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Analysis of the cutting forces in machining of uni-directional carbon fiber-reinforced polymers (UD-CFRP)

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Abstract: Recently, carbon fibre-reinforced polymers (CFRP) have been widely used composite materials in the aerospace, automotive and sport industries. The machining behaviour of CFRPs is difficult to describe and predict due to their anisotropy and non-homogeneity. This means that their mechanical properties depend on the direction of the fibres and thus also their machinability properties. In this study, the influence of fibre cutting angle was analysed during conventional and climb milling of UD-CFRPs. The experiments were designed using the central composite design method and adequate mathematical models were developed to predict the change of the cutting force in the milling of the CFRP with the variation of the fibre cutting angle. The results showed that the optimum points of the force in conventional and climb milling diagrams do not correspond to identical fibre cutting angles.

Keywords: CFRP, cutting force, machinability, milling

1. Introduction

The employment of carbon fibre-reinforced polymers (CFRP) in the aerospace, automotive and sport industries is continuously growing thanks to their low density and good mechanical properties [1]. The machining of these materials is essential due to the constantly increasing requirements for geometrical tolerances and assembly in the above-mentioned fields. Furthermore, a production without waste product is demanded, the analysis and optimization of the machining of CFRPs becomes thus crucial.

CFRPs are difficult-to-cut materials due to the different mechanical and machining properties of the matrix and reinforcement, and the wear-effect of the carbon fibres [1]. Since the mechanical properties of UD-CFRPs are not identical along each direction, even the machining properties are not [2-5]. Therefore, a definition and prediction of the machining properties along several cutting directions is required. Indeed, in case of identical technological parameters (such as feed rate, depth of cut and cutting speed), but different cutting directions, the cutting force and the machined micro-macro geometrical features are different [1-5].

In the present study, the influence of the fibre cutting angle (Θ) on the cutting force (F) was investigated in conventional and climb milling of UD-CFRPs. Several definitions of fibre cutting angle can be found in international journals [5, 8]. One of the most widely used definition is the following [5]: The fibre cutting angle is the angle between the feed rate (vf) and the direction of the fibres (k), as shown in Fig. 1. This angle is a one-dimensional factor that was utilized as input parameter in the experiments.

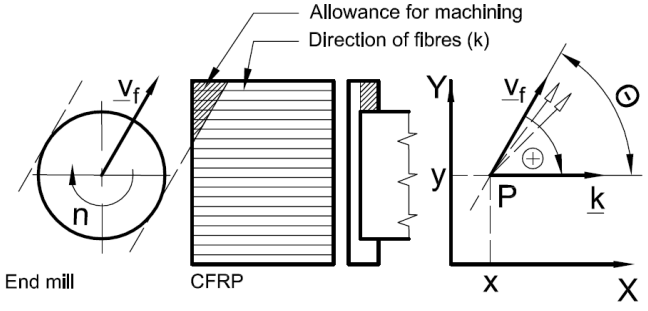

Figure 1. – Definition of fibre cutting angle (Θ)

2. Experimental setup

The 115mm long, 60 mm wide and 25 mm thick UD-CFRP workpiece was produced by means of a hand-laminating technique, 55 carbon-reinforcement layers and a matrix of epoxy resin were used. The face milling experiments were carried out on a VF22 milling machine with a maximum rotational speed of 3,000 rpm. The cutting machine was equipped with a NILFISK GB733 vacuum cleaner (14.7 kPa) to clear off the chips from the cutting area. An Ø50 mm diameter, sharp, solid carbide end mill was used, as shown in Fig. 5. The end mill has five cutting edges.

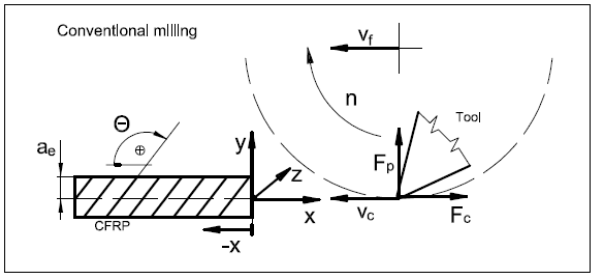

Figure 2. – Schematic diagram of climb milling of UD-CFRP

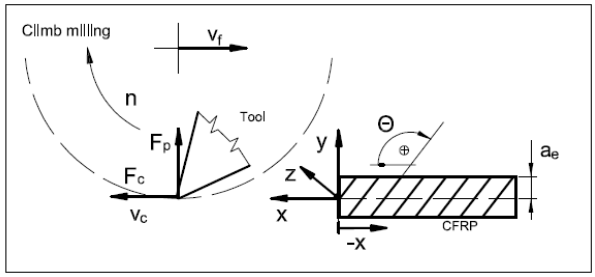

Figure 3. – Schematic diagram of conventional milling of UD-CFRP

The cutting force components (Fc, Fp, Ft) were measured with a KISTLER 9281B three-directional load cell with a sampling frequency of 18,000 Hz. The data were collected using the KISTLER Dyno Ware software. The pictures of the cutting edges were taken with a Dino-Lite AD7013MZT digital microscope.

The experiments were designed using central composite (CC) [7] design. Type of milling (conventional or climb milling) and fibre cutting angle (Θ) are the factors that influence the responses (F_c, F_p, F_t). The technological parameters, i.e. cutting speed (v_c= 230 m/min), feed rate (v_f= 397 mm/min), axial depth of cut (a_p= 7 mm) and radial depth of cut (a_e= 3 mm) were fixed. This parameters were selected based on suggestions from cutting tool producers and on previous works done by other researchers [1-5].

The experimental setup (fibre cutting angles) can be seen in Fig. 4: 1, 3, 5, 7, 9, 11, 13, 15, 17 and 19 are climb milling experiments, and 2, 4, 6, 8, 10, 12, 14, 16, 18 and 20 are conventional milling ones. More experiments were conducted in the middle point of the factor of the field (Θ= 90°) to predict the deviation of the responses and to analyse the tool wear.

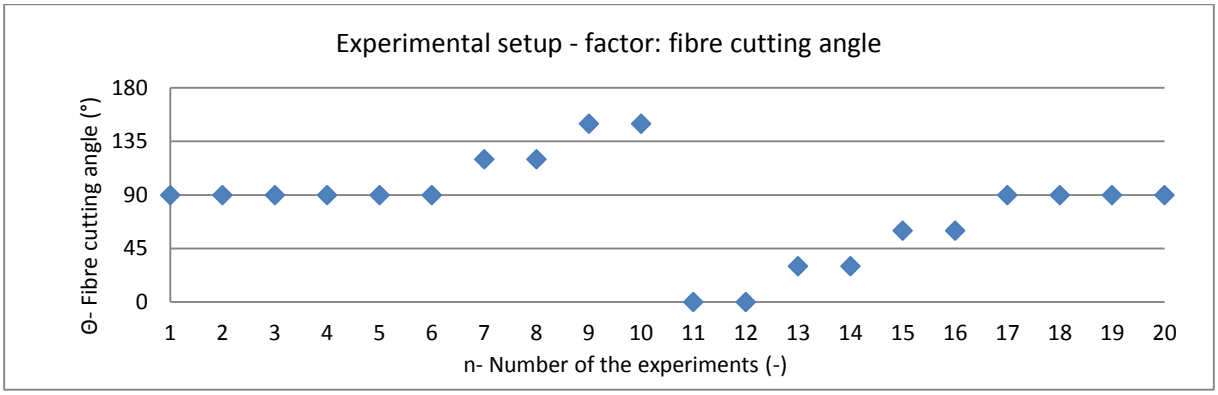

Figure 4. – The design of experiments

The cutting experimental setup (end mill, fixture, workpiece and the visualization of the fibre cutting angle) can be seen in Fig. 5.

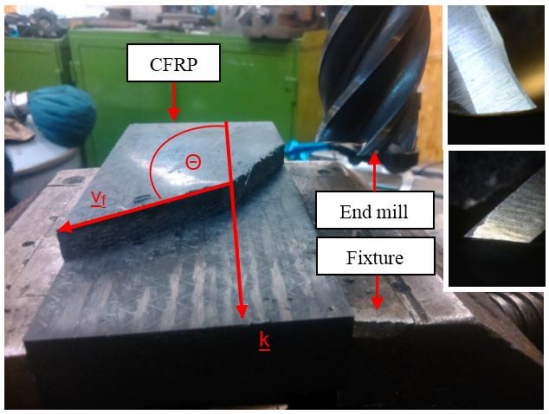

Figure 5. – Cutting experimental setup, Θ- fibre cutting angle, f- feed rate, k- fibre orientation

3. Results

The collected data ($F_c(t)$, $F_p(t)$, $F_t(t)$) were post-processed using the Microsoft Excel 2007 spreadsheet program. During the milling experiments, the technological parameters v_f, v_c, a_p, a_e were fixed while the fibre cutting angle was changed. The reproducibility deviations of the experiments were estimated through the responses in the middle point of the factor of the field (Θ= 90°). This deviation was able to describe the confidence interval of the responses all over the field of the factors, as shown in Fig 8 and 9.

"n"-degree mathematical regression polynomial models were developed based on the response points. The algorithm to define "n" is presented in Fig. 6.

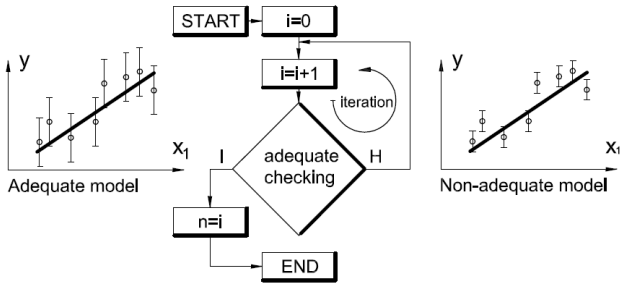

Figure 6. – Definition of the degree (n) of the mathematical model

If the difference between the predicted and the measured values is bigger than the reproducibility deviation, the degree (n) of the mathematical model has to be increased (n+1).

At the end of each experimental session with a different setup, images were generated with the Dino-Lite AD7013MZT digital microscope. Finally, the images were analysed; the results showed that the rate of tool wear is not significant, thus the responses weren't necessary to compensate because of that. Images of the cutting edges (before and after the experiments) are shown in Fig. 7.

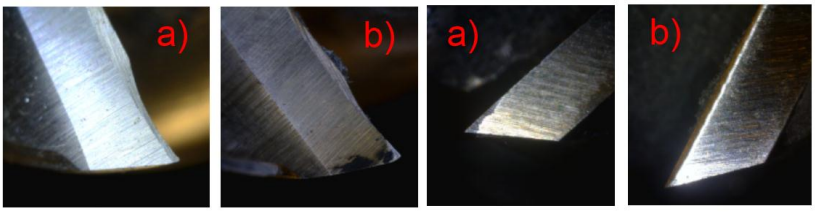

Figure 7. – Images of the cutting edges from an axial and radial point of view a) before the experiments, b) after the experiments

The results of the climb milling experiments can be seen in Fig 8. The directional force component ($F_{climb,c}$) of the feed rate has a minimum point at Θ= 90° degree. The influence of the fibre cutting angle on the passive ($F_{climb,p}$) and on the tangential force components ($F_{climb,t}$) is not significant.

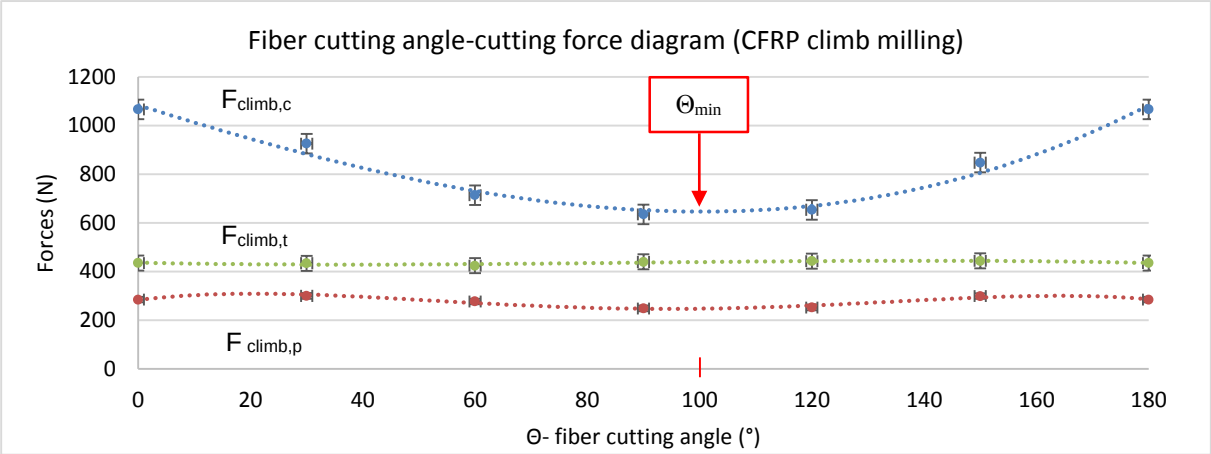

Figure 8. – Influence of the fibre cutting angle on the cutting force during CFRP climb milling

The adequate checked regression models for climb milling (based on Fig. 8) can be seen in Eq. (1). The unit of fibre cutting angle is degree [°] and of force components are Newton [N].

$$\mathbf{F}_{\mathrm{climb}}(\Theta) = \begin{bmatrix} 0{,}0001\Theta^3 + 0{,}0148\Theta^2 - 7{,}2752\Theta + 1083{,}9 \\ -2\mathrm{E}^{-06}\Theta^4 - 0{,}00911\Theta^2 + 2{,}8\Theta + 283{,}62 \\ -3\mathrm{E}^{-05}\Theta^3 + 0{,}0079\Theta^2 - 0{,}4637\Theta + 436{,}71 \end{bmatrix} \quad (1)$$

, where:

$$\mathbf{F}_{\mathrm{climb}}(\Theta) = \begin{bmatrix} \mathrm{F}_{\mathrm{climb,c}}(\Theta) \\ \mathrm{F}_{\mathrm{climb,p}}(\Theta) \\ \mathrm{F}_{\mathrm{climb,t}}(\Theta) \end{bmatrix} \mathrm{N};\ \forall\Theta \in [0{,}180)$$

The results of the conventional milling experiments are presented in Fig 9. In this case, differently from the climb milling experiments results, the directional force component ($F_{conv,c}$) of the feed rate has a minimum point at Θ= 150° degree. Moreover, the influence of the fibre cutting angle on the passive ($F_{conv,p}$) and on the tangential force components ($F_{conv,t}$) is similar to the one on $F_{conv,c}$, but smaller.

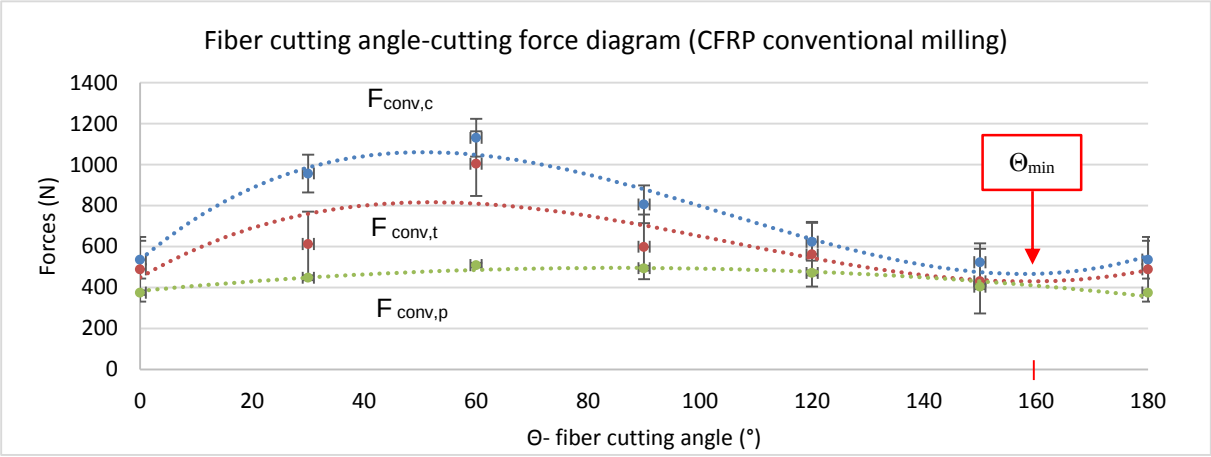

Figure 9. – The influence of the fiber cutting angle on the cutting force during CFRP conventional milling

The adequate checked regression models for conventional milling (based on the Fig. 8) can be seen in Eq. (2). The unit of fibre cutting angle is degree [°] and of force components are Newton [N].

$$\mathbf{F}_{\mathrm{conv}}(\Theta) = \begin{bmatrix} 0{,}001\Theta^3 - 0{,}3028\Theta^2 + 23{,}226\Theta + 534{,}71 \\ 0{,}0006\Theta^3 - 0{,}2026\Theta^2 + 15{,}849\Theta + 448{,}83 \\ -0{,}0155\Theta^2 + 2{,}6352\Theta + 382{,}97 \end{bmatrix} \tag{2}$$

, where:

$$\mathbf{F}_{\mathrm{conv}}(\Theta) = \begin{bmatrix} \mathrm{F}_{\mathrm{conv,c}}(\Theta) \\ \mathrm{F}_{\mathrm{conv,p}}(\Theta) \\ \mathrm{F}_{\mathrm{conv,t}}(\Theta) \end{bmatrix} \mathrm{N};\ \forall\Theta \in [0{,}180)$$

The designed mathematical models are valid for the analysed field of the factors with the estimated confidence intervals and the used cutting tools.

4. Summary and conclusions

In the present study, the impact of the fibre cutting angle (Θ) on the cutting forces (F) was investigated in conventional and climb milling of UD-CFRPs, using an end mill. The factors, here analysed, that have an influence on the responses (F_c, F_p, F_t) were the type of milling (conventional or climb milling) and the fibre cutting angle (Θ). The experiments were designed with the help of the central composite design.

It was determined that the directional component of the feed rate has a minimum at a certain fibre cutting angle (Θ_{min}), as shown in the already presented diagrams of the functions $F_{conv}(\Theta)$ and $F_{climb}(\Theta)$. However, this Θ_{min} in case of climb milling does not coincide with the one for conventional milling.

When machining fibre-reinforced polymer composites, it is required to avoid delamination (i.e. separation of laminated layers from each other), a minimization of the cutting forces is therefore vital. In addition to that, if the cutting forces are large, friction becomes also significant and consequently the temperature increases. Cooling is usually not allowed when machining FRPs, hence once again the necessity of a minimization of the cutting forces.

As far as machining of homogeneous materials is concerned (such as aluminium alloy), the depths of cuts (a_e, a_p) are those geometrical factors that have a significant influence on the cutting forces. However, in CFRPs (inhomogeneous materials), the fibre cutting angle (Θ) also affects the cutting forces. Predicting the effect of fibre cutting angles becomes therefore fundamental in order to achieve a minimization of the cutting forces, thus providing information that can be later employed for the development of new CNC cycles for CFRP machining.

The goal of future further experiments is to analyse the influence of depth of cut, cutting speed, feed rate and fibre cutting angle on the machinability parameters of CFRPs such as cutting forces, delamination, and micro and macro geometrical features. In this regard, the design of mathematical models that could estimate the machinability of CFRPs is a crucial point, with the aim of always reaching a higher level of accuracy, in order to define and control the machining processes of CFRPs with the same precision that the advanced industries require.

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