

A comparative experimental study of the machinability of UD-CFRP using right-hand-cut and left-hand-cut end mills

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Abstract. Recently, carbon fibre-reinforced polymers (CFRP) have been widely used composite materials in the energy, aerospace, automotive and sport industries. The machining behaviour of CFRPs is difficult to predict and to describe due to their anisotropy and inhomogeneity. The most frequent forms of damage are delamination, fibre pull-out, micro-cracking and matrix burning.

In this comparative experimental study, the influence of feed rate, cutting speed and screw pitch of the feeding helix on the cutting force, surface roughness and delamination were analysed for orbital drilling of uni-directional carbon fibre-reinforced plastics (UD-CFRP). Right-hand-cut and left-hand-cut solid carbide end mills were used in the experiments, and both of them had only one cutting edge. The experiments were designed using the central composite design method and were carried out on a NCT Kondia B640 three-axis CNC machining centre. The relations between factors and response variables were analysed using second-degree polynomial models by means of the response surface methodology (RSM).

The results demonstrate that the feed rate is the most significant factor affecting cutting force, delamination and surface roughness using either right-hand-cut or left-hand-cut end mills. The peel-up delamination area of the produced holes drilled with the right-hand-cut end mill is smaller than the one for the holes where the left-hand-cut end mill was used. Moreover, the holes produced with the right-hand-cut end mill also present a better surface roughness.

Introduction

Carbon fibre-reinforced plastics (CFRP) have low density, high damping ability and high strength-to-weight ratio, they are therefore widely used structural (non-metal based) composite materials in the energy, aerospace, automotive and sport industries [1, 2]. Machining CFRPs is necessary because of the high geometrical and position tolerance requirements. Due to the non-homogeneity and anisotropy of FRPs, their machining behaviour is not directly derivable from the expertise in metal machining [3]. The machinability analysis of CFRP is therefore necessary and important.

Their most frequent forms of damage are delamination, fibre pull-out, micro-cracking and matrix burning. Due to high cutting forces and other parameters (such as cutting tool point angle, tool sharpness, temperature, etc.) the laminated CFRP layers can separate from each other's [4, 5, 6, 7, 8]. Those caves between the laminated layers are called delamination. The delamination is observed at the entry face (peel-up delamination) and at the exit face of the hole (push-down delamination), as can be seen in Fig. 1.

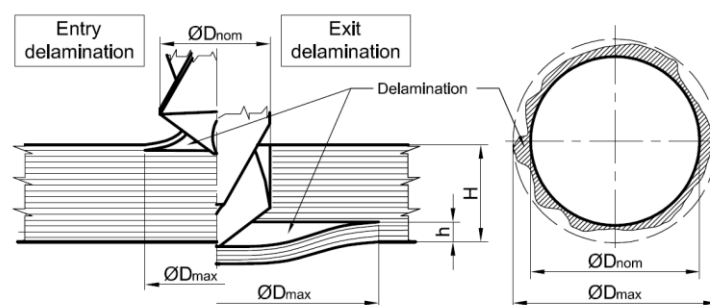


Fig 1. Schematic diagram of the peel-up and push-down delamination during conventional drilling [2]

The delamination factor (D) is a one-dimensional ratio number, which can represent the percentage-size of the delamination area around the drilled hole. The D is the ratio of the maximum diameter of the delamination area (D_{max}) to the nominal hole diameter (D_{nom}) [2], as expressed by Eq. (1).

$$D = \frac{D_{max}}{D_{nom}} \quad (1)$$

The main objective of the present experimental study was the machinability analysis of uni-directional carbon fibre-reinforced plastics (UD-CFRP) using a right-hand-cut and a left-hand-cut solid carbide end mills. The x- directional cutting force (F_x), the delamination factor (D) and the average surface roughness (R_a) were analysed using second-degree polynomial models by means of the response surface methodology (RSM).

Experimental setup

The orbital drilling (hole machining strategy, using an end mill with helical tool patch) experiments were carried out on a Kondia B640 three-axis CNC milling machining centre with maximum rotational speed of 12,000 rpm. The machining centre was equipped with a NILFISK GB733 vacuum cleaner (14.7 kPa) to clear off the chips from the cutting area. A Ø10 mm right-hand-cut and an Ø8 mm left-hand-cut solid carbide end mills were used and both of them had only one cutting edge, as shown in Fig. 3.

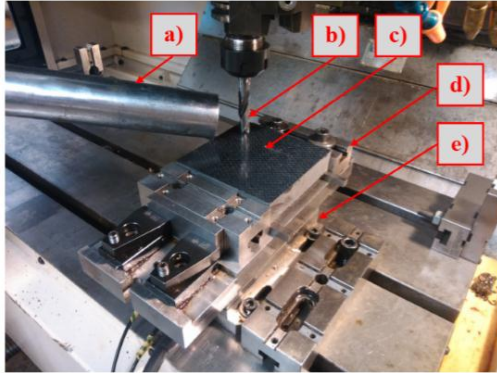
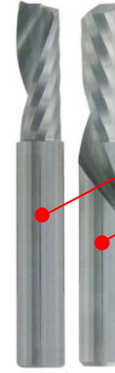


Fig 2. The cutting experimental setup a) Vacuum cleaner; b) Cutting tool; c) CFRP; d) Fixture; e) KISTLER load cell [2]



Right-hand-cut solid carbide end mill

- Type: PERFOR 823665110008
- Diameter: Ø10
- Cutting edges: 1
- Helix angle: 25°

Left-hand-cut solid carbide end mill

- Type: PERFOR 82366610800
- Diameter: Ø8
- Cutting edges: 1
- Helix angle: 25°

Fig 3. The cutting tools used during this study. A right-hand-cut solid carbide end mill (left) and a left-hand-cut solid carbide end mill (right)

The cutting force components (F_x , F_y , F_z) were measured with a KISTLER 9281B load cell with a sampling frequency of 2000 Hz. The data were collected using the KISTLER Dyno Ware software. The delamination was analysed and measured through an Olympus SZX16 optical microscope. The average surface roughness was measured and calculated with a Mitutoyo SJ-400 instrument. The machining experimental setup (vacuum cleaner, cutting tool, workpiece, fixture and load cell) can be seen in Fig. 2.

The experiments were designed using the central composite (CCI) design of experiments (DOE) method. The factors and their levels were defined based on previous works and suggestions of other researchers [1, 2, 4]. The cutting speed (v_c), feed rate (f) and the screw pitch of the feeding helix (h) were the numerical, continuous factors, which have an influence on the responses (F_x , D , R_a). The factors and their levels can be seen in Table 1.

Table 1. Central composite (CCI) experiment parameters for the Ø10 PERFOR 823665110008 right-hand-cut and for the Ø8 PERFOR 82366610800 left-hand-cut solid carbide end mills.

Tools	Factors	Levels				
		-2 ^{3/4}	-1	0	+1	+2 ^{3/4}
Right-hand-cut end mill	Cutting speed (m/min)	50	70	100	130	150
	Feed rate (mm/rev)	0.020	0.028	0.040	0.051	0.060
	Screw pitch (mm)	0.10	0.068	1.55	2.41	3.00
Left-hand-cut end mill	Cutting speed (m/min)	50	70	100	130	150
	Feed rate (mm/rev)	0.020	0.028	0.040	0.051	0.060
	Screw pitch (mm)	0.10	0.068	1.55	2.41	3.00

Results

The response surface methodology (RSM) is a mathematical technique to analyse the influences of the factors on the response. The response surface is an n -degree polynomial regression model which can be generated through the measured values. The machining behaviours of the CFRPs are non-linear [1, 3], a second degree ($n=2$) polynomial regression model was therefore used in the present study, as expressed by Eq. (2).

$$y = b_0 + \sum_{i=1}^n b_i x_i + \sum_{i=1}^n b_{ii} x_i^2 + \sum_{i=1}^{n-1} \sum_{j=i+1}^n b_{ij} x_i x_j + \delta \quad (2)$$

Where y is the corresponding response which we are interested in, x_i are the input variables (factors), which affect the y response. i is the number of the factors, b_i , b_{ij} and b_{ii} are the regression coefficients of the factors, and δ is the random experimental error. The analysis of variance (ANOVA) was used to analyse the main effects and the significant factors. The ANOVA is a statistical test used to decide if rejecting or not the null hypotheses ($H_{0,i}$, which means that the x_i factor doesn't have a significant effect on the response). If the calculated k value is bigger than a critical k value, the H_0 is rejected.

Cutting force

Three cutting force components (F_x , F_y and F_z) were measured by the KISTLER load cell. The axial cutting force component (F_z) was not as significant as the force component in the direction of the feed rate, the x -directional force component was therefore analysed and used to describe the machining behaviour of the UD-CFRP. The RSM based mathematical regression models can be seen in Eq. (3) for the right-hand-cut and in Eq. (4) for the left-hand-cut end mill. The models are shown in the Fig. 4 and 5. As the ANOVA and the diagrams accurately show, the factor that most significantly influence the F_x is the screw pitch of the feeding helix (h). The cutting speed, on the contrary, does not have an appreciable effect on the response.

As observable in Fig. 4 and 5, if the screw pitch increases, the F_x increases as well using both cutting tool. In case of increasing of the feed rate, the F_x also increases. If the diagrams are compared, the maximal measured x -directional force is one order of magnitude higher when using the left-hand-cut than with the right-hand-cut end mill. The reason of this difference can be found in the non-homogeneity and anisotropy of CFRPs.

$$F_{x,R}(v_c, f, h) = 5.58 - 0.0029v_c - 52f - 1.28h - 0.000333v_c^2 - 781f^2 + 0.384h^2 + 1.1v_cf + 0.02v_ch + 34.7fh \quad (3)$$

$$F_{x,L}(v_c, f, h) = 36.9 - 0.191v_c - 1139f - 1.28h - 0.00021v_c^2 + 6687f^2 - 0.01h^2 + 4.67v_cf + 0.0191v_ch + 559fh \quad (4)$$

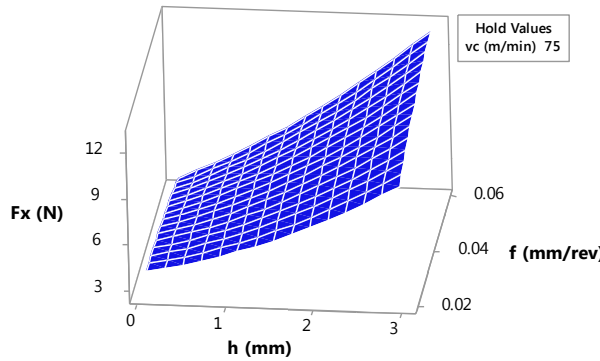


Fig 4. Influence of the screw pitch of the feeding helix (h) and the feed rate (f) on the maximal x-directional force (Fx) using the right-hand-cut end mill

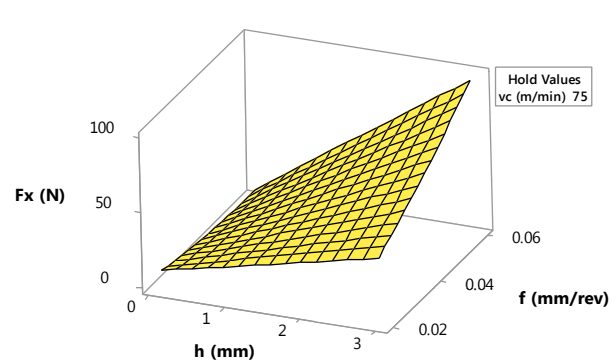


Fig 5. Influence of the screw pitch of the feeding helix (h) and the feed rate (f) on the maximal x-directional force (Fx) using the left-hand-cut end mill

Delamination

The delamination factor was measured and analysed in the entrance of the holes (peel-up delamination). The RSM based mathematical regression models are expressed in Eq. (5) for the right-hand-cut and in Eq. (6) for the left-hand-cut end mill. The models are shown in Fig. 6 and 7. The delamination area at the entry zone of the holes can be seen in Fig. 10.

As can be seen in Fig. 6, the delamination factor increases with the increase of the cutting speed; on the other hand, in case of increase of the feed rate the delamination factor behaves hyperbolically, as shown in Fig. 6. The ANOVA demonstrated that the cutting speed has the biggest impact on the delamination using the right-hand-cut end mill. The interaction terms between the factors are big and the screw pitch of the feeding helix doesn't have any effect on the peel-up delamination.

$$D_R(v_c, f, h) = 1.205 - 0.00039v_c - 6.56f + 0.0183h - 0.000002v_c^2 + 69.3f^2 - 0.00642h^2 + 0.015v_cf + 0.000341v_ch - 0.713fh \quad (5)$$

$$D_L(v_c, f, h) = 1.345 - 0.00093v_c - 4.86f + 0.0233h - 0.000002v_c^2 - 2.3f^2 - 0.0222h^2 + 0.0191v_cf + 0.0000881v_ch + 1.61fh \quad (6)$$

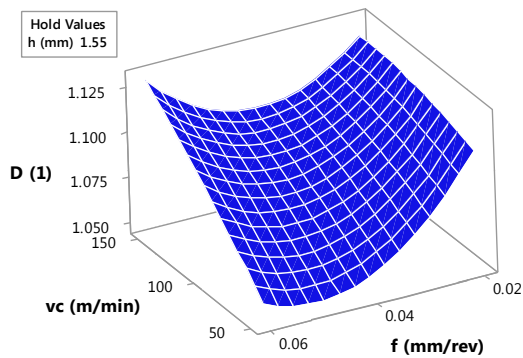


Fig 6. Influence of cutting speed (v_c) and feed rate (f) on the delamination (D) using the right-hand-cut end mill

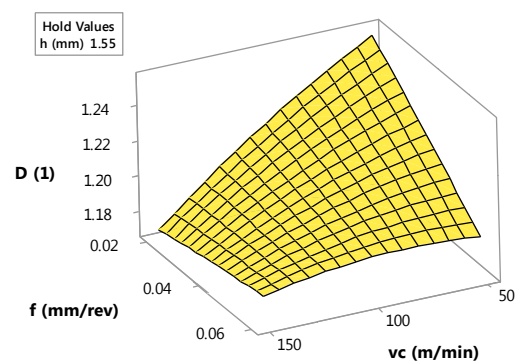


Fig 7. Influence of cutting speed (v_c) and feed rate (f) on the delamination (D) using the left-hand-cut end mill

As can be seen in Fig. 7, the delamination factor increases with the decrease of the cutting speed, on the contrary, in case of increase of the feed rate the delamination decreases. The ANOVA showed that cutting speed and feed rate have the most significant impact on the delamination using the left-hand-cut end mill. The interactions between feed rate and cutting speed is considerable.

Surface roughness

The surface roughness profile was measured five times on every surface of the holes. The average surface roughness (R_a) was calculated through the Mitutoyo instrument and were analysed through the RSM technique. The RSM based second-degree mathematical regression models can be seen in Eq. (7) for the right-hand-cut and in Eq. (8) for the left-hand-cut end mill. The models are shown in the Fig. 8 and 9. The quality of the surface of the drilled holes can be seen in Fig. 10.

As shown in Fig. 8, there is a big interaction between cutting speed and feed rate, using the right-hand-cut end mill. If the feed rate increases, the average surface roughness decreases. If the cutting speed increases the changing direction of the response is heavily dependent on the other factor levels.

Fig 9 shows that the interaction between the analysed factors are negligible using the left-hand-cut end mill. The feed rate and the screw pitch of the feeding helix doesn't have a significant effect on the average surface roughness. In case of increase of the cutting speed the R_a behaves hyperbolically. The surface roughness is one order of magnitude higher using the left-hand-cut end mill, than with the other tool.

$$Ra_R(v_c, f, h) = 14.4 - 0.03v_c - 48f - 9.48h - 0.000263v_c^2 - 2135f^2 + 1.319h^2 + 1.15v_cf + 0.0262v_ch + 38fh \quad (7)$$

$$Ra_L(v_c, f, h) = -753 + 9.34v_c - 1197f + 295.7h - 0.02816v_c^2 + 5716f^2 - 27.4h^2 + 4.53v_cf + 1.629v_ch \quad (8)$$

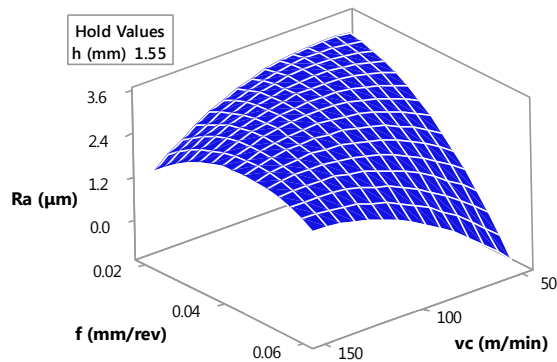


Fig 8. Influence of cutting speed (v_c) and feed rate (f) on the average surface roughness (Ra) using the right-hand-cut end mill

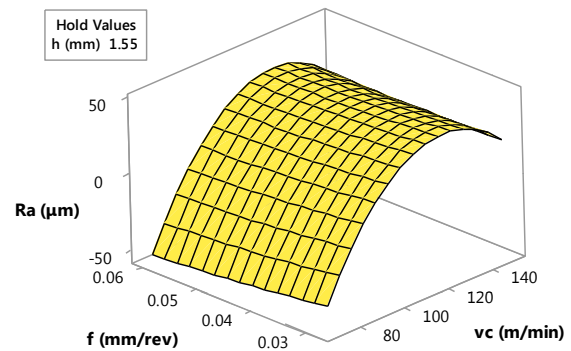


Fig 9. Influence of cutting speed (v_c) and feed rate (f) on the average surface roughness (Ra) using the left-hand-cut end mill

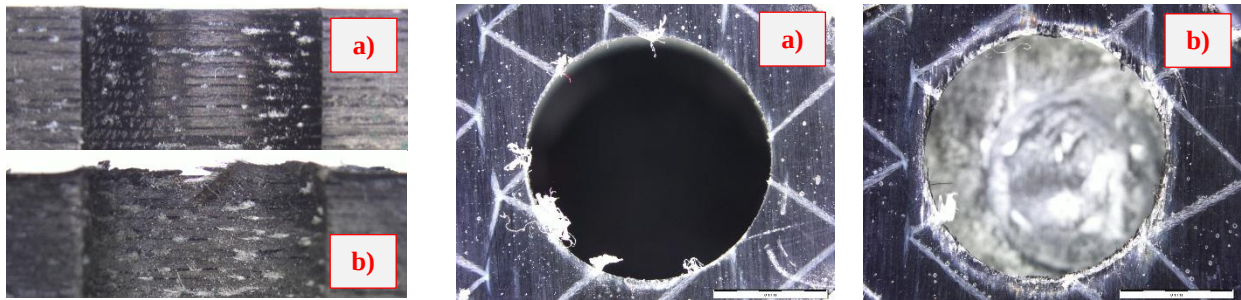


Fig 10. The surfaces and entry zones of the drilled holes a) right-hand-cut end mill b) left-hand-cut end mill

Summary and conclusions

The main goal of the present experimental study was the machinability analysis of a UD-CFRP using a right-hand-cut and a left-hand-cut solid carbide end mills. The x- directional cutting force (F_x), the delamination factor (D) and the average surface roughness (Ra) were analysed using second-degree polynomial models by means of the response surface methodology (RSM).

The results showed that both x-directional cutting force and average surface roughness of the drilled holes were one order of magnitude higher using the left-hand-cut end mill than the right-hand-cut one. The reason of this differences can traced back to the non-homogeneity and anisotropy of CFRPs. The delamination, fibre pull-out, micro-cracking and matrix burning were also more significant using the left-hand-cut end mill. To summarize, the right-hand-cut solid carbide end mill is able to produce a good quality (with respect to delamination, average surface roughness, fibre pull-out etc.) holes contrary to the left-hand-cut end mill.

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References

- [1] Haijin Wang, Jie Sun, Jianfeng Li, Laixiao Lu, Nan Li (2015) Evaluation of cutting force and cutting temperature in milling carbon fiber-reinforced polymer composites. *Int J Adv Manuf Technol* 71:1295–1307
- [2] Geier N, Matyasi G (2015) Machinability study of unidirectional CFRP using central composite design of experiments. *IESB 2015 Conference* ISSN 2062-2872
- [3] Y. Karpat, B. Değer, O. Bahtiyar (2014) Experimental evaluation of polycrystalline diamond tool geometries while drilling carbon fiber-reinforced plastics. *Int J Adv Manuf Technol* 71:1295–1307
- [4] Wang H, Sun J, Li J, Lu L, Li N (2015) Evaluation of cutting force and cutting temperature in milling carbon fiber-reinforced polymer composites. *Int J Adv Manuf Technol* 82:1517–1525
- [5] Wang H, Sun J, Li J, Li W (2014) Investigation on delamination morphology during drilling composite laminates. *Int J Adv Manuf Technol* 74:257–266
- [6] Abrao AM, Faria PE, Campos Rubio JC, Reis P, Davim JP (2007) Drilling of fiber reinforced plastics: A review. *Journal of Materials Processing Technology* 186:1–7
- [7] Singh AP, Sharma M, Singh I (2013) A review of modeling and control during drilling of fiber reinforced plastic composites. *Composites Part B* 47:118–125
- [8] Hocheng H, Dharan CKH (1990) Delamination during drilling in composite laminates. *ASME J Eng Ind* 112:236–239