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Vibration Assisted Machining of Carbon Fibre Reinforced Polymers

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Abstract

Carbon fibre reinforced polymers (CFRP) are essential for high performance sectors like the aerospace industry because of their high stiffness, tensile strength and special properties like corrosion resistance and low coefficient of thermal expansion. The most important facts, that reason the light weight potential, are the high specific mechanical properties. Also, the automotive and the mechanical engineering sector attempt to use the advantages of such composites in an economical way. Despite the fact that products made of such materials are produced in a near net shape manufacturing, reasons like assembling make a mechanical finishing like the production of bores and grooves necessary. This paper shows a possibility to reduce fraying, which is one of three major damage types while machining fibre reinforced polymers (FRP). Therefore vibration assisted machining is used. Especially the vibration characteristics like form, frequency and amplitude should be analysed to find out how they affect the fraying behaviour in milling and drilling processes with uncoated solid carbide tools (VHM). Frequencies up to 300 Hz and amplitudes up to 4 µm are used for the experiments. It is shown that this machining technology can improve the fraying behaviour.

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Keywords: machining; milling; drilling; cfrp; composite; vibration assistance

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1. Introduction

Transport companies, but also the rest of modern industry, are forced to change over to much more economical but powerful products because of the rising energy prices. A systematic approach to do so is the reduction of mass by keeping stiffness and strength. One way to achieve a mass reduction is to use specific materials for certain products and its technical requirement, and to construct in a material efficient way. Using fibre reinforced polymers has shown to be the optimal way in several cases. Especially their specific properties, the properties related to the density, make them suitable for lightweight construction. Using carbon fibre reinforced polymers instead of

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aluminum, which is the most common material in lightweight design, can reduce the mass of a product up to 40% by keeping mechanical properties.

Further advantages in using FRP, are much more freedom in shape design, corrosion resistance or endurance strength. Modern engineering know-how advises to construct parts in a multifunctional and integral way. FRP offers different advantages for such applications. Furthermore, in many cases, it requires to use different materials for individual parts depending on their tasks in the entire structure. Therefore, assembling is going to be necessary, which often requires bores and grooves commonly made by drilling and milling processes. These processing methods used for machining FRP cause several problems like fraying of fibres, delamination of layers and splintering. The main reason therefore is the combination of fibres and the polymer matrix in a FRP. The fibres have much tougher mechanical properties than the matrix. This combination is responsible for the advantages of such materials in lightweight design, but is also the cause for problems in machining FRP. Further problems are the abrasive behaviour of the fibre and the relatively low temperature at which matrix damage occurs. These mechanisms cause high tool wear, what appears in an early decrease in sharpness of the tool`s cutting edges. Furthermore, cutting forces and temperatures are increasing in the area of penetration and so the machining accuracy, the quality of the surface and thus the productivity of the whole machining process, decreases [1]. Delamination, the separation of single layers, is mainly observed in drilling FRP especially at the entrance and the exit site of the produced bores. The main reason for this occurrence is high feeding force, which is related to the tool wear and the feeding velocity. Their maximum can be calculated analytically [2]. The phenomena of uncut fibres which mainly occur on the upper and on the lower site of the machined product are called fraying. Fraying does not damage the structure in a way as it is known of delamination, but requests post processing which increases the costs of production. Therefore it should be prohibited.

Using tools with special cutting geometries make it possible to reduce problems as listed above [2, 3]. Another or additional option is to adopt so called hybrid machining processes. The vibration assisted machining is one of these processes. The basic idea of this type of machining is to superpose the conventional cutting conditions with a vibration, which is characterized by the form, the frequency and the amplitude. So the cutting result can be improved [4, 5, 6]. An elliptical vibration form in the feed direction with an ultrasonic frequency and amplitudes on the µm level has shown that delamination and machining forces can be reduced and the endurance of the tool, which was a core drill, can be improved [4]. It is not necessary to use ultrasonic frequencies for the vibration assistance to enhance the machining results. Also low level frequencies up to 1 kHz and amplitudes up to 20 µm gain much better results as conventional conditions. It’s shown in [5] that such adjustments can reduce machining forces, which simultaneously decrease the tool wear while machining glass fibre reinforced polymer (GFRP). Thereby, the critical feed forces which are described in [2] are no longer reached. The endurance of the tool can be improved up to 40%.

2. Experimental setup

Figure 1 shows the experimental setup at the Institute of Production Engineering and Laser Technology (IFT) of the Vienna University of Technology. The vibration table is a patented invention of the IFT and was put together with the sample holder by a zero point clamping system. The samples were made of woven carbon fibre epoxy composite prepegs with the type designation IPFLCC205T50 of the manufacturer Isovolta. The specimen were built up of 28 layers in a quasi-isotropic architecture of 0/90/, +/-45, …, +/-45, 0/90. The size of the sample was 500 x 200 x 8 mm. The vibration table makes a direct part oscillation possible. This means it is possible to produce vibrations in the plane orthogonal to the tool axis (x-y-plane) in a frequency range from 1 to 1000 Hz and an amplitude range of up to 30 µm. The machine which was used for the experiments is a Haas VF 355, a 4axis portal type CNC milling centre. The tools for the experiments are from Sandvik. The drill is the 860.1-0635-019A1-NM-H10F with a diameter of 6.35 mm and the end mill is the R216.32-06030-AC10A H10F with a diameter of 6 mm.

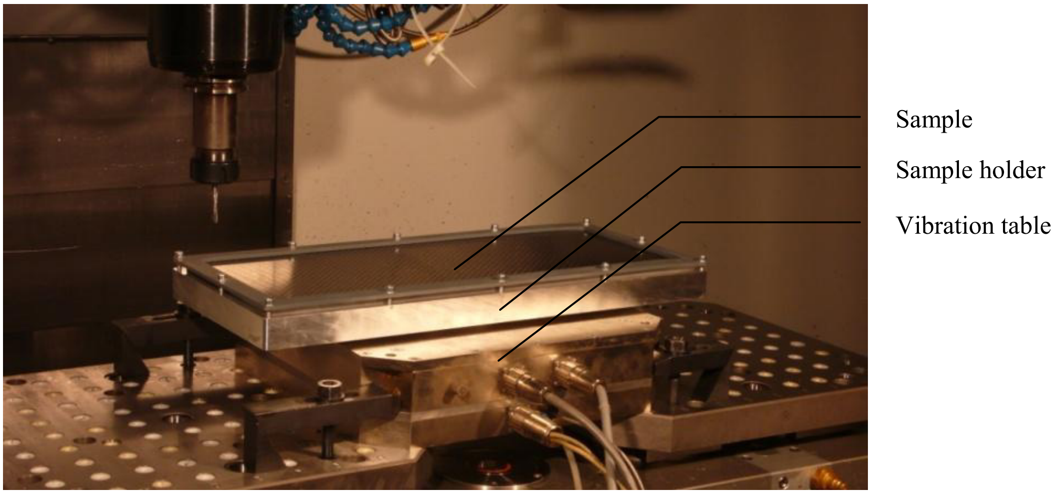

Fig. 1. Experimental setup.

3. Experimental conditions

Finally nine experiments were conducted as shown in Table 1. Two of these experiments (SV1, SV6) were conventional milling and drilling processes to be the reference for the analyses. For the drilling operation 481 bores were made evenly distributed along the sample (Fig. 1 left). For the milling operation 27 grooves with a length of 136 mm were made (Fig. 1 right).

The vibration properties like frequency and amplitude are bounded by the specifications of the vibration table. As it is designed for much lighter sample holders than the one which was used for the samples in the experiments, the attributes of the table could not be totally utilized. Drilling with core drills can be improved by superposing the feed motion with elliptical vibrations as shown in [7]. The experiments should show if even circular plane vibrations improve the results. For further analysis the circular vibration was split up in its basic movements, a movement in feed direction and on perpendicular to it.

Table 1. Experimental specification: f = frequency, A = amplitude, n = spindle speed, v = feed rate.

Experiment	Machining type	Vibration form	f [Hz]	A [µm]	n [rpm]	v [m/min]
SV1	Drilling	None	0	0	4762	476
SV2	Drilling	Circular	300	4	4762	476
SV3	Drilling	Circular	300	2	4762	476
SV4	Drilling	Circular	100	4	4762	476
SV5	Drilling	Circular	100	2	4762	476
SV6	Milling	None	0	0	4775	382
SV7	Milling	Transversal	100	2	4775	382
SV8	Milling	Longitudinal	100	2	4775	382
SV9	Milling	Circular	100	2	4775	382

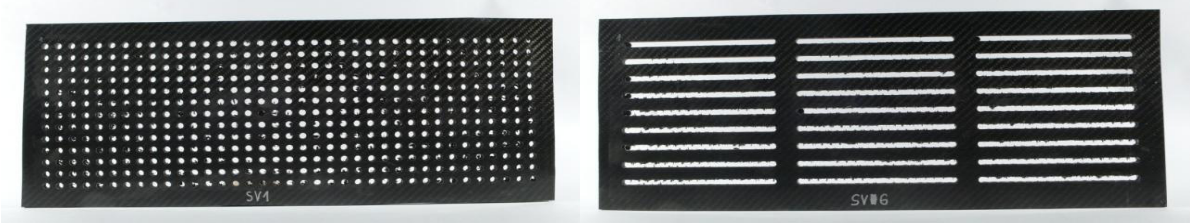

Fig. 2. (left) result of the drilling experiment SV1; (right) Result of the milling experiment SV6.

4. Evaluation procedure

To make a comparison of the conventional and the vibration assisted machining possible, a grading system was chosen, which categorises occurred frayings by their length. The frayings are subdivided into classes and each of them is weighted appropriate to its machining quality so by the length with evaluation points. Thus, bores and grooves without fraying get no evaluation points. Bores with fraying are assigned with one or two evaluation points. Less fraying means less evaluation points. Furthermore these points can be summed up line by line and divided by the number of bores in these lines. So a rating score for each line is created. Thus, the samples can be easily compared among one another. Also, the changing in machining quality along a sample, that indicates the endurance strength of the used tool can be monitored this way. As chipping and delamination do not dominate the damage of these experiments, they are not selected for further investigations in this work.

4.1. Evaluation procedure for drilling

The length which occurred at the bores where categorized in three classes and weighed as follows:

- 0 evaluation points if no signs of fraying are visible to the naked eye (Fig. 2, a)
- 1 evaluation point if signs of fraying are visible to the naked eye, but the fraying is shorter than half of the diameter of the bore (Fig. 2, b)
- 2 evaluation points if sings of fraying are visible and if they are longer than half of the bores diameter (Fig. 2, c)

4.2. Evaluation procedure for milling

A length of 1 mm was chosen to categorise critical fraying. Furthermore, the critical frayings were counted. To analyse differences in upward milling and downward milling critical frayings on the top edge and on the lower edge were evaluated separately.

- 0 evaluation points for frayings shorter than 1 mm (Fig. 2, d, lower edge)
- 1 evaluation point for frayings longer than 1 mm (Fig. 2, d, upper edge))

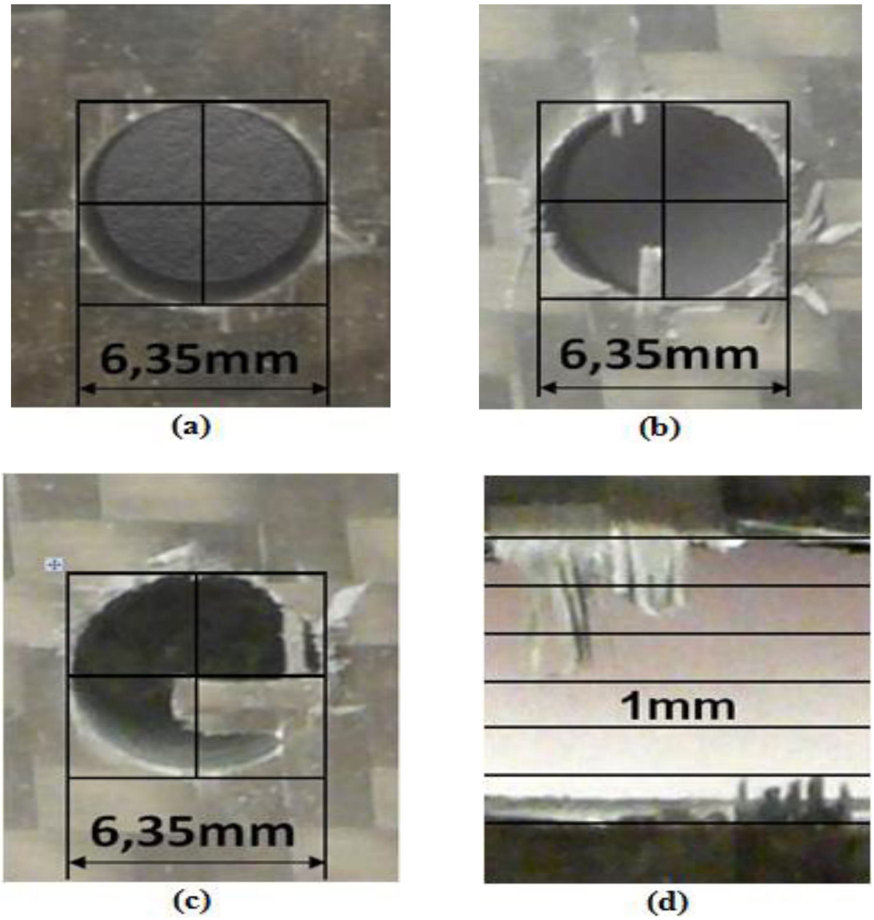

Fig. 3. (a) No fraying, (b) Fraying < d/2, (c) Fraying > d/2, (d) Fraying > 1 mm (upper edge) and fraying < 1 mm (lower edge).

5. Experimental results

5.1. Drilling SV1 - SV5

The first insight you can obtain is the circumstance that fraying just exist at the exit of the bores. The entry of the bores never has any serious sign of fraying. Further tendency cannot be realized by superficial analysis. Just more precise measurements and further assessments make it possible to do so. Significant differences can be shown by comparing the damage free bores of the experiments (those with 0 evaluation points), which are the desired result in machining CFRP. The percentage amount of frayed bores analysed by the machining depth in Fig. 4 indicates that the number of defects can be decreased by using vibration assistance compared to the conventional drilling. The percentage improvement in this case has got a maximum of 27% (= 10 of 37 less frayed bores). This advancement can be seen by comparing the conventional sample SV1 with experiment SV5 which reported best results. The decrease from 54% of frayed bores for the conventional machining process to 27% for the vibration assisted machining indicates the potential of this method.

Fig. 4 shows the percentage amount of frayed bores over the machined depth. This figure displays the influence of the tool wear to the results related to the machining quality. After around 1500 mm machining depth or around 200 drilling cycles the amount of frayed bores increases to over 80%. Such wear behaviour is absolutely untypical for a solid carbide drill and proves the complexity of cutting FRP. For the ranking of the experiments the first line of bores (37 bores and 296 mm machining depth) was chosen to minimize the effect of tool wear. The result is shown in Table 2. Moreover it is shown in Fig. 4 and Table 2 that vibration assistance parameters, like they were used in SV5, can improve the machining result and so the quality on the entire experimental duration. The difference between the results of the vibration assisted machining experiments shows how the parameters affect the process. It is very likely that further investigations with different parameters provide better results again.

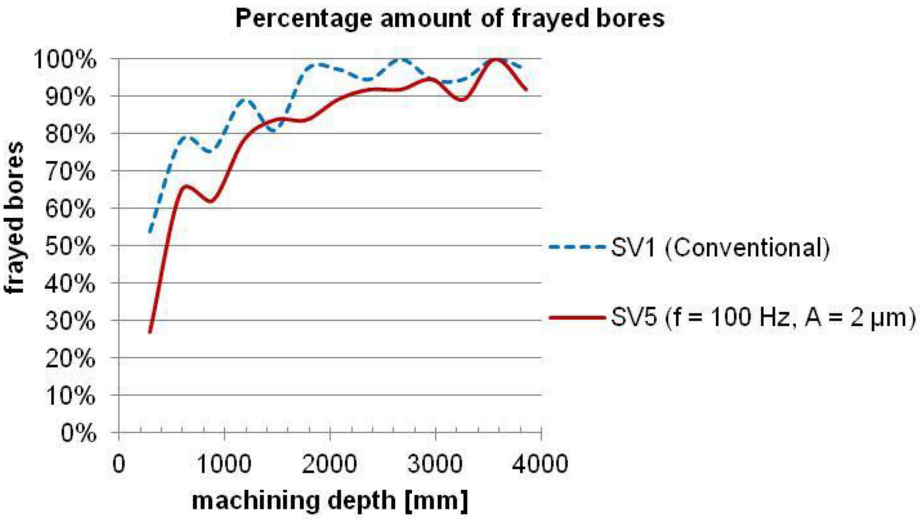

Fig. 4. Percentage amount of frayed bores analysed in the machining depth.

Table 2. Ranking referred to the results of the first machined line.

Ranking	Experiment	Rating	
1	SV5	0,38	Δmax = 42%
2	SV2	0,49	
3	SV3	0,54	
4	SV4	0,57	
5	SV1	0,65	

5.2. Milling SV6 - SV9

For the milling evaluation the frayings are divided into two classes, as mentioned in the chapter “Evaluation procedure”. The first class consists of frayings which are shorter than 1 mm and the second class consist of frayings which are longer than 1 mm. Fraying just occurs on the front side of the sample and therefore it has just been analysed and evaluated on this side. Results show that vibration assistance can partially improve conventional milling (Figure 5). Thus the total number of critical frayings can be reduced by using circular vibrations (SV9) and by using vibrations in feed direction (SV8) up to 37% and 30% compared to the conventional milling (SV6). Vibrations transversal to the feed motion (SV7) did not result in a change of the total number of frayings. Improvements on the lower edge of the grooves (downward milling) could be observed in every experiment compared to the conventional milling. Greatest effects could be monitored by using justifications of experiment SV9. Thereby a reduction up to 64% is reached. The upper edges of the grooves (the downward milling direction) exhibit less reduction. The justifications of SV8 and SV9 could reduce the frayings up to 18% and 29%. In SV7 the number of fraying rises up to 22% compared to the conventional milling (SV6). The circumstance, that upward milling leads to significantly more fraying than downward milling does not meet the norm. Generally upward milling of CFRP results in much better surface and machining quality than downward milling which can be attributed to the fact that CFRP is very brittle [8]. In Figure 6 the tool wear can once again be seen by the increase of frayings.

By comparing the grooves of an experiment, it can be seen that critical fraying already occur after milling the first groove (130 mm machining length). After the first machining line, what corresponds to 390 mm machining length, the total number of frayings is significantly increasing. This condition can be shown in all experiments. At the last machined line (around 3510 mm machining length) SV9 with its circular movement reaches nearly the half of critical frayings than the conventional reference SV6. This shows again the potential of vibration assisted machining for the composite branch. Not only the machining quality but also the wear behaviour of the tool can be enhanced.

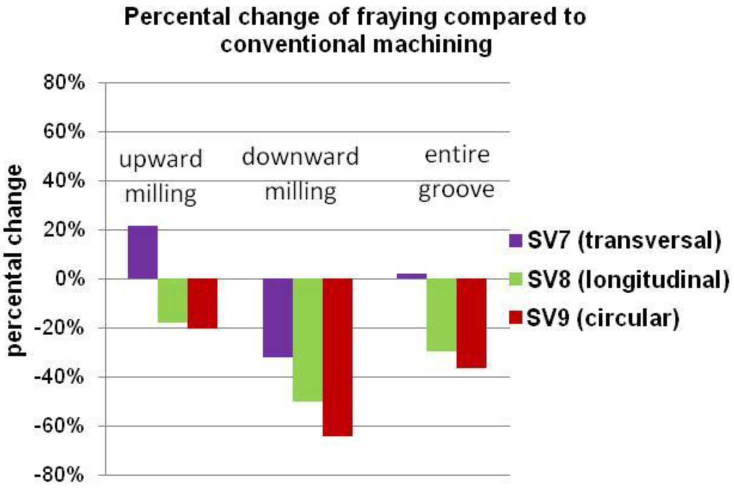

Fig. 5. Percental change of fraying compared to conventional machining.

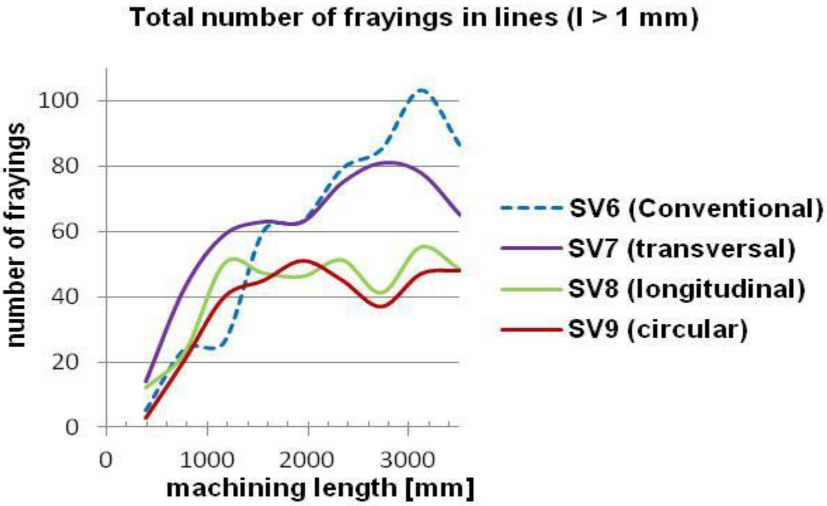

Fig. 6. Total number of frayings (l > 1 mm).

6. Outcome

Vibration assisted machining can improve the machining of parts made of fibre reinforced polymers. Following are the most important facts of the research work listed.

- Vibration assisted machining with uncoated solid carbide tools with geometrical defined blades can improve the fraying behaviour of conventional drilling and milling processes.
- Drilling is mostly improved by superposing the conventional cutting conditions with a circular vibration with a frequency of 100 Hz and amplitude of 2 µm.
- Fraying in the milling process can mainly be reduced by vibrations in feed direction and in a circular way.
- Fraying is furthermore observed in the upward milling area.
- Detailed investigations to the vibration form, frequency and amplitude as well as the interrelation between vibration assisted machining and the specific composite has to be carried out before an industrial application of this technology can be done.

The future work consists in the investigation of broader fields of frequency and amplitude. For this reason the specimen and the mounting parts will be reduced in mass, what affects the potential of movement of the vibration table positively. Another approach is to use the vibration table for the machining of high elastic fibres like PBO, PE or Aramid. The vibrations could improve the cutting through the initiation of the additional cutting force caused by the vibrations.

References

[1] J. Y. Sheikh-Ahmad, Machining of Polymer Composites, New York: Springer Science+ Business Media, 2009.
[2] H. Hocheng und C. Tsao, „The path toward delamination-free drilling of composite materials,“ Journal of Materials Processing Technology 167, pp. 251-264, 2005.
[3] J.-F. Chatelain und I. Zaghbani, „Effect of tool geometry special features on cutting forces of multilayered CFRP laminate,“ in s 4th, International Conference on Manufacturing Engineering, Quality and Production Systems, 2012.
[4] V. K. Astashev, V. I. Babitsky, Ultrasonic Processes and Machines, Springer- Verlag Berlin Heidelberg, 2007.
[5] S. Arul, Vijayaraghavan, S. K. Malhotra, R. Krishnamurthy, The effect of vibratory drilling on hole quality in polymeric composites, International Journal of Machine Tools & Manufacture, Bd. 46 (2005), pp. 252- 259.
[6] D. Brehl und T. Dow, „Review of vibration- assisted machining,“ Precision Engineering, Bd. 32, pp. 153- 172, 2007.
[7] J. Liu, D. Zhang, L. Qin, L. Yan, Feasibility study of the rotary ultrasonic elliptical machining of carbon fiber reinforced plastic (CFRP), International Journal of Machine Tools & Manufacture 53, 2012, pp. 141-150.
[8] P. Müller, Challenge lightweight engineering, International fair for production engineering and automation METAV Messe, Darmstadt, 2011.