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CFRP grinding under different coolant conditions

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Abstract

Carbon fiber reinforced polymers (CFRP) are a class of materials used in various applications such as lightweight construction due to their outstanding physical and mechanical properties. The heterogeneous structure of composite materials makes them more difficult to be machined. Delamination due to machining is a typical quality problem that can ultimately lead to component failure. The high-strength and abrasive carbon fibers cause significant tool wear. The plastic matrix poses a further problem, as it is very temperature-sensitive and hardly thermally conductive. CFRP is usually machined under dry conditions with a geometrically defined cutting edge processes.

This paper investigates the grinding process of CFRP with superabrasive grinding tools in dry condition, Minimum Quantity Lubrication (MQL) and wet lubrication conditions with two different nozzle types. The evaluation is based on the machining forces, delamination on the surfaces and the surface roughness. In addition, the influence of the bond and the abrasive on the machining forces and the wear behaviour of the tools is investigated. The results show that the machining forces depend heavily on the machining conditions. With certain machining parameters, dry machining induces higher process forces than wet machining. In addition, dry and MQL machining causes more residue of the machined material to adhere to the workpiece and tool. The forces and quality of the machined workpieces using minimum quantity lubrication are almost identical to the results of wet machining. From this point of view, minimum quantity lubrication is a good strategy for CFRP grinding. The cleaning effort for the workpieces and the machine should also be taken into the consideration. The chip spaces of vitrified bonded grinding tools tend to be filled with chips caused loading of the wheel. Finally, the study shows that grinding with cooling lubricant outperforms dry machining and results in better quality parts.

Keywords: Grinding; CFRP, MQL, CBN tool, Diamond tool

1. Introduction

In recent years, the use of carbon fiber reinforced plastics (CFRP) in technical applications has significantly increased [1]. These Materials have high specific stiffness, strength, toughness, resistance to fatigue, creep, wear and corrosion. CFRP components also have good damping properties [2]. Due to the outstanding material properties, fiber composite components are used in many applications. They are particularly well established in medical technology and aviation. Compared to conventional materials such as steel and aluminum, the use of fiber composites allows weight reductions of up to 30%. In many cases, the components are produced as close as possible to their final shape during manufacture. In certain cases, however, mechanical post-processing by machining is necessary. The milling process [3,4] or grinding process [5-10] is usually used here.

Biermann et al [5] have reported that drill grinding is well suited to producing holes in CFRP components. Machining takes place below the glass transition temperature of the resin matrix. The process is a combination of drilling and grinding and enables high surface qualities on the cut edges.

The studies by Arisawa et. al [6] showed that end mills electroplated with CBN are better suited for machining CFRP than conventional milling tools. The fine CBN (Cubic boron nitride) abrasive particles are fixed to the steel body of the milling cutter by the nickel matrix. The advantage of diamond-tipped tools is that they produce fine surfaces on the cutting edges. Machining CFRP places significantly less stress on the cutting edges of tools than is the case when machining metals.

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Hu et al [7] investigated the behavior of grinding forces during the machining of multidirectional CFRP composites. The measured forces increased almost linearly with increasing the depth of cut and were generally greater than for unidirectional samples under the same grinding conditions. The surface roughness in the longitudinal direction of the ground multidirectional samples varied strongly with the measurement location where the local fiber orientations differed. The typical chip shapes during grinding of the multidirectional CFRP composites are a mixture of fine powder, broken fibers and pieces of broken composite bodies.
Studies by Klocke et al [8] showed that by the drilling CFRP, better results can be achieved if tools with plated or bonded diamond coatings are used instead of conventional twist drills.
Sasahara et al [9] conducted an experimental study to achieve high-performance machining of CFRP. The aim of the study was to show the effects of the internal coolant supply through the grinding wheel on the cutting-edge quality of the CFRP. Surface grinding was carried out with a cup grinding wheel. The results showed that the load on the grinding wheel was significantly reduced by the internal coolant supply. Therefore, the grains of the grinding wheel were able to cut the fibers in a sharp condition without delamination or burr formation on the ground surface. The surface roughness was also lower compared to the surface machined with the end mill.
Soo et al [10] concluded that the use of CBN tools for edge milling under roughing conditions results in greater tool wear, higher workpiece surface roughness and process forces than diamond tools. It was expected that the higher wear on the CBN grains could lead to increasing machining temperatures on the workpiece, which could damage the resin matrix. No significant delamination of the workpieces was observed during the tests.
Even if CFRP components are manufactured as close to the final contour as possible, some interfaces must be precisely machined for use in demanding environments. This also involves machining with grinding tools. It is known from experience in metalworking that cooling lubrication during grinding can have a major influence on the results that can be achieved. This work focuses on the influence different cooling lubrication systems in the CFRP machining.

2. Experimental setup and parameters

For the investigations, grinding tests are carried out using a surface and profile grinding machine (ELB SmartLine N10 KGT 840D) with different grinding tool and cooling systems.

2.1. Experimental setup

The grinding spindle has a maximum output of 30 kW and a maximum speed of 12,000 rpm. A hydraulic tool holder (Gühring) with an HSK-C63 interface the tool holder to the tool shank with the diameter of 8 mm. To coonect the chuck in the machine spindle, an HSK adapter (Mapal) is used, which is shown in figure 1. The workpiece is clamped in a clamping system (FRIBOSA). In order to record the process forces, the clamping system is located on a Dynamometer 9255C from Kistler. A 5070A charge amplifier and the DAQ 5697A data acquisition system from Kistler are used for data acquisition. The force measurement is carried out with a sampling frequency of 20,000 Hz.

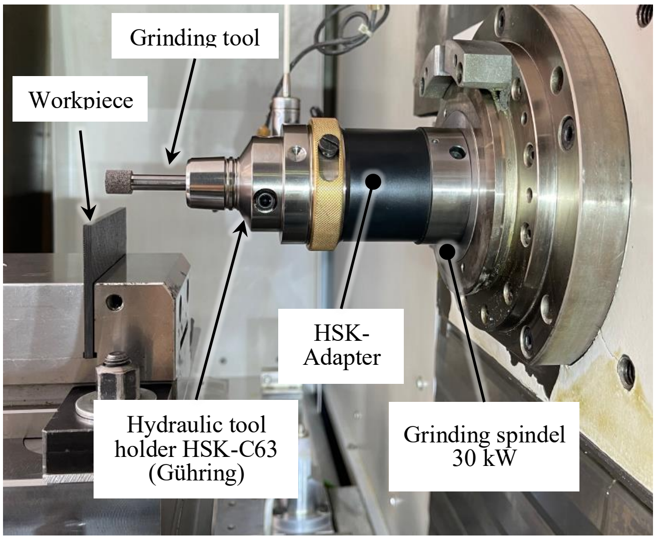


Fig. 1. Machine setup.

2.2. Coolant system

Four different cooling lubricant systems are used for the tests. The Table 1 shows the arrangement and characteristics of the three cooling lubricant systems. The fourth variant, dry machining, is not included in the table as it does not require any installations.

Table 1. Overview of the coolant systems used in the investigation.

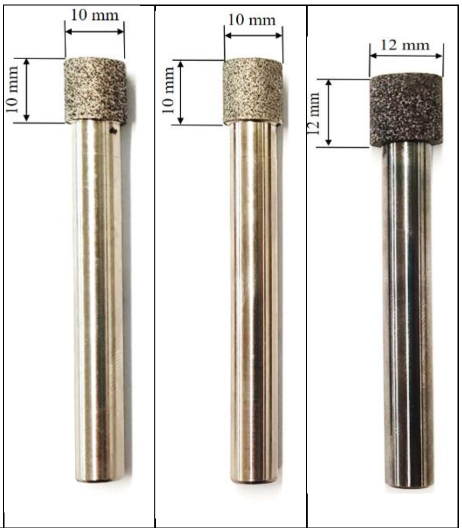
Emulsion; conventional nozzle Abbreviation	**Emulsion; additive manufactured nozzle Abbreviation**	**MQL**
		
Nozzle width: 18 mm Gap height: 2.5 mm Cross section: 45 mm^2 Distance: 13 mm Angle: 30 °	Nozzle width: 47 mm Gap height: 2 mm Cross section: 94 mm^2 Distance: 13 mm Angle: 40 °	Nozzle diameter diameter: 1 mm Cross section: 0.8 mm^2 Distance: 10 mm Angle: 30 °
Volume flow: 50 l/min	Volume flow: 50 l/min	Volume flow: 0.057 l/min
Medium: Emulsion - Grindex 10 (Blaser Swisslube)	Medium: Emulsion - Grindex 10 (Blaser Swisslube)	Medium: Oil - Ferrofluid (ML Lubrication)

The conventional nozzle represents the standard used in the industry. The additively manufactured nozzle is a flat nozzle that was originally produced for use with grinding wheels with diameters of up to 300 mm and a width of 45 mm. The inner contour is designed for a high speed and laminar flow at the outlet. Both nozzles are operated with Grindex 10 emulsion from Blaser. The minimum quantity lubrication system HTR from the company HPM technology is used with lubricating oil Ferrofluid Epsilon MO 9340 from ML Lubrication.

2.3. Tools and workpieces

Three different types of grinding tools are used for the machining operations. These have dimensions and specifications illustrated in Table 2. All tests are carried out at the same cutting speed. The different diameters of the grinding tools are compensated by adjusting the spindle rotational speed.

Table 2. Specification of the grinding tools.



Mounted point	B151	D151	B151
Grain	CBN	Diamond	CBN
Bonding	electroplated	electroplated	vitrified
Concentration	-	-	C100

In the SEM images (Figure 2), it can be seen that the diamond grains protrude more clearly from the surface than the CBN grains. With vitrified bonded tools, the grains are deeply embedded in the matrix and the chip spaces between the grains are therefore smaller.

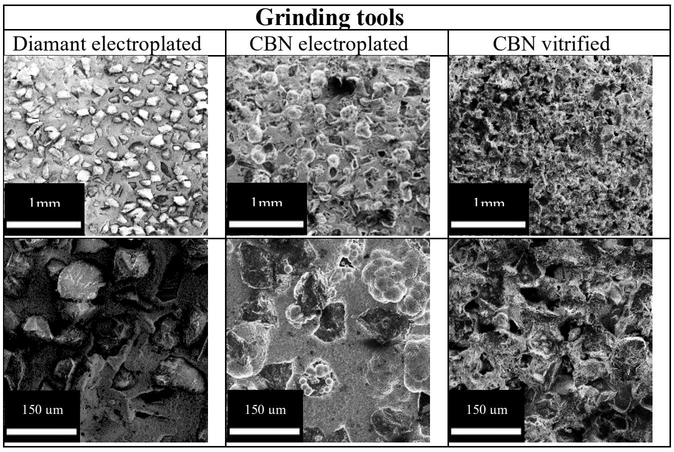


Figure 2: SEM images of the grinding tools

The CFRP samples for the tests have the thickness of 4 mm with a two-component epoxy resin matrix as shown in figure 3. The fibers are arranged bi-directionally in the layers as a plain weave. The layer structure corresponds to a repeating 0°/+90° and +45°/-45° orientation. One side of the panel has a smooth surface, which is covered with a gelcoat. The other side shows the raw and rough panel structure. Under the smooth side of the sample is a fine mesh of copper wires.

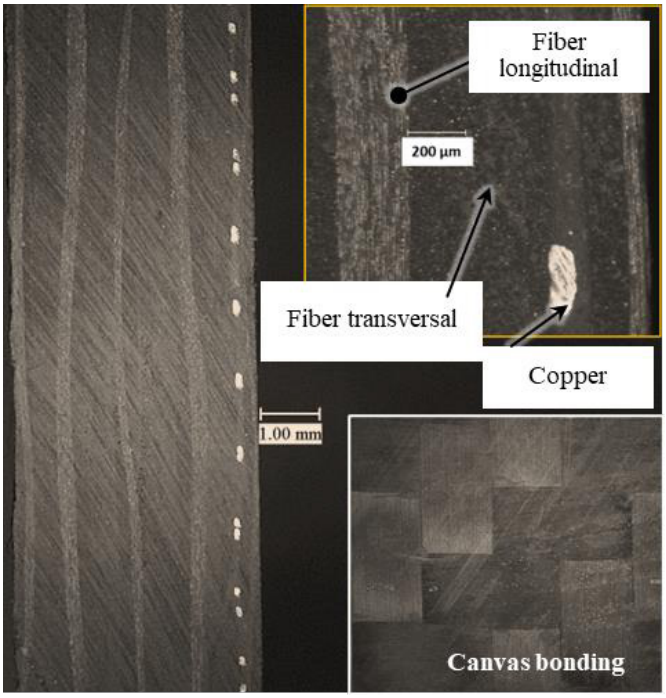


Figure 3: Cross section of CFRP inclusive the binding

This is used particularly in aviation to achieve a Faraday effect of the aircraft fuselage in the event of a lightning strike. This additional component represents a further challenge for the tests. The layers are shown in Figure 3. When preparing the samples, care was taken to ensure that the fibers in one direction were as parallel as possible to the cutting edge.

2.4. Process parameters

The tests are carried out with different parameters. This is partly due to the different tool diameters. In addition, the maximum speed of the grinding spindle prevents tests at different cutting speeds. The tool manufacturers Diametal and Häfeli recommend significantly higher cutting speeds for machining. The tests are therefore carried out exclusively at the maximum possible cutting speeds. When machining metallic materials with CBN, cutting speeds of 80 m/s or higher are used in order to keep tool wear low. In a first test, the parameters of the Table 3 are used to investigate the influence of the grain material under the different cooling conditions.

Table 3: Cutting data for short-term tests Differentiation of grain material with electroplated bonding

Short-term experiments electroplated bonding		
Material removal rate	Q'_w :	444 mm^3 /mm*min
Cutting speed	v_c :	6.2 m/s
	Diamond electroplated / CBN electroplated	
Parameter set	Feed rate v_f mm/min	Depth of cut a_e mm
1	888	0.5
2	1184	0.375
3	592	0.75

In a further step, a comparison between the electroplated and vitrified bond is investigated. Table 4 shows the parameters of the short-term tests applied in this investigation. The long-term tests of electroplated grinding tools are performed between cooling using MQL and an additively manufactured nozzle.

Table 4: Cutting data for short-term tests Differentiation of bonding material for CBN grains.

Short-term tests CBN		
Material removal rate	Q'_w :	44.4 mm³ /mm*min
Cutting speed	v_c :	6.2 m/s
Parameter set	Feed rate v_f mm/min	Depth of cut a_e mm
	CBN electroplated	
1	888	0.05
2	1184	0.0375
3	592	0.075
	CBN vitrified	
1	740	0.05
2	986	0.0375
3	493	0.075

In order to increase the stress and wear on the tool, the metal removal rate is increased by a factor of 2 compared to the first test. The cutting data used in the investigation can be seen in Table 5. The same sample geometries are used for all tests.

Table 5: Long-term cutting data with diamond tools and galvanic bonding

Long-term tests Diamond electroplated		
Material removal rate	Q'_w :	888 mm³ /mm*min
Cutting speed	v_c :	6.2 m/s
Parameter set	Feed rate v_f mm/min	Depth of cut a_e mm
1	888	1

Roughness measurements are carried out to assess the surface quality of the cut edges. A MahrSurf DU130 roughness and profile measuring device from Mahr is used for this purpose. Three measurements are taken at different points for each cut surface. The measuring points are each 10 mm apart.

3. Results

In addition to the machining forces (tangential and normal force), the surface quality and the condition of the tool after machining are assessed for the evaluation of the grinding tests. Three force measurements are carried out for all parameter constellations. The standard deviation of these values is shown in the diagrams with error indicators.

3.1. Short term tests

The specific tangential force F_t in figure 4 shows that the lower forces occur at greater cutting depths and lower feed rates (by constant material removal rate). It can also be seen that this behavior is more pronounced when emulsion is used for cooling. The results with dry machining and MQL show these trends to a lesser extent. This leads to the conclusion that higher cutting depths can preferably be selected with greater cooling capacity.

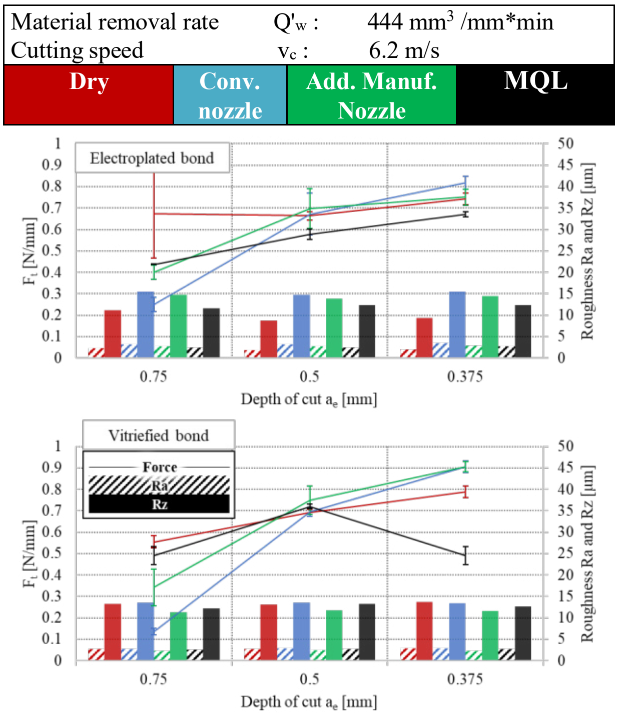


Fig 4: Related tangential force and roughness as a function of infeed; diamond (top) and CBN (bottom)

The roughness values on the cut surfaces shows that the diamond tool can achieve the lowest roughness values with dry machining. During dry grinding of CFRP, smearing effects can possibly occur due to the complex nature of the material's composition, including both the carbon fibers and the polymer matrix. These smearing effects can impact the surface quality and integrity of the CFRP component. Cooling with emulsion causes higher roughness. This can be explained by the fact that the good cleaning effect through high volume of coolant makes less loading of tool happened so the chip spaces are always existing. As a result, individual grains protrude significantly from the bond. This behavior is confirmed in Fig 5.

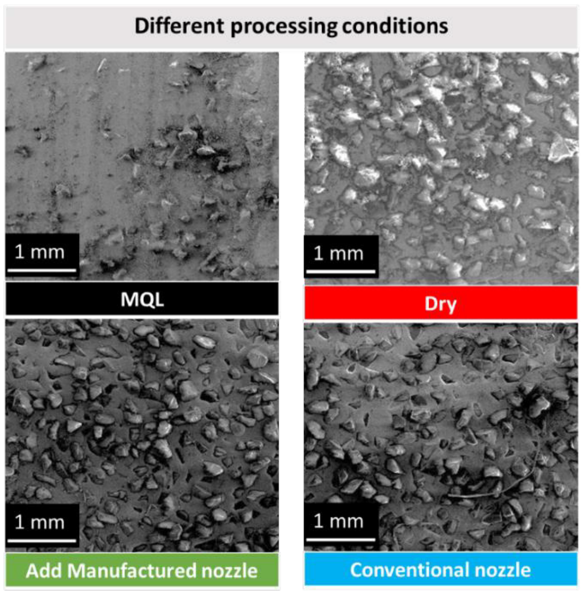


Fig 5: SEM images of the electroplated grinding tools after short-time machining of 487.5 mm³/mm

The images of the Fig 5 clearly show that the spaces between the grains are free of grinding chips even after long term use. In contrast, the tool shows clear clogging and loading with the sample material after dry and MQL processing.

By machining with CBN tools, the same effects are no longer recognizable. It can be seen that the grinding forces are more dependent on the cutting data than diamond tools. Figure 6 shows the results from test 2. The comparison between cooling with emulsion (additive manufactured nozzle) and minimum quantity lubrication (MQL) clearly shows that higher forces occur in both cooling systems with the grinding tools of the vitrified bond. At the same time, there is less roughness on the cutting surfaces.

The smaller chip space in the vitrified-bonded tools is thought to be a possible cause of this behavior. Figure 6 shows that the CBN grains in the vitrified bond have a smaller grain protrusion. This results in smaller inter-grain spaces that can be used for chip removal. The grinding tool therefore tends to be loaded more quickly. As a result, the tool cuts less and rubbed more the workpiece. Another influence is the lower thermal conductivity of the vitrified bond. The electroplated bond has a higher thermal conductivity and enables a greater heat flow across the tool, compared to the vitrified bond. Since a lower cooling capacity is expected with MQL, a tool with good thermal conductivity can have a positive effect. This statement is confirmed by the fact that, in contrast to the electroplated bond, the cutting forces are higher with vitrified bonded grinding tools with MQL.

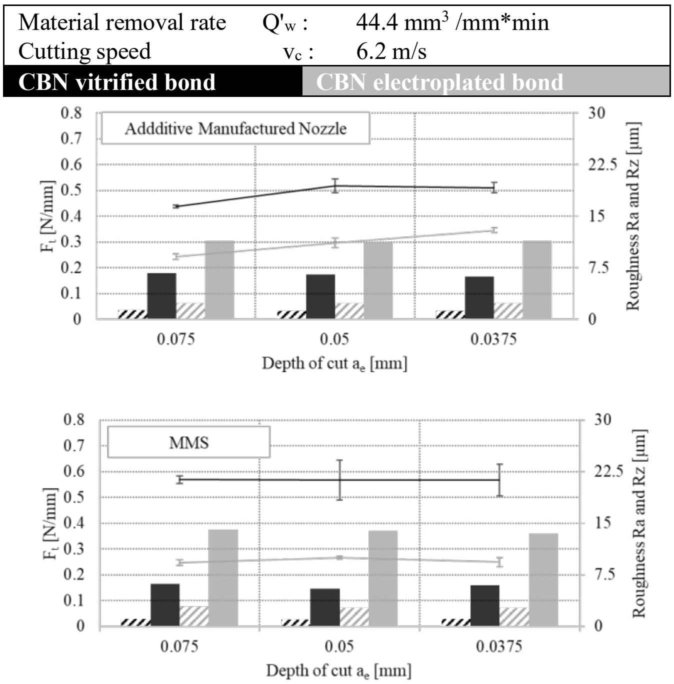


Fig 6: Specific tangential force and roughness as a function of feed rate; vitrified (black) and electroplated (gray)

Based on the results, an electroplated bonded tool appears to be more efficient when machining CFRP if the productivity is a target (higher material removal rate). If the focus is on high surface qualities and small metal removal rates are possible, a vitrified bond is more suitable.

3.2. Wear behavior (long-term tests)

Cooling lubricant systems have a significant influence on wear behavior during machining. In order to investigate this influence, larger volumes of material are machined in addition to the short-term tests. Fig. 7 shows the tangential and normal forces versus the specific material removal rate by using electroplated diamond tool.

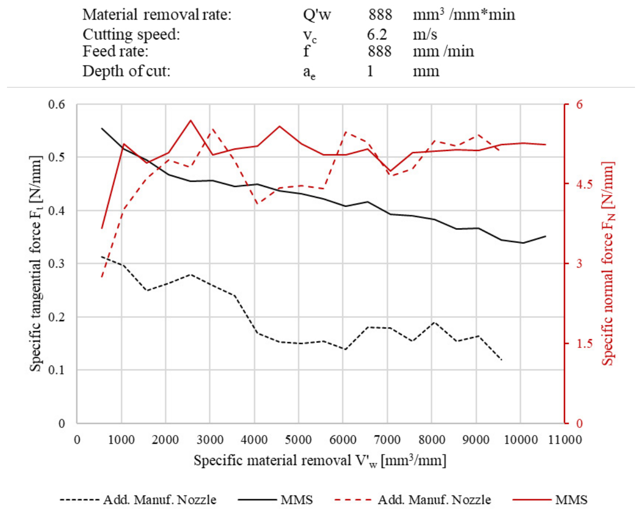


Fig 7: Specific tangential and normal force F_T (black) and F_N (red) as a function of specific material removal in long-term tests

A decrease in the tangential force can be seen both when machining with MQL and with an additively manufactured nozzle. This is approximately linear. The decrease in the tangential force can be attributed to the fact that the diamond grains, which were initially still coated with a bond, were exposed by the wear. The bond is significantly softer and therefore wears faster than the grains. This effect can be interpreted as a natural sharpening of the tool. In this case, the curves do not yet show any clear wear of the cutting grains, but rather the wear of the protruding bond. The normal force remains relatively constant after an initial increase. The tangential cutting force is a bit more decreased. This can be shown as force ration in Fig. 8 . The results show that, for both cooling lubricant systems, the ratio between tangential and normal force is reduced with increasing cutting volume. As the material removal rate is constant for each measurement, it can be assumed that the friction between the tool and the workpiece is reduced due to the increasing wear of the bond on the electroplated tool. The SEM images in Fig. 9 show that the tools do not exhibit any clearly recognizable signs of wear on the abrasive grains after the long-term tests.

By using MQL, the tool is clogged with chips both with the smaller metal removal rate of the short-term tests and with the larger metal removal rate of the long-term tests. The cleaning effect of the additively manufactured nozzle is more effective at the lower metal removal rate. In the upper half of the Figure 8, a grain breakout is marked. Such effects can also cause the machining forces to decrease after a certain time. The break-out of grains that are not deeply embedded in the bond results in more uniform chip thicknesses and therefore lower cutting forces. With the consideration of possible clogging effect, the decreasing the force ration shown in figure 8 can be justified.

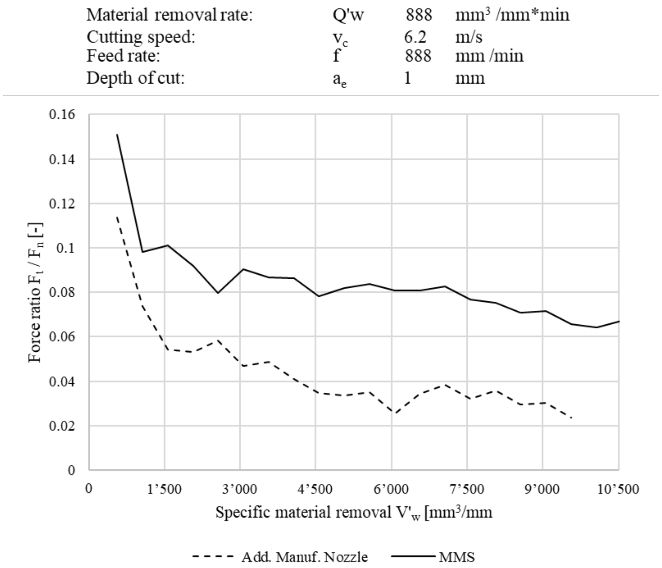


Fig 8: Force ratio as a function of the machined volume in long-term tests;

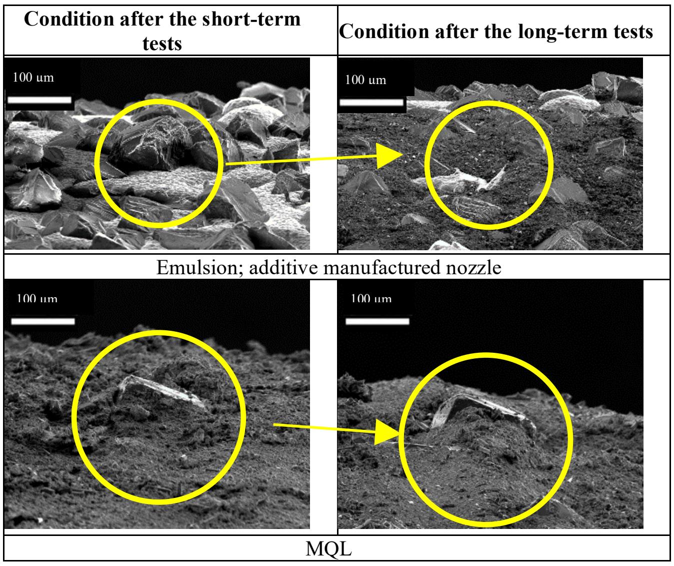


Fig 9: SEM image of the diamond tools before and after the long-term tests within the same positions

3.3. Delamination

For all samples, no delamination was detected on the cut surfaces in any of the tests. When viewed under the microscope, no fibers can be observed being pulled out of the matrix. Figure 9 also shows that the fibers that run in the same direction as the feed direction have been cut lengthwise. These cut surfaces can be seen as light-colored lines. No detachment of different layers can be found either. Furthermore, no influence of the cooling lubricants on the CFRP samples can be determined. It should be noted that the samples are only exposed to the cooling lubricants for rather a short time.

4. Conclusions

The investigations show that a suitable cooling system can significantly improve the process conditions for processing of carbon fiber-reinforced plastics.

The process forces are lower when using MQL than with dry machining. Particularly with large depth of cut, cooling with emulsion achieves an additional reduction in force. With lower forces, a longer tool life can be expected.

The surface quality behaves in the opposite direction to the grinding forces. The deepest roughness is achieved with dry processing. MQL is a compromise between a lower grinding force and a slightly higher surface roughness compared to dry processing.

Electroplated bonded grinding tools are more suitable for the processed sample material. This is due to the larger grain protrusion. The vitrified bond tools used in this work allows only small material removal rates. If the depth of cut and feed rate are too high, the small chip spaces are completely loaded and clogged during the process. This results in a lot of frictional heat at the contact zone, which has led to the decomposition of the component matrix.

No problems due to delamination were identified during the tests. As this is not only dependent on the tool properties, the cutting parameters and the cooling lubrication, different composite material combinations must be taken into the consideration in order to make a well-founded statement.

The potential of machining carbon fiber-reinforced plastics with grinding tool lies primarily in the low tool wear caused by the abrasive fibers. Future investigations will provide further insights into the suitability of cooling systems and tools for machining CFRP.

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