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Machinability of Continuous-Discontinuous Long Fiber Reinforced Polymer Structures

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Abstract

In the present paper a new material system which combines the properties of continuous and discontinuous fibers (CoDiCoFRP) is investigated. The machinability and the induced damage effects of six material variations are investigated for a milling process at various cutting speeds and feed rates with an uncoated cemented carbide tool. The resulting forces and cutting torque were measured and analyzed for each material. After the milling process, the surface layers of the specimens were analyzed to quantify damage introduced during the milling process. The results show a strong influence of the material structure on the machining forces and damage.

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Keywords: fiber reinforced plastic, machinability, milling, damage, force

1. Introduction

Machining of fiber reinforced plastics (FRP) is an important task for utilizing FRP parts. Whether for trimming the edges or introducing holes or grooves that could not be introduced during the forming process, the machining process is an essential operation. The machinability of FRP is under continuous investigation since the mechanics of the machining behavior is not yet fully understood. The inherent structure of FRP leads to a substantially different behavior during machining and also regarding the overall mechanical properties. For industrial applications, milling and drilling operations are the most significant ones. These operations are under investigation for different configurations of glass fiber reinforced plastics (GFRP) or carbon fiber reinforced plastics (CFRP), respectively. Most studies examine CFRPs with continuous fiber reinforcement, i.e. woven fabric, unidirectional or multidirectional laminates.

Drilling, as the main way to introduce holes into a FRP part, often results in delamination and fraying [1]. The severity of this failure modes was found to depend not only on the drilling parameters, cutting speed and feed rate [1], but also on the clamping situation [2], the tool geometry [3], the processing strategy [4] and finally also on the wear state of the tool [2,4,5]. The clamping situation has a heavy influence on the resulting process forces which, in turn, is influencing the resulting failure modes [2]. By choosing the machining parameters accordingly, the resulting failure can be reduced or completely avoided [2,3]. Up to a certain point, this is also true, even if the tool wear increases with time [5]. Machining strategies that direct the resulting forces into the material can significantly reduce the defects that would normally result from introducing holes [4].

Machining of FRP, as a cutting method to introduce grooves, pockets and also holes, shows similar resulting defects as the drilling process. The resulting failure modes are also depending on the machining parameters, cutting speed and feed rate. But the feed rate seems to have a greater influence [6]. The question how the clamping situation affects the damages in milling of CFRPs has received little attention. In [7] no influence on damage was recognized, but the resulting forces were changed when changing the clamping situation. As for drilling, the tool wear state has a significant influence on the quality of the machined area. For small cutting edge radii, damages were rarely seen. Medium to heavy worn tools show significant damages for the same process parameters [8]. An additional effect, which arises from machining along the material, is the influence of the fiber orientation. While drilling is directed through the material cutting the fibers at every angle, depending on the

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cutting edge position, the milling process mostly passes the fibers at a certain angle. The size of this angle seriously determines the resulting outcome of the machining process [8,9]. In woven fabric FRP, the weave structure additionally alters the damage behavior of the material [10].

In one study a further specimen was used made of woven glass fiber reinforces plastic to directly compare the used parameters with CFRP-specimens. Using the same machining parameters they showed that machining GFRP required less force to cut [6].

In the present work, a different material combination is examined regarding its machining properties. This combination, called CoDiCoFRP, comprises of continuous (Co) and discontinuous (DiCo) fibers. The discontinuous fibers are represented by short glass fiber reinforced thermosets in the form of sheet molding compounds (SMC) while the continuous fibers are represented by carbon fiber reinforced thermosets in the form of unidirectional fiber tapes (UD-Tapes). This new type of combination holds a great potential for further use of FRP in commercial applications. Since glass fibers are cheaper compared to carbon fibers the basic structure of a part can be made of SMC while defined load paths can be reinforced locally by UD-Tapes. A structure that is constructed like this could cost less since less stressed areas are made of inexpensive material, while keeping the structural stability through smart placement of the high-priced carbon tapes. The comparison to effects seen for uniform material is important to understand how the structure changes the resulting defects and forces and to allow better analyzing strategies for upcoming investigations. Machining of fiber reinforced plastics (FRP) is an important task for utilizing FRP parts.

2. Experiments

2.1. Material Structure

The investigation of the CoDiCoFRP materials is done in a joint project of several institutes of the KIT. The specimen were manufactured in this context by the Fraunhofer Institute for Chemical Technology. Figure 1 shows the layer structure of the specimen. The specimen differ in the thickness of the laminate, depending on the number and the type of layers used. As shown in the figure, there are three types of layers: glass fiber SMC, carbon fiber UD-tapes, and carbon fiber UD-layers. In table 1 the structure of all specimen materials is described. The layer setup was chosen to investigate whether the order of layers has an influence and how the UD-Tapes change the material behavior. Since the orientation of all UD-tapes and layers are the same, namely perpendicular to the milling direction (y-axis), only the thickness and the layer setup is named. The tapes were always placed in the middle of the specimen along the x-axis. To minimize the deformations due to the manufacturing process, the layers were stacked up symmetrically. Furthermore, the cure cycle of molded plates was chosen in a way to minimize resulting deformations. For manufacturing, a pressing time of 112 seconds was chosen and the mold temperature was fixed at 145°C. The closing speed of the press was adjusted to 1 mm/s. A more detailed description of the manufacturing processes was done in a partner study by Buecheler and Henning [11]. First material characterization tests were carried out in subsequent partner study by Trauth et al. [12] to identify the properties of the unidirectional CFRP material, which was also used to manufacture the specimen investigated in the present study.

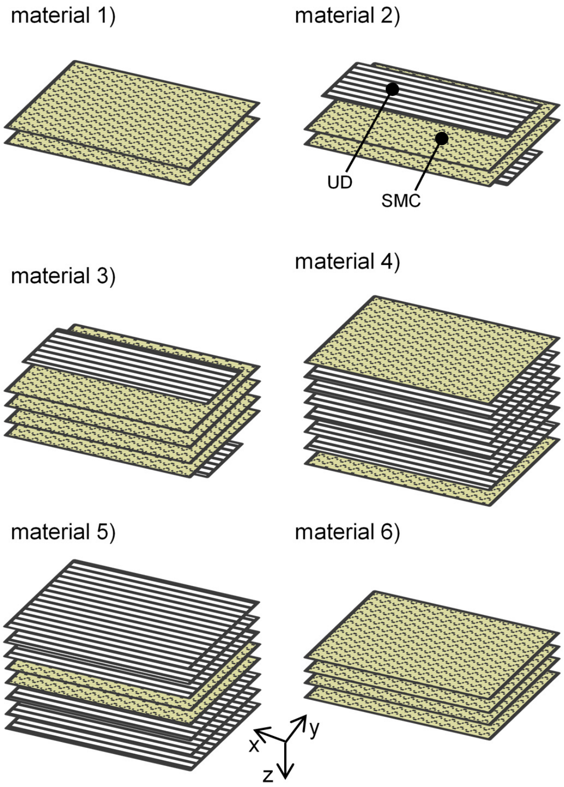

Fig. 1. Structure of the examined specimens (details in Table 1)

Table 1. Specimen structural details.

Material Number	Layer structure	Total Thickness
1	2 SMC-Layers	2 mm
2	1 UD-Tape, 2 SMC-Layers, 1 UD-Tape	2 mm
3	1 UD-Tape, 4 SMC-Layers, 1 UD-Tape	4 mm
4	1 SMC-Layer, 6 UD-Layers, 1 SMC-Layer	4 mm
5	3 UD-Layers, 2 SMC-Layers, 3 UD-Layers	4 mm
6	4 SMC-Layers	4 mm

2.2. Experimental Setup

To investigate the machinability of the different materials milling experiments were performed. Figure 2 shows a schematic representation of the experiments on the left side and an image of the machine tool on the right side.

A machining center HELLER MC16 was used. The resulting forces were captured by a rotating dynamometer of the type 9125A11 on the spindle and a 3 component force measuring platform of the type 9255SP by KISTLER. The measuring platform was oriented in a way that the z-axis of both measuring systems line up. A custom made clamping system was used to minimize the distance between the machined area and the clamping area to minimize any vibrations resulting from the flexibility of the material. On the left side of figure 2 the schematic arrangement of the clamping system can be seen, while on the right side one clamping jaw was removed to allow an inside view into the machining area.

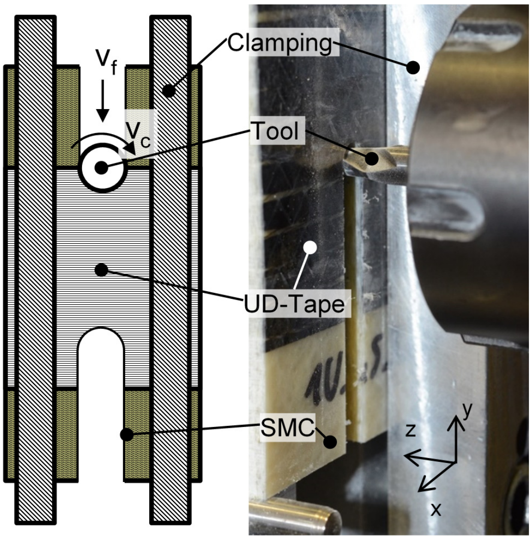

Fig. 2. Left: schematic depiction of the experiment, right: view of the experiment in the machine

To cut the slots in the specimens an uncoated cemented carbide end mill by Walter AG with a diameter of 6 mm, which complies with DIN 6527 L, was used. The end mill has two cutting edges and a spiral angle of 30°. The cutting edge of the unused tool was measured with a confocal measurement device of the type µsurf custom by nanofocus. The cutting edge had a radius of around 6 µm. Since the influence of the cutting edge was not investigated, the influence was minimized by changing the tools after two meters of milling, which corresponds to one tool per specimen. Also, the experiments were executed in an arbitrary order as to further minimize the influence of the cutting edge on one particular parameter set. A full factorial DOE was used with four repetitions for every set of parameters as shown in table 2.

Table 2. Used parameters for v_c and f_z..

Cutting speed v_c in m/min	Feed per tooth f_z in mm
100, 200, 300	0.01, 0.03, 0.05

2.3. Measured forces

Since the forces were measured separately in all three dimensions (F_x, F_y, F_z) the total machining force (F) has to be calculated using equation 1.

$$F = \sqrt{F_x^2 + F_y^2 + F_z^2} \qquad (1)$$

The machining Force F is a superposition of the feed force, the cutting force and the passive force. This superposition does not allow a separation through the applied measurement system. Figure 3 shows the graph of a section of the machining force F. The oscillations result from the rotation of the tool with two edges. When only one cutting edge is fully engaged the force rises to a maximum (1). When the cutting edge reaches a point where the superposed forces start to turn in different directions (mainly the cutting force and the feed force) there is a stagnation of the machining force (2). Turning further the superposed forces point in different directions and the resulting machining force F declines (3). Before the first cutting edge can fully leave the material the second cutting edge begins to enter the material in the opposite direction thereby compensating the cutting force and the passive force of the first cutting edge (4). Theoretically only the feed force is measured at that moment. After the first cutting edge has completely left the material the cycle starts again (1).

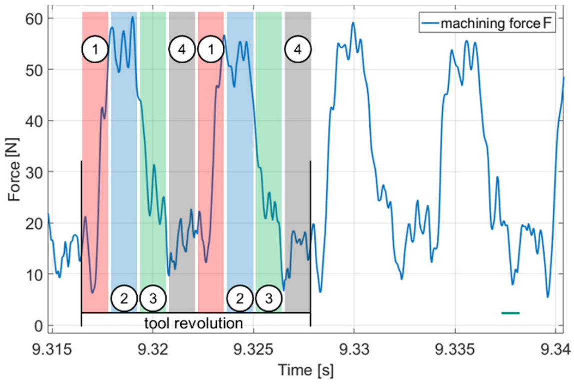

Fig. 3. Total machining force F (blue) calculated from the measured signals, the colored patches show the phases during one revolution of the tool v_c = *200 m/min and* f_z = *0.03 mm,* material 6

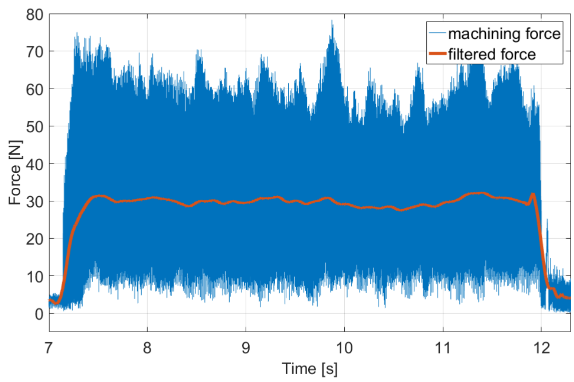

Fig. 4. Total machining force F (blue) calculated from the measured signals, filtered machining force (orange), v_c = *200 m/min and* f_z = *0.03 mm,* material 6

Since the difference between the maximum and the minimum of the oscillations are rather high, a Savitzky-Golay-filter was used to get an average force progression over the milling time. Figure 4 shows the calculated machining force F (blue color) and the filtered measurement (orange color) for milling of one slot. The machining force progresses periodically (see fig. 3) from near zero to the maximum force during one single cut of one cutting edge. Therefore, the filtered forces were used to interpret these experiments to see a tendency of the measured forces for different materials and the standard deviations were neglected.

3. Results and Discussion

3.1. Influence of cutting speed and feed rate

The influence of the cutting speed should be less than the influence of the feed per tooth on the machining force when these parameters are increased by the same factor. The machining should progress almost linearly in both directions, with a steeper increase in the feed direction [6]. The performed experiments of this work can partly support this claim. As expected, figure 5 (material 4) shows a higher increase of the total machining force for the step from $f_z = 0.01$ mm to $f_z = 0.03$ mm than from $v_c = 100$ m/min to $v_c = 300$ m/min. The higher total machining force of material 4 is due to the high ratio of carbon fiber layers.

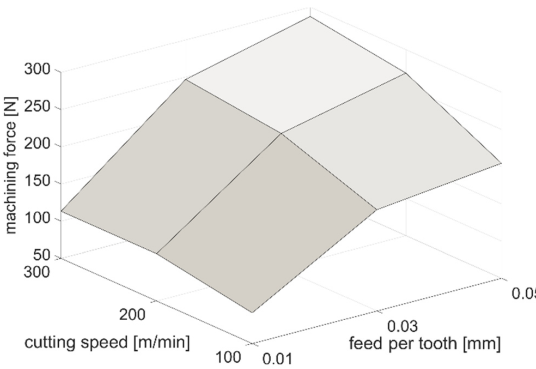

Fig. 5. Total machining force F as a function of cutting speed and feed per tooth for material 4.

In Contrast, figure 6 (material 3) shows a higher increase of the total machining force in the step from $v_c = 100$ m/min to $v_c = 300$ m/min than from $f_z = 0.01$ mm to $f_z = 0.03$ mm.

Fig. 6. Total machining force F as a function of cutting speed and feed per tooth for material 3.

3.2. Influence of material thickness

The influence of the material thickness is visible for materials with a similar structure like material 2 and 3. In figure 7 and 8 these two materials are compared with different cutting speeds and feed rates. To allow an easier view only the maximum and minimum values for cutting speed (Fig. 7) and feed per tooth (Fig. 8) are depicted.

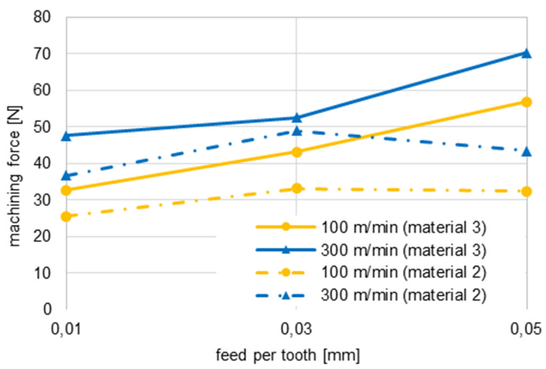

Fig. 7. Total machining force F as a function of the feed per tooth for material 2 and 3.

Figure 7 shows the machining force as a function of the feed per tooth at two constant cutting speeds (100 m/min, 300 m/min). It can be seen that the thickness of the material has a great impact on the total machining force since the total forces for material 3 are on a higher level than for material 2. The decline of the total machining force at a feed per tooth of 0.05 mm for material 2 needs to be further investigated.

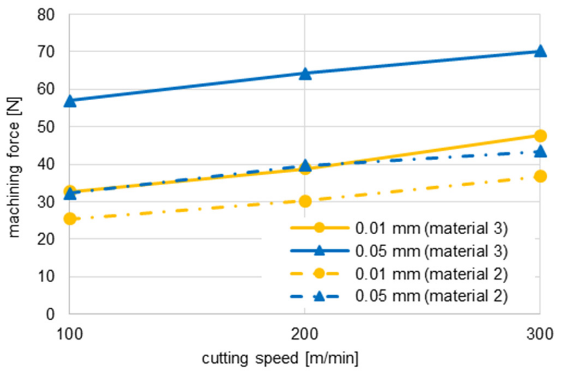

Fig. 8. Total machining force F as a function of the cutting speed for material 2 and 3.

Figure 8 shows the machining force as a function of the cutting speed. The feed per tooth is held constant at 0.01 mm and 0.05 mm. In this figure it is clear that the machining force rises with higher specimen thickness. This result is expected since the machining of a thicker material requires more power. Material 3 shows similar behavior of the machining force in relation to the cutting speed and the feed per tooth as described by Mathivanem et al. for smaller cutting parameters [6].

3.3. Influence of layer structure

To analyze the influence of the layer structure only material 4 and 5 can be considered. These are the only materials that have the same thickness as well as the same layers but in a different order. The materials will be compared similarly as in chapter 3.2.

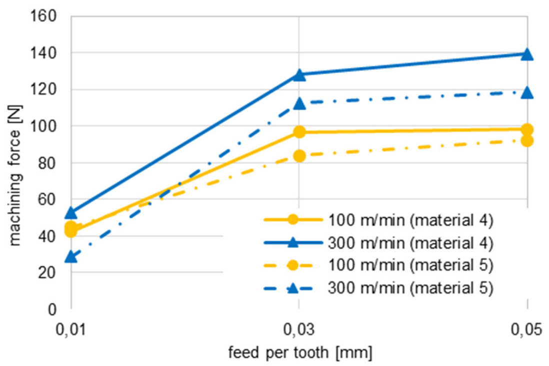

Fig. 9. Total machining force F as a function of the feed per tooth for materials 4 and 5.

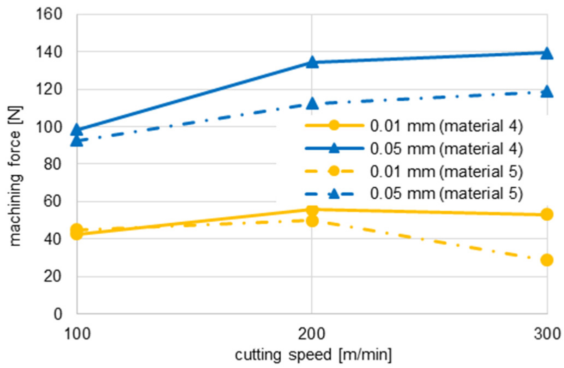

Fig. 10. Total machining force F as a function of the cutting speed per tooth for materials 4 and 5.

Figure 9 and figure 10 show that the layer order has an influence on the machining force. Both figures show that a higher machining force is needed for material 4 than for material 5. A possible explanation is that the six carbon fiber layers of material 4 are all stacked onto another, building a strong compound which is harder to machine. Material 5 on the other hand has also six carbon fiber layers which are symmetrically parted by two glass fiber SMC layers. Since three layers of carbon fiber are easier to machine the total machining forces of material 5 are lower. The stagnant and the declining force in the step from 200 to 300 m/min is a rather unexpected result and needs to be further investigated. A possible explanation is the higher cutting temperature, which can decompose the matrix material and thereby lower the machining force.

3.4. Damage behavior

The resulting damages after machining showed surprising results. After a visual inspection of all specimen there was no or hardly any damage at the bottom side of the specimen independent on the used parameters. On the upper side predominantly fraying of the fibers could be observed. The occurring delamination always appears combined with frayed fibers as was also found by Hintze et al. [8]. In this case, the frayed fibers have a greater interfering effect than the delamination itself.

The most interesting specimen regarding the damage behavior is material 4. The two glass fiber layers on the outer side of the specimen seem to facilitate a proper machining process leaving substantially less damage than if carbon fiber layers are outside like material 5 has. Figure 11 shows a comparison between the materials 4 and 5 with the parameters that are most prone to damage which are $v_c = 300$ m/min and $f_z = 0.05$ mm

While material 4 shows only light fraying of the short glass fibers the other material shows more severe fraying of the carbon fibers. Voß et al. also stated that woven glass fiber layers covering CFRP material on the outside are known to reduce the delamination defects [9]. Material 4 shows that this effect is also observable with SMC layers on the outside.

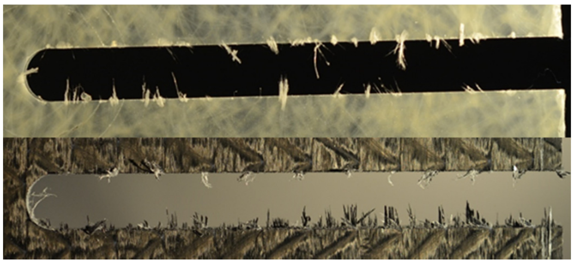

Fig. 11. Machining damage at the top layer of material 4 (top) and material 5 (bottom), machining parameters: v_c = 300 m/min and f_z = 0.05 mm

Since the damage in all materials only occurs on the upper side, it seems reasonable to conclude that the reason for these damage effects is the use of a tool with a helix angle larger than 0°. This statement can be partly supported by Hintze et al. [13]. They showed that the fibers could avoid being cut by being deflected away from the cutting edge. With the present helix angle of 30° the fibers can be deflected not only in the feed direction but out of the material plane. At the lower surface, the fibers would be deflected into the material, which is not possible, facilitating the cutting process in this position.

In the present results, the influence of the cutting edge wear was ignored, since a new tool was used after approximately 2 m of milling and the measurement of the tool used for material 5 showed a progression of the cutting edge radius from 6 µm of around 23 µm, which is a high increase, but still can be interpreted as sharp with the used cutting conditions. The tool wear resulting from the machining of this material will be subject of further experiments.

4. Conclusion and Outlook

In this paper an investigation of the machinability of combined continuous and discontinuous fiber reinforced plastics (CoDiCoFRP) is presented. The performed experiments led to following conclusions:

- The machining force is influenced by the machining parameters. The higher influence of the feed per tooth on the total machining force compared to the influence of the cutting speed could only be partly confirmed.
- The machining forces rise with higher ratio of CF-layers since they possess a higher machining resistance.
- The order of the layers has an effect on machining as well as on the damage behavior. Separating adjacent layers of carbon fibers through a glass fiber layer seems to have a lowering effect on the machining force. Glass fiber layers on the outside of a CFRP seems to lower the damages associated with certain machining parameters.
- The tool geometry has a great effect on the damage resulting from the machining process and also on the force distribution into the material.

The results of these experiments are a first step to describe the machinability of this new material system. Taking these findings and refining them further will lead to specific operation instructions to avoid damages through the machining process. Combined with further experiments, the layer stacking orders can be optimized for specific applications, e.g. minimal machining forces with equal load capacity and an ideal damage behavior.

Acknowledgements

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