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High Speed Cutting of carbon fibre reinforced plastics

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Abstract

The effects of high speed cutting (HSC) on metallic workpiece materials have been widely studied and the benefits are commonly employed in the machining industry. However, in the machining of composite materials, these effects have not yet been a focus of significant research work and core questions such as what impact HSC cutting parameters have on tool wear, process forces and workpiece quality remain open. As such, the work described in this paper shall focus on the use of HSC cutting parameters with spindle speeds up to 60000 rpm for the machining of carbon fibre reinforced composites. Workpiece quality and tool wear are quantified in dependence of cutting speed and feed rate and the known phenomena of reduced cutting forces at high cutting speeds are examined in the case of CFRP machining.

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Keywords: High Speed Cutting; CFRP; Milling; Chip formation; Tungsten Carbide; CVD-Diamond Coating

1. Introduction

Sustainable manufacturing from an environmental, economical and social point of view is key for the continued growth of the automotive and aeronautical industries. Cars and airplanes of the future must be quieter, lighter and more efficient. One way of achieving this is the use of innovative composite materials such as carbon or glas fibre reinforced composites (CFRP, GFRP), which are significantly lighter whilst exhibiting comparable or higher strength and wear resistance. CFRPs have been used in the manufacturing of airplanes for a number of decades, however their further development in recent years, for example in relation to the strength of the carbon fibres, plays

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a significant role for their increased use [1]. As such, large proportions of airplane structural components are now made of composite materials, for example the Airbus model A400M (Figure 1). In the automotive industry the use of CFRPs and GFRPs is relatively recent in series production, and is expected to increase dramatically in the coming years.

With few exceptions, CFRP/GFRP components are not produced as near-net shape, meaning machining is almost always required. Commonly this is done using milling, drilling and water jet cutting. Due to the continuous development of cutting tools, machining centres, robot-based machining and control systems, a significant productivity increase is expected, and also required in order to allow series production of CFRP components. In particular, the processing times and part qualities must be improved upon to achieve an economically viable production process of these parts.

Fig. 1. Airbus A400M - The wings (over 20 m long and 4 m wide) consist mainly of CFRP

In recent years research work has focused on the mechanisms of material removal in the machining of CFRPs using conventional machining parameters, with few studies on the use of high cutting speeds and feed rates [1, 2, 3, 4, 5]. Of course, the machinability of fibre reinforced composites depend on the selected materials of the matrix and the reinforcement, the cohesion between the two, the orientation of the fibres in the matrix, the volume fraction of fibres and matrix and the ratio of fibre length to fibre diameter [6]. A number of authors [1, 5, 7, 8, 9, 10] show that when milling fibre reinforced plastics, the type and orientation of the fibre, cutting parameters, and tool geometry have an essential influence on the machinability. When speaking about fibre orientation, it must be differentiated between the fibre orientation and the fibre orientation with respect to the cutting direction $\theta = 0°, 45°, 90°, 135°$ [7, 10, 11]. Everstine and Rogers [12] presented the first theoretical work on the machining of FRPs in 1971, since then the research carried out in this area has been based on experimental investigations. Hashin and Rotem [13], Koplev et al. [14] and Kaneeda [15] established that the principal cutting mechanisms are strongly related to fibre arrangement and tool geometry. Colligan and Ramulu [16, 17] carried out studies on machining of polymeric composites and concluded that an increasing of the cutting speed leads to a better surface finish.

Depending on the fibre orientation with respect to the cutting direction, different fundamental failure modes commonly occur in composite machining: fiber-tensile failure, fiber-compression failure, matrix-tensile failure and matrix-compression failure [7, 11, 13, 18, 19, 20, 21].

These fundamental failure modes usually occur in combination with one another and determine the chip formation modes in CFRP machining, with fibre buckling, fibre cutting, fibre delamination, fibre deformation, shearing and macrofacture being the main modes of chip formation [7, 10, 20]. Figure 2 shows the fundamental correlations between rake angle and chip formation modes with fibre orientations $\theta = 0°$ and 90°. The different chip formation mechanisms strongly influence the tool loading situation, thus defining the tool wear and lifetime as well as the machined part quality.

Teti et al. [10] showed that at fibre orientations between $\theta = 0°$ and 30° it is possible to achieve high part qualities, as the cutting forces are low. With rising fibre orientations, for example between $\theta = 90°$ and 135°, achieving high part qualities becomes more difficult. It should be noted that the tests were undertaken at a relatively low cutting speed of v_c = 77 m/min.

The influence of the cutting parameters has been studied by Alexandraki et al. [6] and Xu et al. [22], where it was shown that the feed rate affects the surface quality obtained, with highest feed rates causing local cracks and delamination, particularly when the cutting plane is parallel to material layers (θ = 0°). A number of authors show that the use of higher cutting speeds led to a reduction of cutting forces and a higher part quality [1, 3, 10, 22, 23, 24, 25, 26].

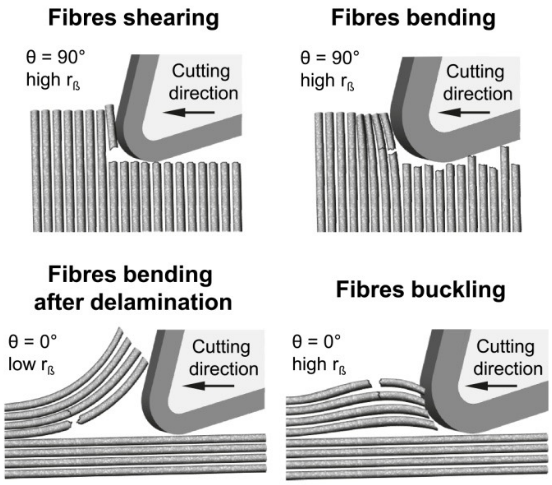

Fig. 2. Dominant chip formation modes and cutting mechanisms in CFRP machining according to [7]

It can be concluded that currently only few publications related to high speed cutting of CFRPs exist. An analysis of the fundamental effects, such as chip formation mechanisms and failure modes using HSC parameters has to date not been undertaken. Furthermore, most of the experimental activities in the literature on composite materials machining have been carried out in laboratory settings with simple analogy tests, without testing of milling processes. Previous work has shown that the use of high speed cutting parameters has led to substantial improvements in the machining result [1, 3, 10, 23, 24, 25, 26]. In those studies, the surface quality and tool wear were mostly focused on, whilst the complex chip formation mechanisms remain to be analysed.

As such, the aim of this work is to analyse the influence of high speed milling of carbon fibre reinforced plastics with a high fibre content on cutting forces, to investigate the relationship between the cutting forces and the part quality a function of the cutting parameters, such as the cutting speed, axial depth of cut, and the feed rate. Finally, an analysis of the failure modes and chip formation mechanisms is undertaken.

2. Experimental setup and materials

In order to study the influence of high speed cutting parameters on fundamental failure and chip formation mechanism CFRP workpieces were face milled in an orbital milling path. The orbital milling path was oriented at a relative fibre orientation with respect to the cutting direction θ = 0°. Tungsten carbide milling tools with eight cutting teeth were used, of which four cutting teeth had a fine tooth pitch. The tools were prepared by Hufschmied Zerspanungssysteme GmbH especially for high speed cutting of CFRP, particularly in relation to the macro- and micro geometries and the concentricity. For tool preparation, a new patented method was used, the Internal Combined External Experience (ICE-X). For the analysis of the chip formation mechanisms the tools were used in an uncoated state, to allow for an extremely high cutting edge quality with low cutting edge radii. Preparatory testing showed that the uncoated tools wear in a controlled, abrasive manner with a slight, continuous increase of the process forces with increasing wear. Cutting edge break-outs were not observed.

In a second test row, the focus lay on the economical analysis of the HSC process in comparison to conventional CFRP machining processes. For these tests, CVD diamond coated cutting tools were used in the trimming of CFRP. Details of the tools and the workpiece material are given in Figure 3. To allow a comparison with conventional milling processes, process parameters commonly used in the aeronautical industry were chosen as a benchmark. As such, cutting speeds between v_c = 250 m/min and 300 m/min and feed rates of f = 3 m/min and 4.5 m/min were used [4].

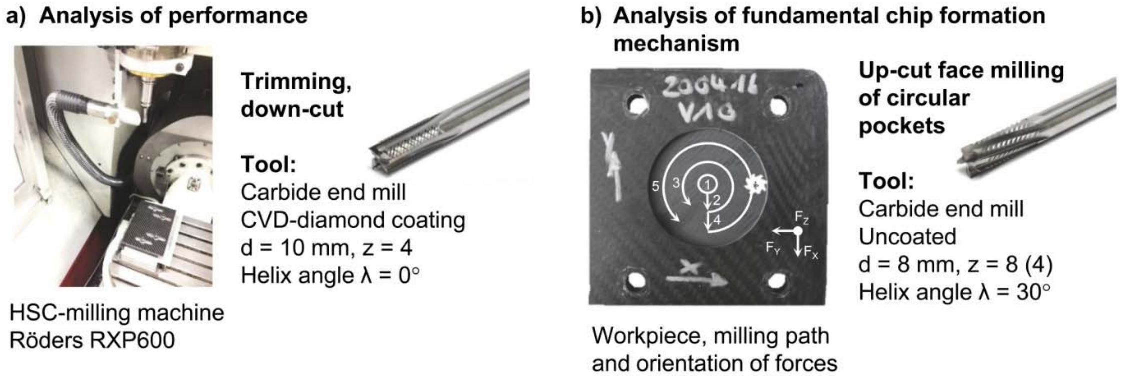

Fig. 3. Setup - Machine tool with external dust extraction system and force dynamometer, cutting tools as well as CFRP workpiece and milling path

The CFRP workpieces were t_p = 6 mm thick panels with eleven inner layers of unidirectional prepreg with the fibre type SGL CARBON SIGRAFIL C30 T050 and epoxy resin content of 35 %. The two outer layers consist of the woven fibre SIGRATEX PREPREG CE 8201-200-45/ 1200 MM/ 3K with an epoxy resin content of 45 %. The milling processes were undertaken using a RÖDERS RXP600 HSC-milling machine with a maximum rotational speed of n = 60000 rpm. In order to allow sufficient dust extraction, a NA35-D1-Type III Zone 22 extraction system from RUWAC, Melle-Riemsloh, Germany was used. The cutting force measurements were taken by fixing the CFRP plates over large screws directly onto the force measurement device type 9257B from KISTLER. The directions F_X, F_Y and F_Z are defined in Figure 3b.

3. Results and discussion

It has been previously shown by the authors in milling of CFRP with 60 % fibre content that the process forces can be reduced significantly due to the use of high speed cutting parameters. A 40 % reduction of the process forces could be achieved by increasing the cutting speed from v_c = 250 to v_c = 600 m/min. The workpieces machined with higher cutting speeds showed better surface qualities, with no delamination, fibre protrusion or thermal effects on the workpiece surface being observed [24, 25].

With the goal to increase the productivity further and to determine the limit between conventional machining and high speed machining phenomena, the cutting speed was then further increased to v_c = 1800 m/min, with a maximum spindle rotational speed of n = 60000 rpm. In Figure 4 the feed forces F_f and the tool life at different feed rates v_f and radial cutting depths ae are illustrated. At relatively low cutting depths and feed rates, the tools machined $L_{c,max}$ = 40 m without the wear criterion of VB_{max} = 0.2 mm being reached. It can thus be concluded that longer tool lifetimes are possible, as a number of milling tools showed a width of flank wear land of VB_{max} = 50 µm after a cutting distance of L_c = 40 m.

It was also observed that the increase in the feed rate and radial depth of cut led to increased feed forces and reduced tool lifetimes. Besides the higher loading on the cutting edge at higher feed rates, which leads to higher tool wear rates, issues in relation to the capacity of chip and dust evacuation were also evident.

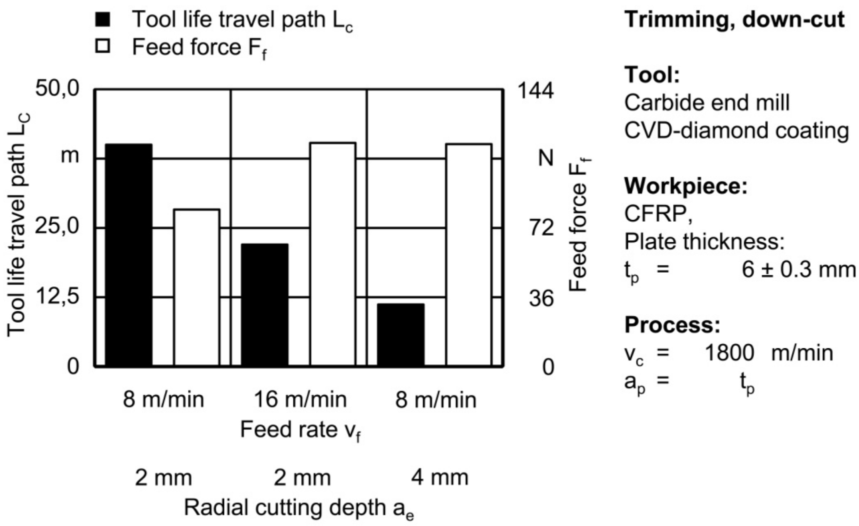

Fig. 4. Tool lifetimes at different HSC process parameters

Optical analyses of the milling process using a high-speed camera showed that the CFRP chips exit the flute periodically if end mills with a low helix angle are used and that the volume of the flutes are a limiting factor at high removal rates, as described in previously published articles [23, 25, 26]. If the dust evacuation is not sufficient, adhesion of CFRP material on the tool occurs, which leads to increased process forces and reduced tool lifetimes.

Current research and development goals are therefore the development of HSC cutting tool geometries with optimised geometries for chip and dust evacuation. At the same time, new technologies for extraction systems are also being developed. Within this work, a prototype extraction system with rotational speeds of up to n = 15000 rpm has been tested. The enormous potential of internal tool dust extraction could be shown at relatively low rotational speeds. It was observed that efficient dust extraction can be achieved with optimized internal extraction channels in the tool, which significantly reduces process forces (Figure 5).

In order to allow the effect of high speed cutting on the fundamental failure modes and chip formation mechanisms to be analysed, the influence of dust extraction and tool wear must be kept to a minimum. For that reason, circular pockets were milled using a relatively low radial depth of cut a_e = 2 mm. The process forces in dependence of the cutting speed and feed rate were determined and the machined surface quality analysed. Due to the circular milling path and force measurement on the workpiece, the maximum forces in the x-, y- and z-direction oriented on the machine/workpiece coordinate system are analysed.

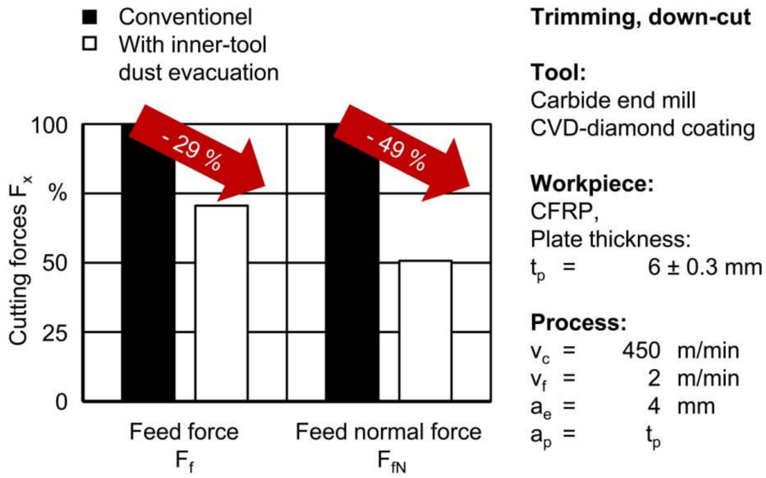

Fig. 5. Reduction of process forces by chip and dust extraction through internal tool extraction system

The measured forces in the y-direction and z-direction at difference cutting speeds and feed rates are shown in Figure 6. In comparison to conventional cutting parameters of $v_c = 276$ m/min and $v_f = 5.3$ m/min, all tested HSC process parameters led to a significant reduction of the cutting forces. The direct comparison between HSC cutting speed and conventional cutting speed at constant feed rate showed a reduction of 400 %. An increase in the feed rate has a lower influence on the cutting forces, although higher feed rates generally cause higher process forces.

With the goal of productivity increase in mind, the use of high cutting speeds in combination with high feed rates is of course most interesting. Results, as shown in Figure 6, show that an increase of the feed rate of 230 % in combination with high cutting speeds still leads to a reduction of cutting forces by 50 %. The reduction of the axial force component F_Z is particularly relevant in the milling of pockets, as high axial forces can lead to chatter and tool deflection and thus reduced component quality.

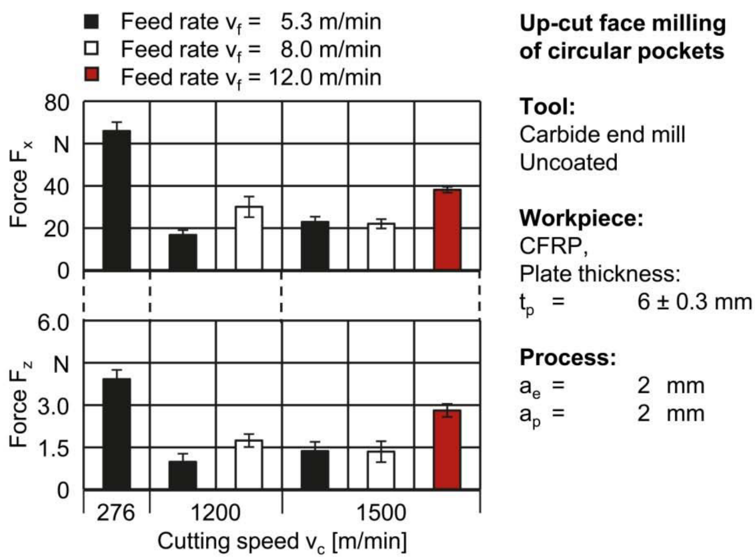

Fig. 6. Process forces using conventional parameters and HSC parameters

The guarantee of high quality workpieces is a second important factor besides productivity increase. Often, fibre delamination and protrusion occure. The machined surfaces at a fibre orientation with respect to the cutting direction θ = 0° were thus analysed using SEM images. Figure 7 shows the machined surfaces of the pockets. The pockets milled using HSC parameters with high material removal rates exhibit a high surface quality, with uniform fibre orientation without delamination or protrusions. Those pockets machined with conventional cutting parameters (v_c = 276 m/min and v_f = 5.3 m/min) have comparatively low part qualities. The structure of the fibres in the matrix materials is less uniform, with fibre protrusion of single fibres and fibre bundles. In both cases the tool´s geometry is identical and the fibre orientation with respect to the cutting direction was θ = 0°. It can therefore be assumed that the use of high speed cutting parameters changes the fundamental failure modes and chip formation mechanisms.

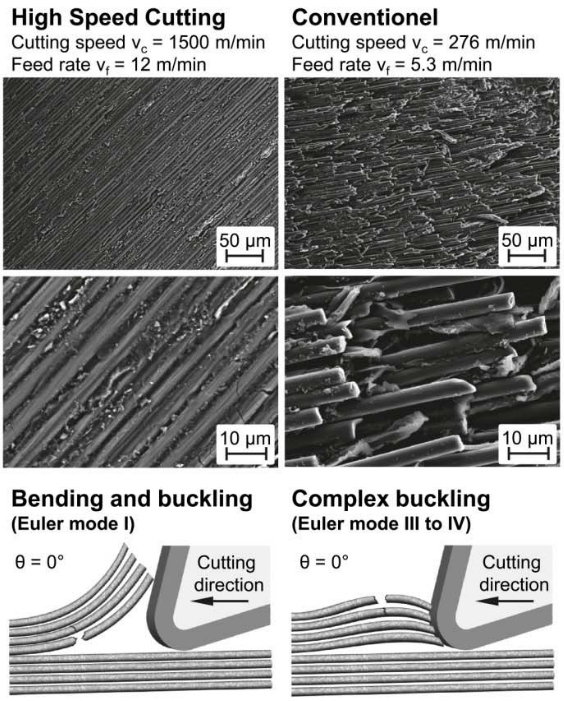

Fig. 7. Surface quality as result of changes in chip formation mechanisms at high speed cutting parameters for fibre orientation θ = 0°

At conventional cutting parameters the chip formation can be described as a multistage looping process comprising of a periodical decrease of compressive stress in the tool material contact zone followed by progressive split propagation in the matrix material parallel to the fibre direction and finally ending in „brooming“ failure with multiple random spaced fibre splits after extensive fibre buckling and progressive fibre bending. The different failure mechanisms act together, although fibre buckling can be described as the main chip formation mechanism [10, 21].

With identical tool geometries with sharp and unused cutting edges as well as identical fibre orientation with respect to the cutting direction θ the chip formation mechanism changes due to the high speed cutting parameters applied. The SEM-analysis of machined surfaces with HSC-parameters allows the conclusion to be drawn, that the main chip formation mechanism changes into fibre bending, resulting in fibre cracking and "well-defined" splitting if the critical bending stress of the fibres is reached. These effects take place in a defined direction, mainly spaced in the direction of the radial depth of cut, and produce a high surface quality with less damage of the subsurface, as depicted in Figure 7.

Similar changes in the chip formation mechanisms through an alteration of the cutting edge radii are described by a number of authors [7, 10, 11, 13, 18, 19, 20, 21]. These results showed that best surface qualities can be achieved using small cutting edge radii, as this allows for a more defined fibre failure. When cutting with higher cutting edge radii, fibre bending and particularly undefined fibre buckling become more dominant, which results in higher process forces and tool wear as well as lower surface qualities, as shown in Figure 2. In machining CFRPs, ideally sharp cutting edges should therefore be used. It must be noted however that extremely sharp cutting edges with radii $r_ß < 5$ µm can only be produced with significant additional costs, and coatings of course lead to an increase in the cutting edge radius.

The approach followed here, to avoid extensive fibre and fibre bundles buckling through the use of HSC parameters, is independent of the cutting edge radius however. As exact description of the failure modes and cutting mechanisms at HSC parameters is currently being developed, a possible explanation is given by Xu and Zhang [20, 27, 28], who researched the mechanics of fibre deformation and fracture of unidirectional fibre-reinforced polymer composites in vibration-assisted cutting. It is described, that the use of high frequency vibrations, comparable to high dynamic accelerations due to the use of high speed cutting, is advantageous for achieving high surface integrity. The high frequency vibrations lead to a rapid increase of tensile stresses and the critical tensile stress, required for fibre fracture and defined cutting of fibres, is reached faster than without ultrasonic assistance.

The failure mechanisms observed in the SEM analysis can also be explained theoretically. Through a combination of technical mechanics and strength theory, a stress hypothesis according to the acting load type can be made. At a fibre orientation with respect to the cutting direction of $\theta = 0°$, the main loading direction is a compressive loading in the fibre direction, which leads to Euler buckling. According to Euler, four different relevant buckling cases can be differentiated between. Using this for the analysis of CFRP chip formation mechanisms at high speeds, allows a classification of fibre orientation with respect to the cutting direction $\theta = 0°$ as buckling case I, in which the compressive loading leads to bending of the fibres. Conventional speeds presumably lead to the complex buckling cases Type III and Type IV, which lead to complex buckling with bending of fibres in different planes and directions. Euler's theory states that in a load situation of Type IV, approx. 16 times the buckling load is necessary compared to Type I in order to cause a fibre breakage. This may explain the significant reductions in the cutting forces at higher cutting speeds, which allow a Type I buckling to occur.

This theoretical explanation is supported through analyses of CFRP workpieces. Finnegan et al. [29] studied the compressive response of carbon fiber composite parts and showed that the two main failure modes were delamination and Euler buckling. The measured peak stress occurs before any visible failure such as cracking or shearing is observed, associated with large bending deformation that precedes the onset of Euler buckling. The experimental studies confirmed that complex Euler buckling cause higher forces compared to other failure modes.

The discussed results and explanations relate to one CFRP material and only a fibre orientation with respect to the cutting direction of $\theta = 0°$ was studied in this case. Of course, the loading situation is impacted by both the mechanical and thermal loads. In order to allow a first estimation of the influence of thermal conditions, additional process cooling using a vortex tube was used. Results showed that when using uncoated milling tools with HSC process parameters, cooling led to increased feed forces but lower tool wear rates (Figure 8).

It is known from literature, that cooling the machining process leads to an embrittlement of the CFRP matrix material and thus may lead to better chip formation mechanisms. However, a higher alteration in the thermal load may lead to higher tool wear [30, 31]. The results of the work described here showed that the use of process cooling in HSC machining of CFRP can have significant advantages in relation to tool life. Detailed analysis of the impact of cooling on the chip formation mechanisms and failure modes is a current research topic at the IWF.

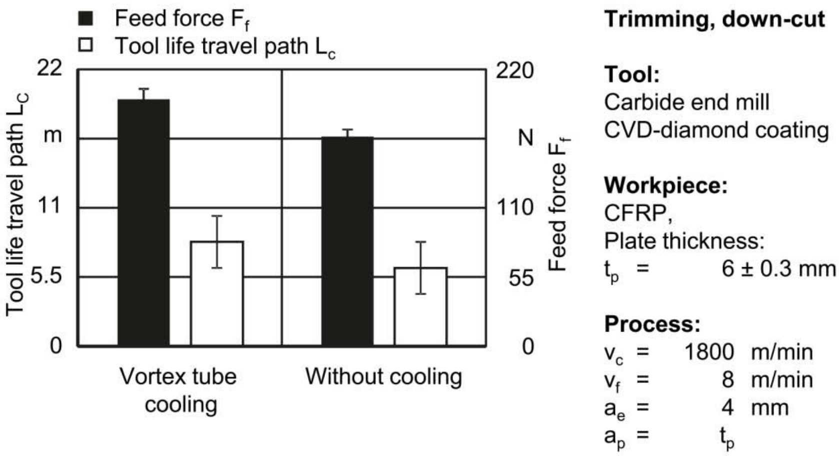

Fig. 8. Impact of vortex cooling on process forces and tool wear in HSC milling of CFRP

4. Economical assessment

An important criterion for the evaluation of productivity in CFRP machining is the material removal rate Q_W. In order to allow a direct comparison of the maximum material removal rates using HSC parameters, industrially used process parameters for conventional milling (cM) and of alternative processes were calculated, as shown in Figure 9. Within the described tests using HSC parameters, material removal rates of $Q_W = 288$ to $384\ cm^3/min$ were validated, with CVD diamond coated tools reaching high tool lifetimes at such high material removal rates (see Figure 4). The increase of the material removal rate compared to conventional milling is therefore more than +300 %.

The typical removal rates for the alternative processes were taken from literature, with ablation rates for laser machining of CFRP ranging from $Q_W = 0.03$ to $0.04\ cm^3/min$ [32, 33]. New results from Onu et al. [34] showed that through a further development of the process strategy and the laser parameters, higher ablation rates of $Q_W = 0.06\ cm^3/min$ could be reached.

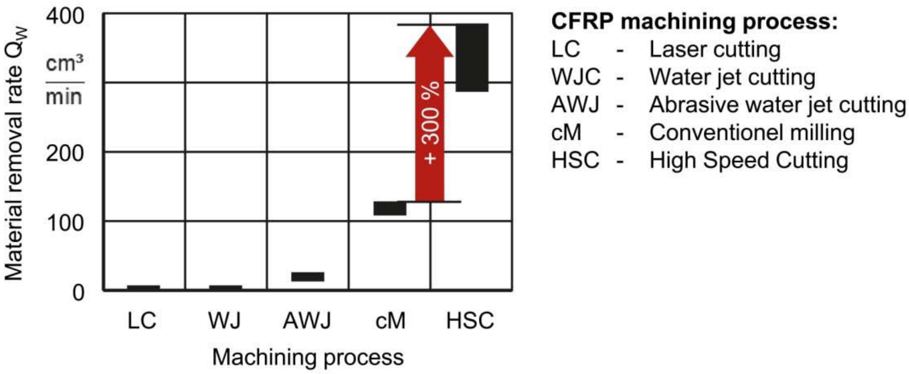

Fig. 9. Productivity of HSC milling compared to conventional milling and alternative processes [32, 33, 34, 35, 36]

The material removal rates for laser cutting shown in Figure 9 are for the maximum thickness which can be machined, $a_p = 2$ mm and a typical width of kerf $a_e = 0.2$ mm. For waterjet-based processes, feed rates $v_f = 0.1$ to

0.6 m/min (water jet cutting - WJC) and v_f = 2.1 to 4 m/min (abrasive water jet cutting - AWJ) are recommended for CFRP machining, with a plate thickness of a_p = 6 mm and a radial depth of cut a_e = 1 mm [35, 36].

It can be concluded that using HSC milling allows for a significant productivity increase compared to conventional milling and current alternative processes. Of course it must be noted that the material removal rate is only one indicator for productivity, as the required workpiece quality and the tool wear rates also play important roles in relation to tool costs and idle times. Finally, investment costs for machine tools and periphery must also be considered.

5. Conclusions

Milling of CFRPs with high cutting speed allows a productivity increase and thus has enormous cost saving potential. HSC milling of CFRPs can also positively influence the workpiece quality and as such reduce waste and necessary post-machining work.

It is however not as trivial as simply increasing the cutting speed. HSC of CFRPs must be understood as a complete system of cutting tool geometry, machine tool conditions and process parameters. Key factors for successful HSC milling are tool geometries with low tolerances, with macro and micro geometries that have been adapted to the requirements of CFRP milling. Furthermore, the machine tool, clamping of tool and workpiece and the dust extraction system must all be adapted for HSC milling. The mechanisms of HSC machining of metallic materials have been the focus of research work for a long time. The effects of force and temperature decreases as well as the influence of HSC parameters on the chip formation are therefore largely known. However, in CFRP machining, these effects have thus far not been analysed, and due to the complex nature of the matrix and fibre composite, pose questions which remain to be answered.

Within this work the authors showed, for the first time, that the use of HSC parameters in comparison to conventional cuttings speeds leads to a fundamental change in the chip formation mechanisms in CFRP machining. A correlation between reduced process forces, workpiece qualities and higher cutting speeds was identified.

When evaluating the productivity of a process, the feed rate is of particular importance, as this largely defines the time required to produce a component. Higher feed rates generally lead to higher cutting forces and thus have a negative impact on tool lifetimes and workpiece quality [22]. Within the work presented here it could be shown that the significant increase in cutting speed led to a reduction in process forces. This reduction in forces can be used to increase tool life or to increase the feed rate whilst keeping tool life at a similar level. Results shown here demonstrated that high feed rates could be successfully used in combination with high cutting speeds, thus resulting in a drastic improvement in productivity.

Acknowledgements

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References

[1] R. M'Saoubi, D. Axinte, L. Soo, C. Nobel, H. Attia, G. Kappmeyer, S. Engin, W. Sim, High performance cutting of advanced aerospace alloys and composite materials, CIRP Annals - Manufacturing Technology 64 (2015) 557-580.

[2] J. C. C. Rubio, A. M. Abrao, P. E. Faria, A. E. Correia, J. P. Davim, Delamination in High Speed Drilling of Carbon Fiber Reinforced Plastic (CFRP), Journal of Composite Materials 15 (2008) 1523-1532.

[3] S. Rawat, H. Attia, Characterization of the dry high speed drilling process of woven composites using Machinability Maps approach, CIRP Annals - Manufacturing Technology 58 (2009) 105-108.

[4] T. Geisa, C. Klingelhöllera, W. Hintze, Constant depth scoring of fibre reinforced plastic structures to prevent delamination, Procedia CIRP 14 (2014) 205-210.

[5] L. Sorrentino, S. Turchetta, Cutting Forces in Milling of Carbon Fibre Reinforced Plastics, Hindawi Publishing Corporation, International Journal of Manufacturing Engineering Volume 2014 (2014) 1-8.

[6] S. Alexandrakis, P. Benardos, G. C. Vosniakos, N. G. Tsouvalis, Neural surface roughness models of CNC machined Glass Fibre Reinforced Composites, International Journal of Materials and Product Technology (2008) 276-294.

[7] D. H. Wang, M. Ramulu, D. Arola, Orthogonal cutting mechanisms of graphite/epoxy composite. Part I-unidirectional laminate, ln. J. Mach. Tools Manufact. 35 (1995) 12, 1623-1638.

[8] S. Gordon, M. T. Hillery, A Review of The Cutting Of Composites Materials, Proceedings of the Institution of Mechanical Engineers, Part L: Journal of Materials Design and Applications, 217 (1) (2003) 35-45.
[9] J. P. Davim, P. Reis, Damage and dimensional precision on milling carbon fiber-reinforced plastics using design experiments, Journal of Materials Processing Technology 160 (2005) 160-167.
[10] R. Teti, V. Lopresto, A. Caggiano, High performance cutting of fibre reinforced plastic composite materials, Procedia CIRP 46 (2016) 71-82.
[11] D. Arola, M. Ramulu, D. Wang, Chip formation in orthogonal trimming of graphite/epoxy composite, Composites, 27A (1996) 2, 121-133.
[12] G. Everstine, T. Rogers, A theory of machining of Fiber-Reinforced Materials, J. Comp. Mater., 5 (1971) 94-106.
[13] Z. Hashin, A. Rotem, A Fatigue Failure Criterion for Fiber Reinforced Materials, Journal of Composite Materials 7 (1973) 448-464.
[14] A. Koplev, A. Lystrup, T. Vorm, Cutting process, chips and cutting forces in machining CFRP, Composites, 14 (1983) 4, 371-376.
[15] T. Kaneeda, CFRP Cutting mechanism, Proceeding of the 16th North American Manufacturing Research Conference, 1989, 216- 221.
[16] K. Colligan, M. Ramulu, The Effect of Edge Trimming on Composite Surface Plies, Manufacturing Review 5 (1992) 4, 274-283.
[17] M. Ramulu, Machining and surface integrity of fibre-reinforced plastic composites, Sadhana 3 (1997) 449-472.
[18] D. Purslow, Some fundamental aspects of composites fractography, Composites 12 (1981) 4, 241-247.
[19] A. Puck, Festigkeitsanalyse von Faser-Matrix-Laminaten: Modelle für die Praxis, Hanser, Wien, 1996.
[20] W. Xu, L. Zhang, Mechanics of fibre deformation and fracture in vibration-assisted cutting of cutting of unidirectional fibre-reinforced polymer composites, International Journal of Machine Tools & Manufacture 103 (2016) 40-52.
[21] D. Iliescu, D. Gehin, I. Iordanoff, F. Girot, M. E. Gutiérrez, A discrete element method for the simulation of CFRP cutting, Composites Science and Technology 70 (2010) 73-80.
[22] J. Xu, M. E. Mansori, Cutting Modeling of Hybrid CFRP/Ti Composite with Induced Damage Analysis, Materials 9 (2016) 1, 67-70.
[23] R. Hufschmied, S. Richarz, Hochgeschwindigkeitsbearbeitung von carbonfaserverstärkten Kunststoffen, VDI-Z Integrierte Produktion, Spezial Werkzeuge II 8 (2015) 32-33.
[24] E. Uhlmann, F. Sammler, S. Richarz, Machining of Carbon Fibre Reinforced Plastics, Procedia CIRP Volume 24 (2014) 19-24.
[25] E. Uhlmann, I. Rieck, Advanced machining processes for CFRP, Advanced Materials Research 1018 (2014) 67-74.
[26] E. Uhlmann, F. Sammler, S. Richarz, G. Reucher, R. Hufschmied, A. Frank, B. Stawiszynski, F. Protz, Machining of carbon and glass fibre reinforced composites. Procedia CIRP 46 (2016) 63-66.
[27] W. Xu, L. Zhang, A finite element analysis of fibre fracture in a polymer composite during vibration-assisted cutting, Proceedings of 8th Australasian Congress on Applied Mechanics, Engineers Australia, 2014, s1-s8.
[28] W. Xu, L. Zhang, Y. Wu, Elliptic vibration-assisted cutting of fibre-reinforced polymer composites: Understanding the material removal mechanisms, Composites Science and Technology 92 (2014) 103-111.
[29] K. Finnegan, G. Kooistra, H. N. G. Wadley, V. S. Deshpande, The compressive response of carbon fiber composite pyramidal truss sandwich cores, Int. J. Mat. Res. 98 (2007) 12, 1264-1272.
[30] N. Sorbo, J. Dionne, Dry Drilling of Stackup Composite: Benefits of CO2 Cooling, SAE Int. J. Aerosp. 7 (2014) 1, 156-163.
[31] Y. Yildiz, M. Nalbant, A review of cryogenic cooling in machining processes, International Journal of Machine Tools & Manufacture 48 (2008) 947-964.
[32] K. W. Jung, Y. Kawahito, S. Katayama, Ultra High Speed Laser Cutting of CFRP Using a Scanner Head, Transactions of JWRI, 42 (2013) 2, 9-14.
[33] V. Onuseit, R. Weber, M. Wiedenmann, C. Freitag, T. Graf, Efficient Laser Processing of CFRP. 8th International Conference on Photonic Technologies LANE 2014.
[34] V. Onuseit , C. Freitag , M. Wiedenmann, R. Weber, J.-P. Negel , A. Löscher, M. Abdou Ahmed , T. Graf, Efficient processing of CFRP with a picosecond laser with up to 1.4 kW average power, Proc. SPIE 9350, Laser Applications in Microelectronic and Optoelectronic Manufacturing (LAMOM) XX, 935012 (2015).
[35] K. Lange, M. Liewald, Umformtechnik: Handbuch für Industrie und Wissenschaft, Springer-Verlag, 2013.
[36] E. Uhlmann, M. Manthei, S. Motschmann, M. Bilz, Marktstudie Wasserstrahlschneiden 2011. Berlin: Fraunhofer IPK, 2011.