# Machinability analysis of carbon fibre-reinforced plastics (CFRP) using compression tools

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***Abstract* — The widely spread use of polymer composites and their difficult machining behaviour have directly led to the appearance of tools with unique geometry, specialised for carbon fibre-reinforced plastics (CFRP). These so called compression tools are crafted in a way to reduce delamination, which is a common machining caused material defect. The present study focuses on the effect of technological factors on various optimization parameters in cases compression tools were used. Cutting width and feed rate have been chosen as factors. The factor levels have been determined beforehand, using central composite inscribed (CCI) design. The machining experiments were carried out on a Kondia B640 milling machine centre. A KISTLER 9257BA load cell was used for the measurement of the cutting force, likewise a Mahr Federal Pocket Surf IV instrument for surface roughness. Collected data were processed using analysis of variance (ANOVA) and response surface methodology (RSM) via Minitab 17. As a result of this research the change of tool-geometry and process parameters of CFRP machining were determined, induced by technological parameters, on two various compression tools. It was found that the feed rate has the most significant effect on the cutting force and surface roughness, followed by the cutting width.**

***Keywords* —** CFRP; milling; compression tool; multitooth tool; cutting force; surface roughness

## 1 INTRODUCTION

Lately widespread of carbon fibre-reinforced plastics (CFRP) was caused by it's outstandingly high specific strength and specific modulus [1], [2]. Nowadays, composites are widely used in military-, automotive- and aviationindustry. Aircraft constructions such as a Boeing 787 consist composites up to 50% by weight and 70% by volume [3]. Manufacturers aim to mold CFRP parts, to match their final size and shape. Moreover they use force bounded and glued joinings [4], [5]. However machining of these components is inevitable to meet required tolerances, and in some cases the final desired shape [6]. There have been preliminary studies on the milling of CFRP in order to optimize milling parameters. Geier et al. [7] have determined that the feed rate is the most significant parameter when it comes to cutting force. They also stated that the increase of feed rate results int the growth of cutting force. Wang et al. [8] have also verified this statement, and also concluded, that the next most determinative factor during face milling is the cutting width. In their paper they stated that parameter's raise also causes the increase of cutting force. One of the most systematic studies on surface roughness optimalization was conducted by Khairusshima et al. [9]. In their analysis they found that the most important factor in this aspect of research is the feed rate. Furthermore, at a constant feed rate surface roughness is the lowest, when the lowest cutting width is applied. Although all these previous studies, CFRP specific tools have been rarely reseached.

### *1.1 Compression tools*

Compression tools (in some papers also called multitooth tools) are crafted specifically for the milling of CFRP. These tools are fabricated with a geometry, which directs passiv force components towards the center of the layers, thus pressing them together. This mechanism is favorable to avoid delamination (separation of layers in the composite material). Tool manufacturers reach this effect for instance with the formation of a double opposed helix along the tool's cyclinder surface, represented on Fig. 1.

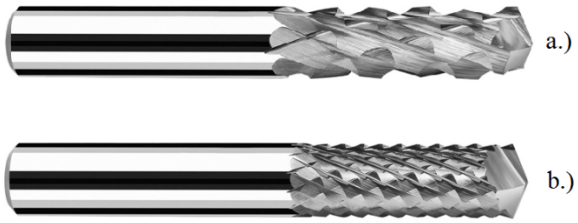


**Fig. 1** a.) Fraisa 20340.450 and b.) Fraisa 20360.450 compression end mills

In a previous study Lacalle et al. [10] researched these tool's wear, and wear dependent efficiency. Despite this interest, the investigation of optimized machining parameters for these special tools is still neglected.

The main objective of the present study was to reach a deeper understanding on how basic machining factors (tool and cutting width) influence the optimization parameters (cutting force and surface roughness), in cases where compression end mills were applied.

## 2 EXPERIMENTAL SETUP AND CUTTING CONDITIONS

### *2.1 Environment*

The machining experiments were carried out on a Kondia B640 milling machine centre. A KISTLER 9257BA type load cell was used for the measurement of the cutting force, likewise a Mahr Federal Pocket Surf IV instrument for surface roughness. A Fraisa 20340.450 (referred as coarse tool) and a Fraisa 20360.450 (referred az medium tool) compression end mills (Fig. 3) were used with climb milling technology.

The examined UD-CFRP block was fixed with two clamps as can be seen in Fig. 2. Two microscopes were placed in the workspace for the detection of tool wear.

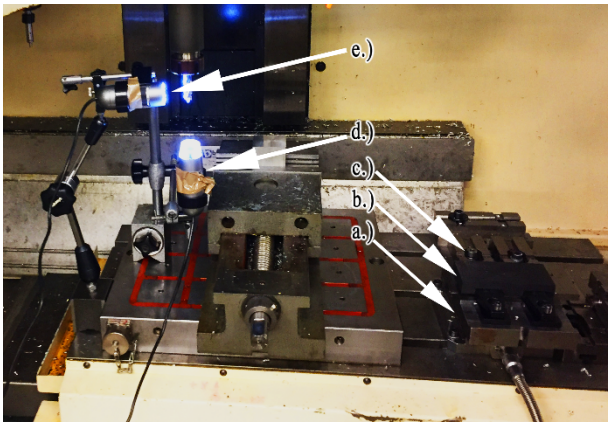


**Fig. 2** Experimental setup. a) UD-CFRP specimen; b) fixture c) KISTLER load cell d.), e.) digital microscopes

Milling experiments were designed using central composite inscribed (CCI) design. Cutting with and feed rate were chosen as factors in order to analyse their influence on the optimisation parameters: cutting force and surface roughness. Other process parameters, such as revolutions per minute ($n$= 3185 1/min), milling style (down milling) and depth of cut ($a_p$=18 mm), as well as extreme values for the CCI design were fixed based on previous works [11], [12] and suggestions of tool manufacturers.

During the experiments, workpiece was face milled The edges of the cutting tool are captured in original state, to be used later as a control picture. The three dimensionas cutting force data were collected at 8000 Hz frequency. During the machining the abrasive chips were vacuumed. After the machining, images of the machined surface were taken by a Dino-lite AD7013MZT digital microscope. Thereafter the surface roughness was measured perpendicularly to the toolpath five times along the cut. In the meantime photos of the tool were taken for subsequent comparison.

## 3 Results and Discussion

Thirteen experiments were carried out for each tool. The randomised experiment design tables were calculated with MiniTab 17. The results for each experiment are shown in Table 1 and Table 2

Using response surface methodology (RSM), a quadratic polinomial model on data was developed. The second-degree formula was used in this study is expressed by Eq.(1).

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

,where $y$ is the optimisation parameter, $b$ marks constant multipliers, $x$ marks the factors, and $n$ is the number of factors, while δ is the error-factor.

### *3.1 Cutting force*

The cutting force data were interfered with distortion such as machine noise from the milling centre. The data has been low-pass filetered with discrete Fourier transfomation (DFT). The signals which belong to higher frequency domains has been removed. The results shown in Table 1 and Table 2 are the maximum force values given by the filtered data set. The resultant maximum force is calculeted as expressed by Eq.(2).

$$F_{momentary} = \max_{j:1\in n} \left\{ \sqrt{F_{x,j}^2 + F_{y,j}^2 + F_{z,j}^2} \right\} \quad (2)$$

, where $F_{momentary}$ (N) is the momentary cutting force, $F_x$ (N) is the radial, $F_y$ (N) is the feed-directional and $F_z$ (N) is the axial (passiv) component of the cutting force. As can be seen on the Fig. 4, on both tool's main effect diagrams, the feed rate has the most significant effect on the cutting force, followed by the cutting width. Furthermore, both factor increases the cutting force.

Analysis of variance (ANOVA) and interaction plots confirm that the two analysed factors have no considerable interraction terms. The response surfaces for the tools are shown in the Fig. 3. Both the increase of feed rate and cutting width results in rise of the cutting force. It can be seen that in each case, the maximum cutting force is awaked at maximum factor levels ($v_f$=1200 mm/min and $a_e$= 5 mm).

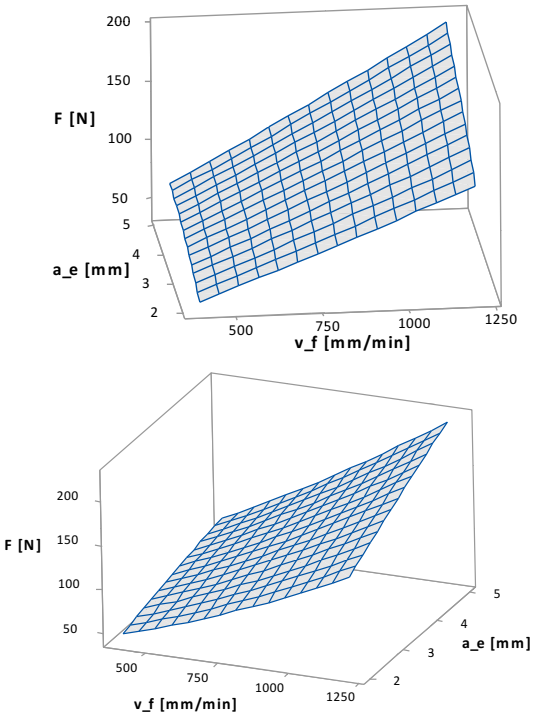


**Fig. 3** Response surfaces of cutting force for tools 20340.450 and 20360.450, respectively.

**Table 1** Experimental setting for the Fraisa 20340.450 tool, with parameters generadted by CCI design, and avareged *Ra* values, and the resultant *F* force

| Nr. | Factors | | Results | | | | |
|---|---|---|---|---|---|---|---|
| | $v_f$ (mm/min) | $a_e$ (mm) | Ra (µm) | $F_x$ (N) | $F_y$ (N) | $F_z$ (N) | F (N) |
| 1 | 800 | 3.50 | 2.56 | 68.28 | 74.44 | 37.03 | 106.89 |
| 2 | 517 | 4.56 | 2.94 | 60.71 | 42.69 | 30.80 | 79.47 |
| 3 | 800 | 2.00 | 3.21 | 46.28 | 62.90 | 28.66 | 83.14 |
| 4 | 800 | 5.00 | 3.19 | 100.62 | 70.54 | 50.37 | 131.52 |
| 5 | 1083 | 4.56 | 2.67 | 120.53 | 98.34 | 65.27 | 166.09 |
| 6 | 400 | 3.50 | 1.73 | 43.34 | 33.75 | 21.73 | 57.58 |
| 7 | 1200 | 3.50 | 2.59 | 103.57 | 118.47 | 58.50 | 166.53 |
| 8 | 800 | 3.50 | 2.45 | 72.80 | 74.55 | 40.09 | 110.96 |
| 9 | 1083 | 2.44 | 2.81 | 72.00 | 97.25 | 44.94 | 126.88 |
| 10 | 800 | 3.50 | 2.39 | 76.34 | 76.31 | 43.24 | 112.87 |
| 11 | 800 | 3.50 | 2.37 | 72.87 | 74.15 | 38.67 | 109.77 |
| 12 | 517 | 2.44 | 2.40 | 39.76 | 40.63 | 20.38 | 59.38 |
| 13 | 800 | 3.50 | 3.06 | 73.52 | 73.77 | 38.08 | 109.05 |

**Table 2** Experimental setting for the Fraisa 20360.450 tool, with parameters generadted by CCI design, and avareged *Ra* values, and the resultant *F* force

| Nr. | Factors | | Results | | | | |
|---|---|---|---|---|---|---|---|
| | $v_f$ (mm/min) | $a_e$ (mm) | Ra (µm) | $F_x$ (N) | $F_y$ (N) | $F_z$ (N) | F (N) |
| 1 | 400 | 3.50 | 2.04 | 45.15 | 39.18 | 25.55 | 63.60 |
| 2 | 800 | 2.00 | 1.44 | 47.56 | 66.36 | 36.93 | 88.94 |
| 3 | 517 | 4.56 | 2.32 | 72.66 | 44.70 | 37.39 | 92.65 |
| 4 | 800 | 3.50 | 2.25 | 76.91 | 75.38 | 48.05 | 116.16 |
| 5 | 517 | 2.44 | 2.27 | 43.63 | 43.32 | 26.79 | 66.42 |
| 6 | 800 | 5.00 | 2.37 | 117.60 | 67.04 | 62.90 | 147.09 |
| 7 | 800 | 3.50 | 1.76 | 81.73 | 74.92 | 52.70 | 121.11 |
| 8 | 800 | 3.50 | 1.68 | 82.27 | 75.69 | 53.41 | 121.89 |
| 9 | 800 | 3.50 | 1.85 | 83.30 | 74.98 | 54.89 | 122.91 |
| 10 | 1083 | 2.44 | 2.38 | 84.54 | 99.07 | 61.18 | 141.52 |
| 11 | 1200 | 3.50 | 1.70 | 127.71 | 118.08 | 85.62 | 188.29 |
| 12 | 1083 | 4.56 | 1.73 | 140.59 | 101.59 | 85.51 | 190.25 |
| 13 | 800 | 3.50 | 1.80 | 83.25 | 75.18 | 52.06 | 121.73 |

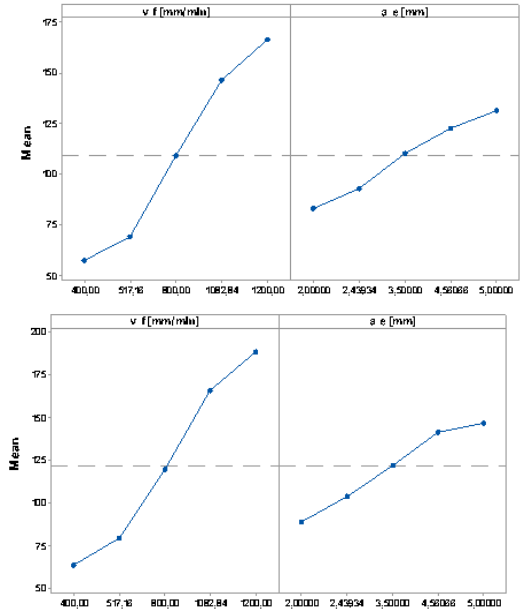


**Fig. 4** Main effenct diagrams of cutting force for tools 20340.450 and 20360.450, as is

The developed models are shown by Eq. (3) and (4). According the models and the response surfaces, the compression end mill with coarse tooth is affected by up to 20% smaller force. The possible reason if this is, that the sufficient energy for starting chip splitting is higher than the amuont of energy needed for maintaining a cut. The tool with fewer edges starts new chips more often, in other words transmit more energy towars the workpiece, hence generates greater forces.

$$F = -20.8 + 0.0677v_f + 13.02a_e + 0.000008{v_f}^2 - 1.531{a_e}^2 + 0.01593v_f a_e \quad (3)$$

$$F = -5.8 + 0.0332v_f + 10.93a_e + 0.000035{v_f}^2 - 1.057{a_e}^2 + 0.01875v_f a_e \quad (4)$$

Moreover, $F_z$ values are considerably lower than the other two components of the cutting force. It caused by the tool geometry in purpose. In this direction, the generated force on the neighbouring edges are opposed, as shown on the Fig. 5, thus resulting a smaller resultant force.

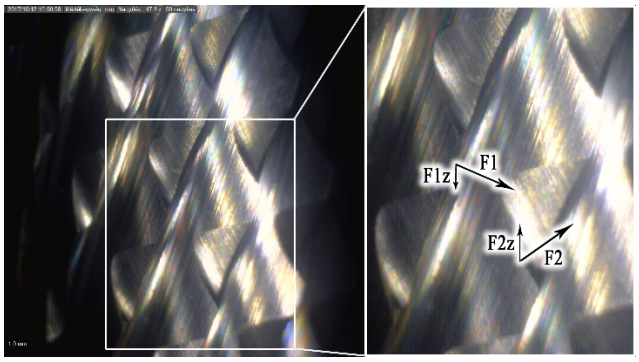


**Fig. 5** Vector sum for z directional local cutting forces

### *3.2 Surface roughness*

The surface roughness was measured five times along the surface, perpendicularly the toolpath, then average surface roughness (*Ra*), roughness depth (*Rz*) and their propotion (*Rz/Ra*) were calculated. The colleted data was filtered for deviant values. the examined values were obtained based on the the avarage of the five points. The response surfaces can be seen in the Fig. 6. It can be observed from the main effect diagrams, shown on the Fig. 7, that both factors have significant impact on the measured *Ra* values. Although, for the coarse tool the data is inconsistent. This was most likely caused by the amuont of uncut fibres along the surface, which is a common machining defect for CFRP [9], [13]. In the case of the coarse tool, the response surface forms a saddle surface. Based on the quadratic equation fitted on the data set, the optimal cutting width for a given feed rate, is 3.03 mm. This can be used for getting smoother surface along the joining points of the finished component.

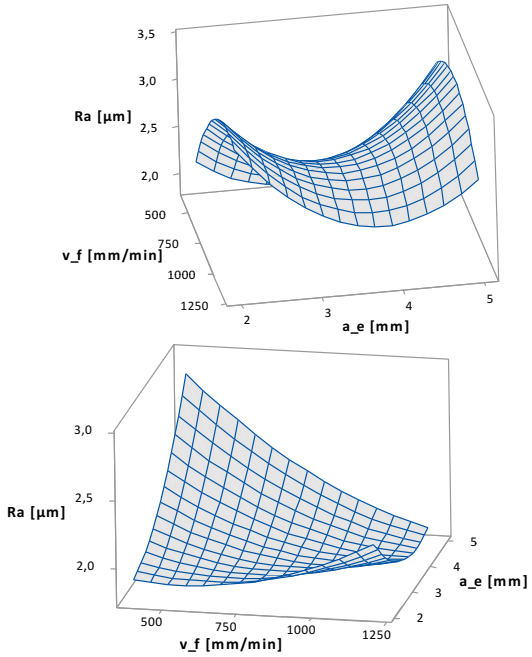


**Fig. 6** Response sourfaces of average surface roughness (*Ra*) for tools 20340.450 and 20360.450, respectively

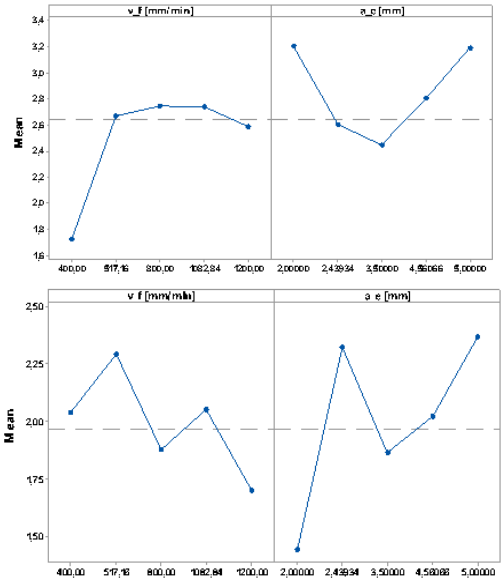


**Fig. 7** Main effects diagram of average surface roughness for tools 20340.450 and 20360.450, respectively

As mentioned before, the amount of uncut fibres is a key parameter during machining of CFRP. We can get broader picture of this amount by inspecting the *Rz/Ra* ratio. Avarage surface roughness (*Ra*) is calculated as the arithmetical avarage value of all absolute differences from the centre line. This method tends to pay little attention for short high peaks, such as these fibres, or short deep valleys, like delamination on the surface. Roughness depth (*Rz*) is measured as the avarage distance from the highest peak to the lowest valley on five sampling lengths. *Rz/Ra* ratio gives us a proper value to represent the quantity of typical CFRP surface defects created during milling [7].

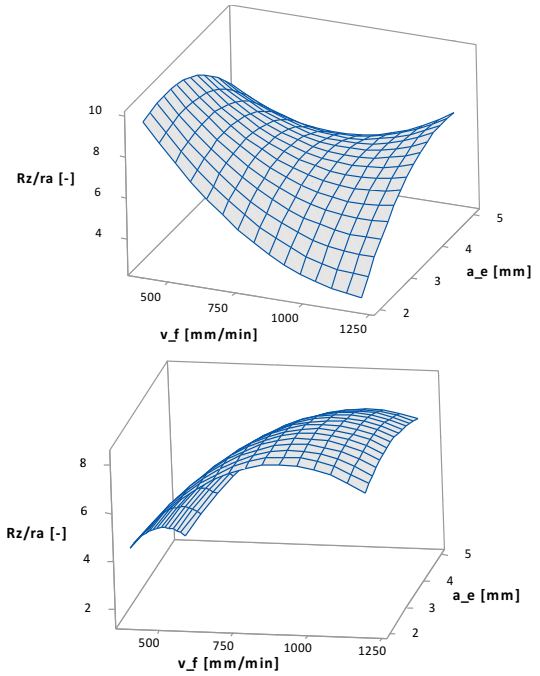


**Fig. 8** Response sourfaces of Ra/Rz ratio for tools 20340.450 and 20360.450, as is

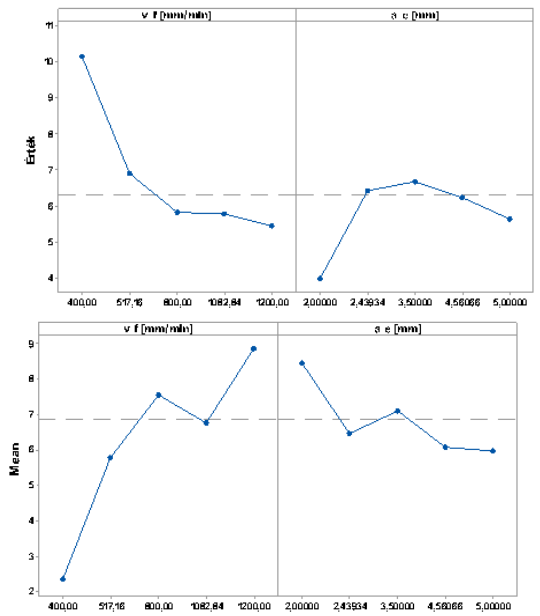


**Fig. 9** Main effect diagram of Ra/Rz ratio for tools 20340.450 and 20360.450, as is

The response surfaces of the Rz/Ra ration are shown in the Fig. 8. On the basis of these and the ANOVA table, it's clear that the feed rate has by far more significant effect on the optimization parameter. Encrease of feed rate results in the decrease of this parameter. Therefore, it is advisable to use high feed near the joining points of the finished component.

## 4 Conclusions

In the present study, milling experiments were carried out in uni-directional CFRP using compression end mills in order to analyse and optimise process parameters. According to the present study, the following conclusions can be drawn:

- In the case of both compression end mills, both analysed factors (feed rate and cutting width) increase the cutting force, moreover the feed rate has the most significant effect on the cutting force, followed by the cutting width.
- RSM models were developed to analyse the influence of the factors on the cutting force. Cutting force were observably greater in the case of the compression tool with coarse tooth. This was possibly caused by the higher energy need of new chip formation.
- *Fz* (passiv) force component values are significantly lower than the other two components of the cutting force. It's caused by the tool geometry. The axial forces on the neighbouring edges are opposed, therefore these add up to smaller resultant passiv force.
- Both factors have significant impact on the measured *Ra* values. For the compression end mill with coarse tooth the optimal cutting width for any given feed rate, is 3.03 mm.
- Feed rate has by far more significant effect on the *Rz/Ra* ratio than the cutting width. Encrease of feed rate results in the decrease of this parameter. Therefore, use of high feed rates near the joining points during the finishing of the component leads to better surface quality, therefore better bonding.

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