time required for machining. Furthermore, assuming the holes have the same geometry at each setting, the average material removal rate could be determined.

Since the tool follows a longer path without machining in the case of 5D technologies, material is removed over a longer period of time. Therefore, the average material removal rate is needed to precisely compare these technologies.

**Analysis of variance**

In this study, the impact of technologies on burrs was investigated by ANOVA. The null hypothesis states that the technologies have no significant effect on the burrs at a significance level of $\alpha = 0.05$.

## 3. Results and discussion

### 3.1 Analysis of burrs

The results show that the holes machined by conventional drilling and wobble milling are the most burr-free compared to the ideal hole, whereas the holes machined by tilted helical milling and helical milling contain a larger number of burrs as is shown in Fig. 4. Helical milling resulted in the greatest amount of burrs, contradictory to the statements made by Denkena et al. [5] as well as Eguti and Trabasso [7] that helical milling can yield less burrs compared to conventional drilling. Given the main effect of technologies shown in Fig. 5, the null hypothesis was rejected, that is, these technologies have a significant impact on the burr ratio factor.

There is a significant difference between the length of burrs achieved by different technologies as can be seen in Fig. 6. The length of burrs was less than 1 mm for holes machined by conventional drilling and wobble milling, while the length of burrs in holes machined by tilted helical milling exceeded 2 mm at all settings. The longest burrs were produced by tilted helical milling and conventional helical milling, the latter resulted in burrs that were more than four times as long compared to conventional drilling and wobble milling at the greatest examined feed rate. Wobble milling, causing short burrs and a low burr ratio factor, yielded outstanding results compared to technologies based on helical milling.

Analysis of variance showed that with a significance level of $\alpha = 0.05$ the null hypothesis was rejected, thus

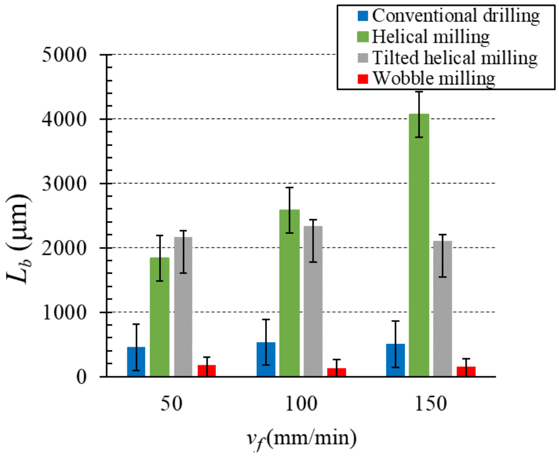


*Figure 6:* Length of burrs – feed rate

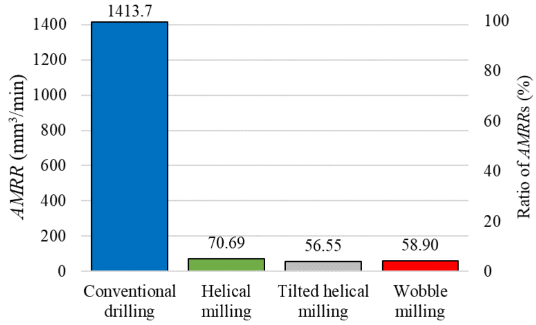


*Figure 7:* AMRR of the technologies compared to conventional drilling

the technologies have a significant effect on the length of burrs.

### 3.2 Analysis of AMRR

AMRR was greatest in the case of conventional drilling. The AMRRs resulting from milling technologies were lower but similar. As is illustrated with the second axis of the diagram in Fig. 7, the AMRRs of the milling technologies are far greater than that of the drilling technology (4 − 5% of the AMRR). The AMRR values are shown in Fig. 7 with a feed rate of $v_\text{f} = 50$ mm/min.

## 4. Conclusions

In this study, 32 holes were machined by conventional drilling, helical milling, tilted helical milling and wobble milling technologies using solid carbide end mills. The conclusions are summarized as follows.

- The experimental results show that the hole machining technology has a significant effect on the burr ratio factor defined at the exit of the holes.
- It was observed that holes machined by conventional drilling and wobble milling are characterized by the smallest amount of burrs compared to the other examined technologies. Since the burr ratio factors of holes machined by tilted helical milling and helical milling were larger, these holes contain a larger amount of burrs. Holes machined by helical milling are the least ideal of the four technologies examined concerning burrs.
- ANOVA results show that the technologies have a significant effect on the length of burrs in the holes.
- The length of burrs was the longest in the case of holes machined by helical milling, followed by tilted helical milling. However, with a feed rate of $v_\text{f} = 50$ mm/min, holes machined by tilted helical milling contained the longest burrs. Holes machined by conventional drilling and wobble milling contained shorter burrs compared to the other milling technologies. Burrs of holes machined by wobble milling were the shortest, independent of the feed rate.
- The AMRR of conventional drilling is the largest due to the simplicity of its kinematics and the AMRR of the milling technologies is around 4 − 5% of that of drilling for the parameter set applied during the experiment.
- Although wobble milling is a promising novel hole machining technology, further development is required to increase its material removal rate.

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