WET MACHINING OF CFRP

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Abstract
The machining of carbon reinforced plastics (CFRP) is considerably different from the machining of metallic materials. CFRP is a heterogeneous material, because fibres and matrix have different properties. Furthermore carbon fibres are hard which causes high abrasive tool wear and thus induced high costs. Moreover the sensitivity to temperature of the polymer matrix hinders the adjustment of the process factors (chipping thickness, cutting rate, feed rate) by limiting the maximum cutting rate. Also hazardous and partly alveolar CFRP-dusts, which occur while machining CFRP, display a major problem. Until now the majority of machining takes place without the use of cooling lubricants. Though wet machining can show significant advantages compared to dry machining in the view of productivity, dust binding, machining quality and tool wear. In this article, the potential of wet machining of CFRP is illustrated by means of the milling process.

1. Introduction

Modern technology places continuously new and higher demands on structural materials, which cannot any longer be complied by conventional materials. [1] One of the fundamental reasons for this purpose are the increasing energy costs combined with avoidance strategies for the CO_2-output. These effects, that in future branches such as the automobile or aircraft industry aspire to increase the weight reduction of cars and planes. Due to the lower masses the energy efficiency is raised. Therefore fibre reinforced plastics (FRP) are more and more used as structural material. Especially carbon reinforced plastics (CFRP), which are colloquial marked as carbon, offer a very high lightweight construction potential because of their excellent ratio of strength and mass. [1 - 3] Especially in the civil aircraft construction the meaning of CFRP is visible. Here commercial aircrafts are in use, whose components consist up to 53 % of CFRP. Also in the automotive engineering one reckons with increased use of CFRP in the future with annual expansion rates of up to 13 %. [4] The manufacturing of those components occurs generally near-net-shape, for instance by moulding or laminating [2,3]. However, final processing can be prevented only rarely based on today's state-of-the-art. Drilling and milling operations are necessary to trim components and produce functional surfaces and boreholes. [5] Generally those final processings are performed by machining. [6]

An essential issue at the machining of CFRP-elements is high tool wear, which occurs due to the very abrasive acting carbon fibres [7 - 9]. This causes high machining costs because of increased tool

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changes as well as costs for the tools themselves. Also the low thermal conductivity of polymer matrix materials is a problem. The process heat, which is introduced to the material, can hardly be taken away, whereby using insufficient process parameters thermal damages on the component occur. [10] In opposition to the machining of metals, CFRP machining creates no continuous chips. Rather fine particles of fibre and matrix material occur, due to the brittle behavior of CFRP. Some of those dust particles are respirable having an aerodynamical diameter smaller than 5 µm and therefore are hazardous to health. According to that, during the dry machining, an adequate enclosure of the machine tool and an effective exhaustion are necessary. [2,11,12]

One method to face the challenges of CFRP-machining is the use of cooling lubricants (CL), which is widely used in metal cutting. Although many examinations exist for the machining of FRP, most are conducted without the use of cooling lubricant. [9] But by using cooling lubricant tool wear and therfore also tool costs can be reduced. Furthermore cooling lubricants can improve the CFRP machining quality . [7-9,13] Therefore, a lubrication effect besides the pure cooling effect is required beeing established by a lubricating layer between the cutting material and the abrasive reinforcing fibre. [7]

2. Literature review

In literature there are different research results to the influence of cooling lubricants on CFRP documented which are analysed in the following. There are concerns that cooling lubricants have a negative impact on the mechanical properties of CFRP. This bases on the fact that there is a multiplicity of available matrix polymeres, fibres, hardeners, blackenings and their almost unlimited possible combinations. [9] *Selzer* reports [14] that by the use of cooling lubricant the humidity of the material changes and therefore the cooling lubricant has an effect on the mechanical properties of CFRP. According to this the epoxy matrix softens whereby the fibre-matrix-adhesion is debilitated. Consequently the fracture toughness of CFRP decreases.

Schneider [15] analysed the influence of cooling lubricant on the mechanical properties of CFRP with epoxy matrix, too. In his study he used a synthetic mineral oil-free cooling lubricant. The concentrations of cooling lubricant were 8 % and 0 % (pure water). Following, vane tests were executed on these CFRP-samples for the determination of the interlaminar shear strength (ILSS) and compared to those of the dry milled sample series. No statistically significant difference (level of significance = 5 %) between the averaged ILSS-values of the dry and wet machined sample series could be determined. There was also no difference of the ILSS-values between the cooling lubricant concentrations of 8 % and 0 %. Within a research project [16] long-term studies were conducted with CFRP-samples embedded in cooling lubricant. The aim of those projects was amongst others to analyse the impact of cooling lubricant on the humidity absorption of the CFRP as well as the subsequent mechanical disturbance. After embedding the CFRP-samples in the immersion bath tensile tests of the CFRP were carried out. As result, it can be noted:

- A saturation of the humidity absorption (0.65 %) could be determined after 200 days of embedding (for the used matrix material). Between samples being embedded in water and cooling lubricant no differences were shown regarding the percentage humidity absorption.
- The performed tensile tests in fibre direction showed no differences between wet embedded samples in comparison to the dry samples. Also no differences exist between pure water and cooling lubricant

Because the tests do not show any differences between the influence of water and cooling lubricant on the strengeth of CFRP, the results of the dissertation by *Adamow* [17], entitled “Einfluss von Wasser auf die Kohlenstofffaser/Epoxid-Polymermatrix Wechselwirkung”, can be transferred on water-soluble cooling lubricants. According to this, epoxy polymers absorb only a maximum of 2 *wt%*

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water. The absorption of water depends on many parameters, e.g. the chemical composition of the epoxy polymer, the network density, the free volume and the thermal previous history of the polymer, e.g. caused by different curing conditions or (thermal) aging. The absorption of water in epoxy polymer can occur reversible. By re-drying the absorbed amount of water can be removed.

Conclusion of the literature research

There are different research studies on the effect of cooling lubricant for the machining of CFRP. Most of them focus on the mechanical effects on the CFRP as a result of the possible liquid absorption. The predominant results show, that the use of cooling lubricant do not influence the mechanical properties of CFRP or that its impact is negligible.

3. Methodic approach

To reach a comprehensive implementation of wet CRFP-machining across the sectors aviation, automotive and mechanical engineering, the productivity compared to dry machining must be increased. Only by this measure wet machining can keep up from an economical perspective. Therefore the main target of wet machining is to perform the component finishing process of CFRP more efficient. Like that, a decrease of the overall production costs of CFRP-components can be achieved. As first approach, the integrated optimization of wet machining of CFRP is aspired as shown in Figure 1.

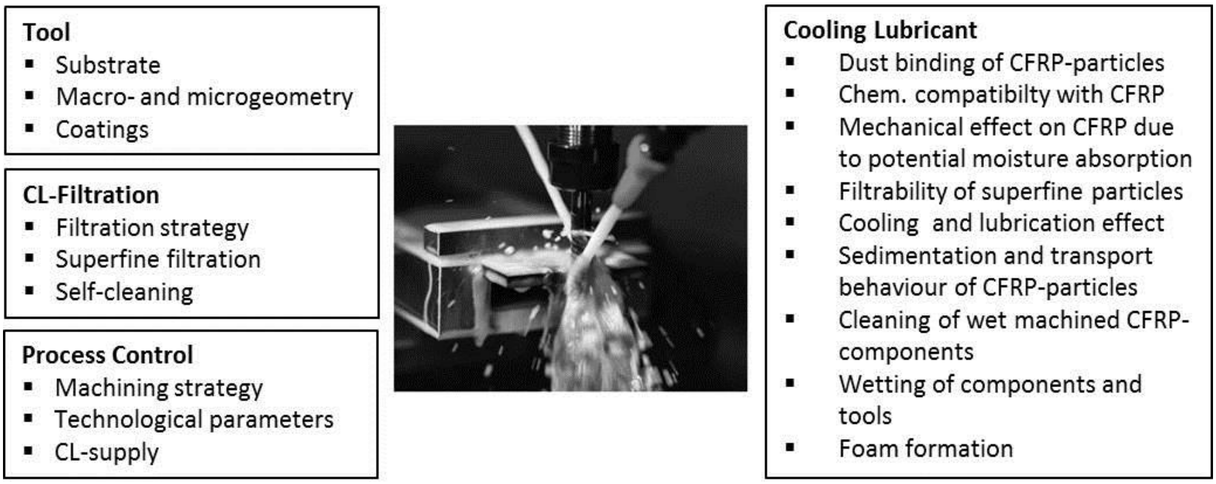

Figure 1. Integrated consideration of the wet machining process.

The technological objective is the development of a robust production process, which, due to higher processing speeds, results in shorter cycle lengths. The energy efficiency of wet machining shall be enhanced significantly by waiver of powerful exhaustion systems, which would be necessary for dry machining.

The adapted cuttuing principle of CFRP is characterised through the physics of fracture mechanics instead of the classic continuum mechanics. Due to the brittle fracture behavior of the C-fibre and the mostly thermoset matrix material, fracturing is expected to show better results than cutting. Therefore the cutting principle known from metalworking is replaced by the physical principle of fracture mechanics. The aim of this approach is to provide an impact stress as high as possible within the separation area. The following is assumed: As higher the deformation speed is, as higher is the impact stress on the materials. The positive influence of the deformation speed on the brittle fracture behavior

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is already known from the notch impact test. The implementation of speed inducting brittle fracture in milling CFRP will be pointed out in Chapter 4.2.

4. Results

4.1 Dust binding

There are occupational exposure limits for airborne dust in Germany. Those are classified by (A-) alveolar or (E-) respirable dust fractions. Alveolar particles are small enough to reach the alveoli. There is also a limit for A- and E-fractions for ordinary dusts without special toxic behaviour. The limit for A-fraction is 1.25 mg/m³, the one for E-fraction is 10.00 mg/m³. These exposure limits should not be reached in the environment around the machine tool where the machine operator stay. [18]

In this study particle measurements were performed within the machining room to be able to determine the dust fractions exactly. The cutting parameters were chosen in according to the manufacturer’s recommendation . The measurement took place during 4 milling cycles, all with a feed path of 0.5 m. The respirable (Ø 0 – 100 µm) and the alveolar (Ø 0 – 4 µm) particles have been recorded, which is shown in Figure 2.

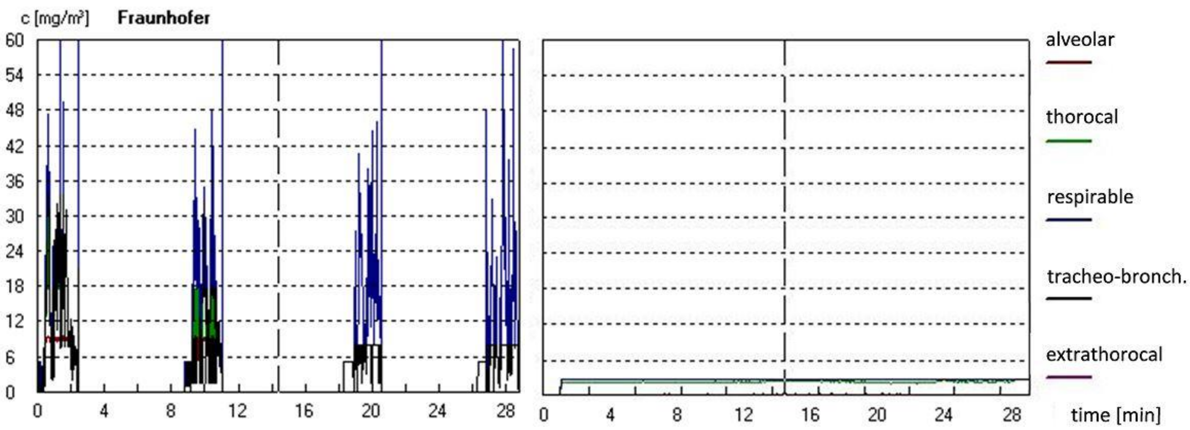

Figure 2. Particle measurement without (left) and with flood cooling (right); v_c = 150 m/min; fz = 0.06 mm; a_e = 1.0 mm; CL-concentration = 8 %; solid carbide end mill ø = 8.0 mm

The results for dry milling show 23.47 mg/m³ for the E-fraction and 6.18 mg/m³ for the A-fraction. This values are five times higher than allowed according to the TRGS 900 for the alveolar particles. Therefore it is extremely important to encapsulate the machine and extract the occuring dust particles. In analogy to the particle measurement of dry milling, Figure 2 shows the resulting dust concentrations during wet machining. Here, the average value of the E-fraction is 2.37 mg/m³, which is significantly below the limit of 10,00 mg/m³. The average value of the A-fraction is 0.05 mg/m³, which is a 25th of the limit allowed by TRGS 900. Based on the results of the performed particle measurements it was possible to prove the dust binding effect of the used cooling lubricant.

4.2 Productivity

When machining, the outlined fracture behaviour of *Chapter 3* could be obtained due to very high cutting speed and feed rates. The process temperature on the other hand could be dissipated by the cooling lubricant. Simultaneously, the lubricating effect has a positive influence on the tool wear.

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Thereby, the process speed could be increased and the time for a whole cycle of component production could be reduced.

Compared to the state of the art, the feed rate of wet milling has been increased by factor 4 compared to the dry milling manufacturer’s recommendations. The processing quality was chosen to be the the evaluation criterion. The goal was to identify the maximum wet milling parameters that create the same machining quality as dry milling with standard parameters. The following Subsection will describe the wear and the process force progression.

4.3 Tool wear and process forces

The wear and force progression of the wet and dry performed milling tests of CFRP are shown in Figure 3.

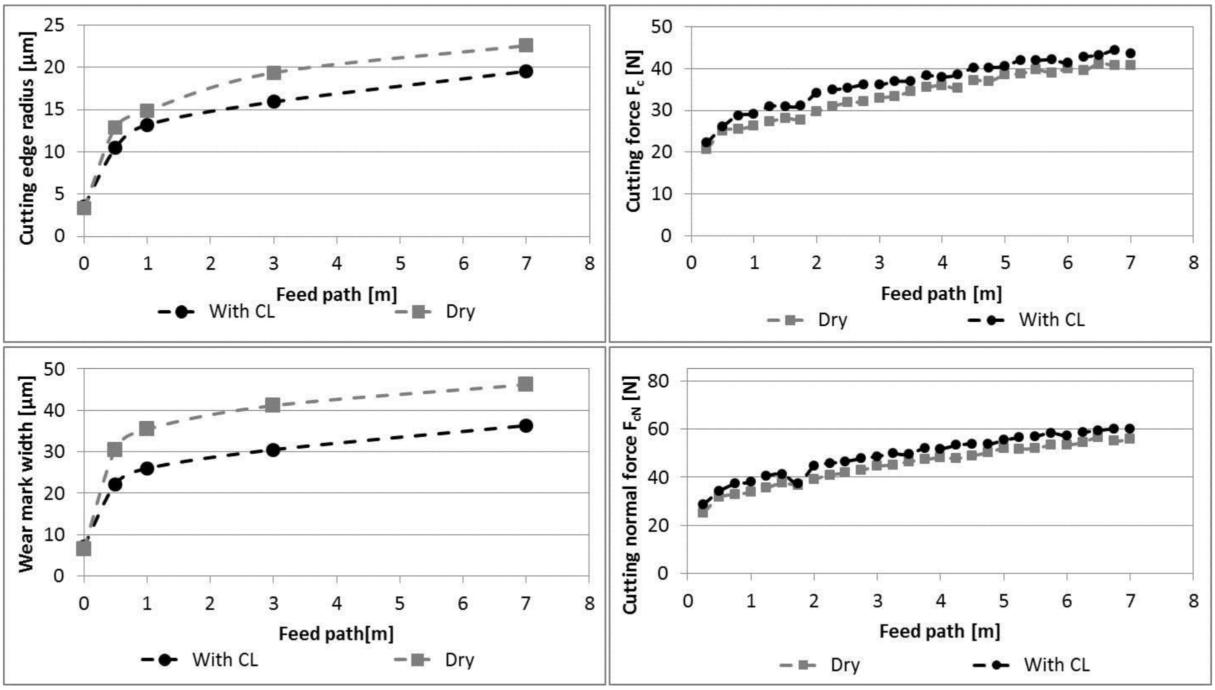

Figure 3. Development of wear mark width and cutting radius as well as the related cutting forces as a function of feed path at dry and wet milling of CFRP; v_c = 600 m/min; f_Z = 0.06 mm; a_e = 1.0 mm; CL-concentration = 8 %; solid carbide end mill ø = 8.0 mm

The end mill used in the dry machining tests shows higher cutting edges radii compared the one with the use of CL along the whole feed path of 7 m. Particularly along the run-in period lower tool wear could be determined on the tool used with CL. So the cutting edge rounding with CL after a feed path of 1 m is 13 % below the value of dry milling. After a feed path of 7 m the cutting edge radius with CL is 19 µm, whereas the dry tool radius rises till 23 µm. Also the width of the wear mark with, as second wear criterion, shows a similar development as the cutting edge radii. The wear mark width as a function of the feed path increases slower at the wet used tool. After the run-in period of around 1.0 m the curves run approximately parallel. So the wear reduction effect of the CL is initiated earlier and enables the tool to achieve a cleary better machining quality within the feed path range > 1.0. After 7 m tool path the wear mark width of the wet milling tool is 10 µm below the dry used end mill.

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The analyze of the associated process forces shows, that the cutting force and cutting normal forces increase as a function of feed path for wet and dry milling. Across the whole feed path of 7 m the measured cutting forces for wet milling are above those of dry milling.

5. Discussion

The tests of Chapter 4 show a reduction of tool by the use of CL at milling CFRP. After the achieved feed path of 7 m a reduction of the cutting edge radius of 17 % and wear mark flank of 17 % was caused by the use of CL.

The analyzes of the cutting forces have shown, that without the use of CL the cutting force and cutting normal force (Figure 3) are lower. These lower forces in comparison to wet milling are presumably caused by a temperature-related matrix softening. It is possible that the glass transition temperature of the matrix was met by the dry process, which resulted in a less tough material behaviour. Probably due to the cooling effect of the CL those temperatures didn't occur within the matrix when milling wet. Hence higher cutting forces have been necessary because of the missing softening of the matrix.

6. Summary and Outlook

6.1 Summary

This article ought to show the potential of cooling lubricants for the machining of CFRP. To reach this goal, initially the state of the art was analyzed. Thereby it was majoritarian cited that the use of CL doesn't effect the mechanical properties of epoxy-CFRP. To investigate the potential of CFRP-machining two methodical approaches are pursued by the Fraunhofer IPA.
On the one hand an overall consideration of the wet machining process. It contains besides the development of a suitable CL an investigation of all peripherical components which influence the machining process. The objective is to reduce the production costs of CFRP components compared to dry machining by an optimal aligned wet machining process.

On the other hand the usage of CL offers another approach which contributes to a more efficient machining process. Therein the cutting process principle is adjusted for the brittle fracture behavior of C-fibers and combined with the CL. Due to CFRP milling tests with CL it was possible to increase the feed rate by the factor 4 compared to the manufactures specifications for dry machining. Thereby the machining quality shouldn't have been lower than the machining quality of dry machining with recommended machining parameters.

Furthermore it has been experimentally proven that the hazardous dust, which occurs in dry machining, can be almost completely bounded by the CL.

6.2 Outlook

Due to the fracture mechanic principle, combined with the wet machining, the tool edges wouldn't have to be designed as sharp as they are used for dry machining. With the lower cutting speed and feed rate of dry machining smaller cutting edges are necessary to cut the C-fibers accurate. When machining dry, high process speed is not possible due to the process temperature. That is the reason why the fracture mechanical effect cannot occur. The currently available CFRP tools are designed for dry processes and therefore show mostly small cutting edge radii. Therefore Fraunhofer IPA works beside CFRP-eligible CLs also in the field of optimized tool geometries for the machining with CL. The objective is, through adjustments of the cutting edge geometry, to generate a more stable cutting tool. High strength coatings as well as extreme small cutting edge radii are thereby avoided. Besides

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an adjusted wedge angle it is possible to reduce the chip space of the tool significantly because of the more effective flushing with the CL. Thereby the possibility is given to use tools for the maching of CFRP with CL in the field of high speed machining. Furthermore these tools could offer higher tool life times than today's tools for dry CFRP-machining.

An important aspect is also attributed to the CL-filtration, since the CFRP dust contains tiniest C-fibre particles. If the filtration class is to low the abrasive particles can reach the machining zone multiple times. Besides higher tool wear the machine itself would suffer from an increased wear due to the exposition to the abrasive CFRP-CL-medium. Therefore Fraunhofer IPA is working on a multi stage filtration, too, which is recommended to remove the whole particle spectrum of CFRP dust from the CL.

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