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Ultrasonic assisted milling of reinforced plastics

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Abstract

The milling of glass and carbon fibre reinforced plastics provides manufacturers from the automotive and aerospace industry with major challenges. The high carbon and glass fibre content increases the risk of insufficient production qualities. The abrasive fibres cause cutting edge rounding which results in the issue that the comparatively thick glass fibre cannot be reliably cut, while the carbon fiber is being less of a challenge. One approach to improve the production quality is the use of ultrasonic assisted milling. At the IWF tests have been undertaken to study the influence of ultrasonic assistance on workpiece quality, cutting forces and dust generation.

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Keywords: fiber reinforced plastics; milling; ultrasonic

1. Introduction

The demand for innovative lightweight design is increasing. Especially in the transport industry, fibre reinforced plastics (FRP) are applied because of their high specific strength, stiffness, toughness, fatigue and creep resistance, wear and corrosion resistance, good attenuation properties, and a low friction coefficient [1, 2, 3]. Recent studies forecast that the globally required quantity of carbon fibre reinforced plastics (CFRP) will more than double from 58,000 tons in 2015 to 2020 [4]. An economically reproducible processing of FRP therefore represents one of the current challenges for the tool and process developing industry. Currently, the manufacturing quality of the workpiece edges due to delamination, matrix defects and fibre protrusion is often not acceptable. Depending on the manufacturing process, defects accumulate mainly in the upper layers of laminates. This is due to the different fibre orientation and an increasing ratio of fibre content [5, 6]. The use of modern production strategies such as bore-milling, high speed cutting or ultrasonic assisted machining have been explored and showed potential for an economic and productive use [7, 8]. The application of vibration assisted machining was tested in the 1950s resp. 1960s for traditional metal cutting applications. The demand for new application fields of this process increased in the 1990s. It was applied in the machining of "difficult-to-cut-materials" such as glass, ceramics or hardened steel [9, 10, 11, 12, 13]. Because of further developments regarding the machine technology, vibration in the ultrasonic range was facilitated. Xu et al. [14, 15, 16, 17] showed that the ultrasonic assisted milling minimize damages on the surface and at the subsurface of CFRP. The aim of the presented work was to show the effects of ultrasonic assisted milling when machining carbon and glass fibre reinforced plastics at different cutting speeds and feed directions. It is often assumed that the reduced cutting forces resulting from a discontinuous cut lead to less fibre protrusion, pull-out and push-out delamination. Also the effects of the overlapping movements at the tool tip can improve the machining process. To investigate these approaches, a suitable parameter field was defined and tests performed with uncoated cemented carbide tools. By comparing the cutting forces and workpiece

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qualities, the difference between conventional and ultrasonic assisted milling of fibre reinforced plastics was analysed.

Nomenclature

a_e	width of cut
a_p	depth of cut
A	vibration amplitude (Peak to Peak)
CFRP	carbon fibre reinforced plastics
d	fibre diameter
d_{ae}	aerodynamic diameter
d_{WC}	average grain size
f	natural frequency
f_z	feed per tooth
GFRP	glass fibre reinforced plastics
F_f	feed force
$F_{f,avg}$	average feed force
F_{fN}	feed normal force
$F_{fN,avg}$	average feed normal force
F_p	passive force
$F_{p,avg}$	average passive force
FRP	fibre reinforced plastics
l	component length
n	rotational speed
PM2.5	mass fraction concentration- $d_{ae} \leq$ 2.5 µm
PM4	mass fraction concentration- $d_{ae} \leq$ 4 µm
PM10	mass fraction concentration- $d_{ae} \leq$ 10 µm
rpm	revolutions per minute
r_β	cutting edge radius
t	time
v_c	cutting speed
w_{Co}	cobalt content
α	fibre alignment
β	fibre proportion

2. Experimental procedure

The milling tests were undertaken on a 5-axis milling machine from Sauer GmbH, Stipshausen, Germany type ULTRASONIC 260 COMPOSITES with a rotational speed up to n = 30,000 rpm when using ultrasonic assistance. The ultrasonic actuators of the latest generation have five rings of piezo-ceramics and shrink chucks, which in combination results in an improved energy transmission and therefore a higher vibration amplitude at the tool tip. To ensure an effective and suitable dust extraction, a Vacomat N-1000 F 20/50 from SCHUKO Schülte-Südhoff Umwelttechnik GmbH und Co. KG, Trebbin, Germany was used. This equipment contains a filter system, which guarantees an average dust concentration of less than 0.1 mg/m^3 at the pressure-side of the extraction. The used milling tools from Hufschmied Zerspanungssysteme GmbH, Bobingen, Germany are specially developed for the milling of FRP and swing under optimized chucking conditions with a natural frequency of f = 22,130 Hz and an amplitude of almost A = 12 µm peak-to-peak. They are made of uncoated carbide with a cobalt content w_{Co} = 6 M-%, a hardness 1620 HV 30 and an average grain size d_{WC} = 1.3 µm. The used workpiece material by BMW AG, Munich, Germany is a meshwork of carbon and glass fibres in an epoxy resin. The carbon fibres have a diameter of d = 7 µm, an alignment of α = 0° and a proportion of β = 67 %. The glass fibres have a proportion of β = 33 %, a diameter of d = 13 µm and are woven around the carbon fibres (alignment α = +/- 45°). Fig. 1 shows the machine tool and the experimental setup.

a b

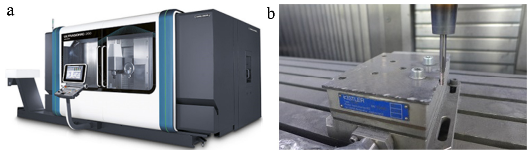


Fig. 1. (a) machine tool; (b) experimental setup.

To identify the effect of ultrasonic assistance, a suitable parameter field was identified for the trials. The parameters width of cut a_e, depth of cut a_p and feed per tooth f_z were kept at a constant level. The first chosen cutting speed v_c was set to a high value of v_c = 377 m/min (n = 24,000 rpm). To generate a discontinuous cut at the tool tip, the vibration velocity must be higher than the rotational speed of the milling tool. Based on the kinematics of an ultrasonic supported turning process according to Brecher et al. [18], a calculation was made to identify the cutting speed v_c which enables a discontinuous cut (v_c = 37.7 m/min). Initial values for this calculation were vibration frequency and amplitude. The final experimental matrix is shown in Table 1.

Table 1. Process parameters for ultrasonic assisted milling.

Test	Down-milling/up-milling	Ultrasonic assistance	Cutting speed v_c (m/min)
1	Up-milling	Yes	37.7
2	Up-milling	No	37.7
3	Up-milling	Yes	377.0
4	Up-milling	No	377.0
5	Down-milling	Yes	37.7
6	Down-milling	No	37.7
7	Down-milling	Yes	377.0
8	Down-milling	No	377.0
Constant parameters:		Width of cut a_e = 1 mm	
		Depth of cut a_p = 3 mm	
		Feed per tooth f_z = 0.042 mm	

In order to analyse the effectiveness of the machining process, the two quality criteria fibre pull-out and fibre protrusion as well as their percentage of a component length l = 143 mm were observed. Also, the length or rather depth of the maximum damage was measured. Fig. 2 depicts the two criteria.

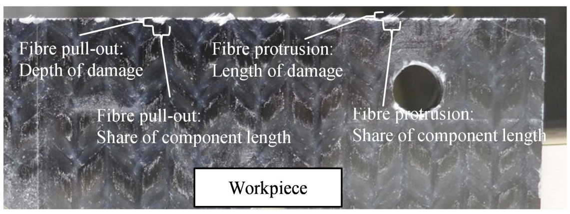


Fig. 2. Quality criteria for workpiece edge.

During the milling process, the cutting forces were measured by a quartz 3-component dynamometer from Kistler Instrumente GmbH, Sindelfingen, Germany type 9257B. This was primarily used to prove a reduction of cutting forces in consequence of a discontinuous cut. Finally, the dust concentration depending on different process parameters was measured by an aerosol monitor from TSI incorporated, Shoreview, USA type DUSTTRAK^{TM} II DRX 8530. This instrument measures the aerodynamic diameter d_{ae} of dust and differentiates dust fractions PM2.5 (mass fraction concentration of the dust particles with an aerodynamic diameter $d_{ae} \leq 2.5$ µm), PM4 ($d_{ae} \leq 4$ µm) and PM10 ($d_{ae} \leq 10$ µm).

3. Results and discussion

Regarding the workpiece quality, the results show, that the cutting speed is not the only important factor to improve the processing quality. Also ultrasonic assistance can be advantageous. Fig. 3 shows the evaluation of the two quality criteria fibre pull-out and fibre protrusion and their markedness in the orthogonal direction to the workpiece edge (test 1 and 4 show only some single fibres protruding). It is clear, that ultrasonic vibration can reduce the percentage of fibre pull-out when using down-milling, but increases the damage when using up-milling. It should be noted, that the percentage of damage is sometimes three times higher when using down-milling.

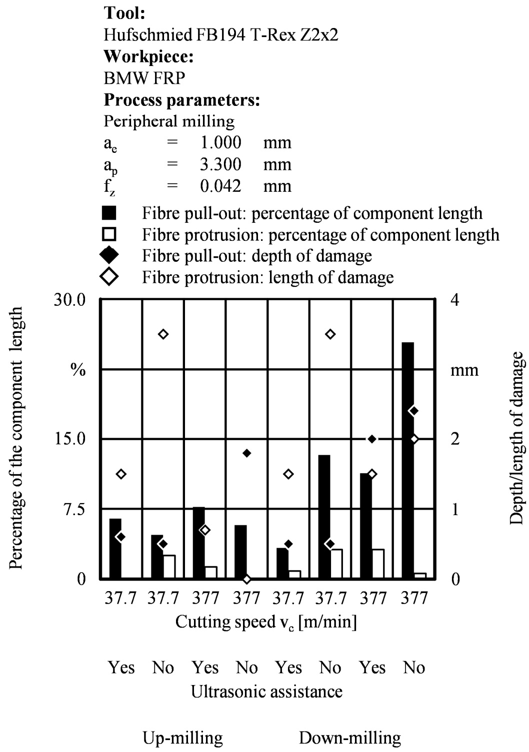


Fig. 3. Observed workpiece quality.

Only ultrasonic assistance at a lower cutting speed v_c = 37.7 m/min makes the process quality comparable to up-milling and even results in the best quality within the tested parameter field.

Regarding the fibre protrusion, no significant influence of the feed direction (up/down-milling) could be identified. Here, the cutting speed v_c is the dealing factor. It is shown, that ultrasonic vibration increases the percentage of fibre protrusion at a cutting speed of v_c = 377 m/min, but reduces the damage at a cutting speed of v_c = 37.7 m/min. Regarding the markedness of the quality criteria in the orthogonal direction to the workpiece edge it is common, that a length or depth of less than 1 mm is acceptable. A higher damage results in expensive post-processing. Fig. 3 shows, that only a lower cutting speed v_c = 37.7 m/min can reduce fibre pull-out reliably. Fibre protrusion can only be sufficiently reduced when using up-milling at a higher cutting speed of v_c = 377 m/min.

Normally, fibre protrusion is the most interesting quality criterion because it makes manual post-processing necessary. Fibre pull-out leads to a weakening of the workpiece edge, which is often of minor importance. Thus, the process parameters of test 1 (up-milling, v_c = 37.7 m/min, ultrasonic assistance) and 4 (up-milling, v_c = 377 m/min, no ultrasonic assistance), Table 1, are the most promising parameters for milling of the investigated workpiece material. Fig. 4 shows two examples for the workpiece quality of test 1 and 4 and compares them with the worst quality (test 6 - down-milling, v_c = 37.7 m/min, no ultrasonic assistance).

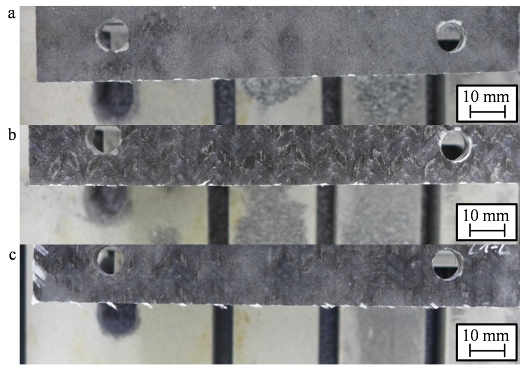
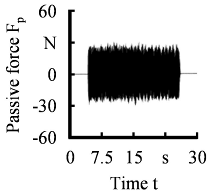
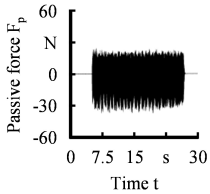
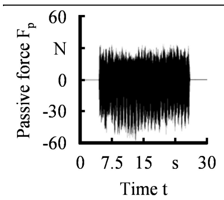
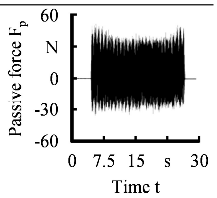
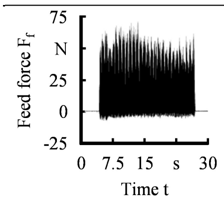
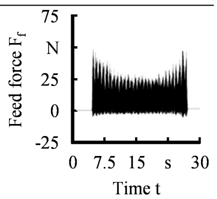


Fig. 4. Workpiece quality (a) test 1; (b) test 4; (c) test 6.

The evaluation of the force measurements shows, that the ultrasonic vibrations have a significant influence on the cutting forces. This results on the one hand from an additional friction component in the direction of the vibration/passive force F_p. On the other hand, this could be a result of a discontinuous cut, which would be the intended effect. When using the appropriate parameters (up-milling, v_c = 37.7 m/min) it could be observed, that ultrasonic assistance change the passive forces F_p in the negative direction of the y-axis (Table 2). When using down-milling, the opposite effect occurs. Additionally the feed force F_f increases by approximately 200 % when using ultrasonic assistance. In all cases an improvement regarding the fibre protrusion could be achieved which relates to the changes in the forces.

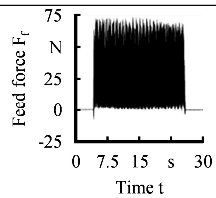
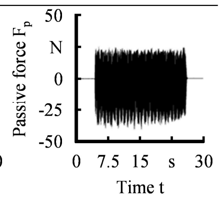
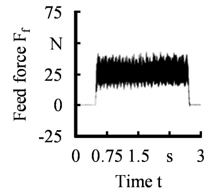
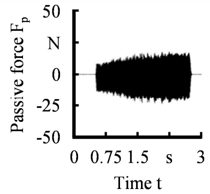
Table 2. Divergent force measurements at v_c = 37.7 m/min.

Parameters/force	Force measurements with ultrasonic assistance	Force measurements without ultrasonic assistance
Up-milling Cutting speed v_c = 37.7 m/min Passive force F_p	 Average passive force $F_{p,avg}$ = -0.1 N	 Average passive force $F_{p,avg}$ = -1.8 N
Down-milling Cutting speed v_c = 37.7 m/min Passive force F_p	 Average passive force $F_{p,avg}$ = -0.5 N	 Average passive force $F_{p,avg}$ = 1.2 N
Down-milling Cutting speed v_c = 37.7 m/min Feed force F_f	 Average feed force $F_{f,avg}$ = 10.5 N	 Average feed force $F_{f,avg}$ = 10.1 N
Constant parameters: Width of cut a_e = 1 mm Depth of cut a_p = 3 mm Feed per tooth f_z = 0.042 mm		

However it is not clear, why this leads to divergent effects regarding fibre pull-out. At a higher cutting speed v_c = 377 m/min no influence of ultrasonic assistance on the passive forces F_p but on the feed force F_f and feed normal force F_{fN} could be observed. This development requires deeper investigations and prevents a systematic derivation.

After evaluating the dust measurements for the up-milling tests it could be determined, that the dust concentration is strongly influenced by the cutting speed v_c. It is shown, that the dust concentration is up to eight times higher when using a cutting speed v_c = 377 m/min instead of v_c = 37.7 m/min. This is due to the failure mechanism of the workpiece material. When milling with comparatively low cutting speeds, there is enough time for the workpiece material to fail in a rather "classic way" with flow of material and chip formation. The failure mechanism at higher cutting speeds is comparable with a fragmentation, which leads to more dust instead of chips. This could be proven by the force measurements, which show higher cutting forces at v_c = 37.7 m/min because of increased material resistance. At v_c = 377 m/min lower cutting forces because of a reduced material resistance occur (Table 3).

Table 3. Divergent force measurements for different cutting speeds v_c

Parameters	Feed force F_f	Passive Force Fp
Up-milling Cutting speed v_c = 37.7 m/min No ultrasonic assistance	 Average feed force $F_{f,avg}$ = 27.3 N	 Average passive force $F_{p,avg}$ = -1.4 N
Up-milling Cutting speed v_c = 377 m/min No ultrasonic assistance	 Average feed force $F_{f,avg}$ = 25.7 N	 Average passive force $F_{p,avg}$ = -2.3 N
Constant parameters: Width of cut a_e = 1 mm Depth of cut a_p = 3 mm Feed per tooth f_z = 0.042 mm		

Another reason for change of dust concentration depending on cutting speed v_c is the material removal rate Q_W, which is ten times higher when using a cutting speed v_c = 377 m/min. However, the sole influence of the material removal rate Q_W can be excluded because the growth rate of the material removal rate Q_W is higher than the growth rate of the dust concentration. Fig. 5 shows the measured dust concentrations during up-milling.

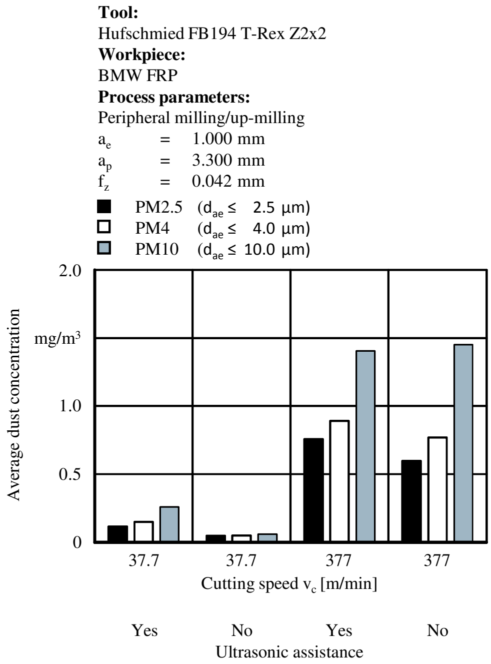


Fig. 5. Dust concentration comparison for up-milling.

In the down-milling tests, it could be shown, that next to the cutting speed v_c the ultrasonic assistance has a significant effect on the dust concentrations (Fig. 6).

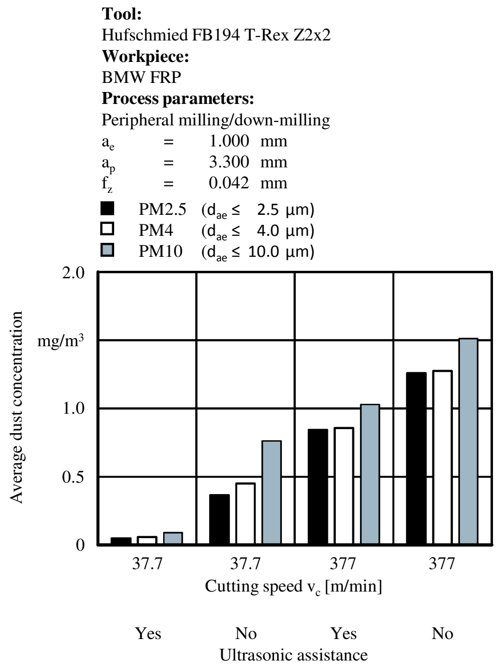


Fig. 6. Dust concentration comparison for down-milling.

At both cutting speeds, a reduction of the dust concentration as a result of ultrasonic assistance was observed. According to the theory, that the dust concentration depends on the cutting force level, it could be determined that the feed force F_f and the feed normal force F_{fN} are in some cases higher when using ultrasonic assistance during down-milling. This could be the reason for the reduced dust concentration and makes further investigation necessary.

4. Conclusions

Following conclusions can be drawn from the work:

- The best workpiece quality regarding the quality criterion fibre pull-out could be achieved when using down-milling, v_c = 37.7 m/min and ultrasonic assistance.
- The best workpiece quality regarding the quality criterion fibre protrusion could be achieved when using up-milling, v_c = 37.7 m/min and ultrasonic assistance as well as up-milling v_c = 37.7 m/min and no ultrasonic assistance.
- Within the tested parameter field only an increase or shift of the cutting forces as a result of ultrasonic assistance could be observed. A reduction of the cutting forces could not be observed.
- The generated dust concentrations could be reduced by up to 80 % when using ultrasonic assistance and down-milling.
- In comparison to conventional milling of fibre reinforced plastics ultrasonic assistance can be advantageous regarding the workpiece quality and dust concentration. This is not caused by reduced cutting forces but by other effects which makes further investigation necessary.

Acknowledgements

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