

DAMAGE OF CERAMIC MATRIX COMPOSITES (CMCs) DURING MACHINING OPERATIONS

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ABSTRACT

Machining is for many products the ultimate operation in a complex manufacturing process with the goal to give the final shape to a part and to reach the required tolerances. If this process damages the part a big economic loss is the consequence. However during those operations mechanical damage can occur which only lead to a degradation of the material. In the case of ceramic matrix composites, which already play an important role in components like turbine vanes, combustion chambers and brake disks, the damage often cannot be identified. In this paper special machining operations for different CMC materials are compared with respect to influence on part quality. A new method for quantifying the damage using an optical focus variation and image processing is presented.

INTRODUCTION

Ceramic matrix composites are a group of materials, in which ceramic matrices and ceramic or carbon fibers are combined. These materials have typically a high temperature resistance, a high fracture toughness and compared to high temperature resistant metal alloys, a low density. These combination of properties make them interesting for many different applications e.g. turbine vanes and combustion chambers for gas turbines as well as brake and clutch applications [1, 2]. However the market success in the future will depend on further progress in cost reduction combined with reliable prediction of the performance and lifetime. The final machining operation is a challenging process, with high cost and high quality risk. In the past some experimental work regarding drilling of CMC with diamond grinding bits have been published [3, 4]. The experiments presented in this paper were done with diamond tools with determined diamond cutting edges, which is a new approach to machine CMCs. The results will be presented on two different CMCs materials, 2d-Ox/Ox and 2d C-SiC. For the quantitative evaluation a special optical method combined with a 3d digital imaging software was used. The results show two different damage mechanisms of the two materials and a significant influence of the machining parameters on the finish quality.

EXPERIMENTAL

MATERIAL

Two fiber reinforced ceramic composite materials were used in the present investigation:

- 1) A 2d-C-SiC material (Product name CF226 P75), produced by Schunk Kohlenstofftechnik, Heuchelheim, Germany and
- 2) a 2d Ox-Ox material (product name OFC-P1), produced by University of Bayreuth, Germany.

The CF226 P75 [5] is a 2d-C/C-SiC ceramic matrix composite material produced by the so called PCI process (pack cementation and capillary infiltration), a liquid silicon infiltration process used for industrial production. For composition 8 layers of 0/90° woven fabric were laminated. The resulting composite had a thickness of 3 mm, a fiber content of up to 60%, a silicon carbide content of up to 10 vol.-% and a total porosity of 6 vol.-%.

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OFC-P1 is also a 2d laminate based on woven 0/90° fabrics of 3M™ Nextel™ alumina (Al_2O_3) fibers. The investigated composite consists of a lay-up of twelve 0/90° layers. The composite was infiltrated with a pre-ceramic slurry and then sintered resulting in a fiber content of up to 40 vol.-% and a porosity of 30 vol.-%. The laminate thickness was 4 mm. The low density also leads to a low ILT strength.

TOOLING

Polycrystalline Diamond (PCD) 8 mm diameter twisted drills with massive PCD tip, 120° point angle, 25° rake angle, 15° clearance angle, 50° wedge angle (producer: Hufschmied GmbH, Bobingen) were used.

MACHINE

DMG Ultrasonic 55-5, linear (Fig.1) was used for all experiments. The machining environment was 8% cooling liquid at 23 bar applied through flexible ducts directly onto the tool tip.



Work area X-, Y-, Z-axis	450x580x460
Max. drive power (KW)	29
Max. rotation speed (rpm)	28 000
Max. torque (Nm)	71
Max. feed range X, Y, Z (m/min)	80
Tool holder	HSK-A63
Year of manufacture	2010

Fig. 1 Test machine DMG Ultrasonic 55-5 linear with basic parameters

The machining setup for drilling operation is schematically shown in Fig. 2.

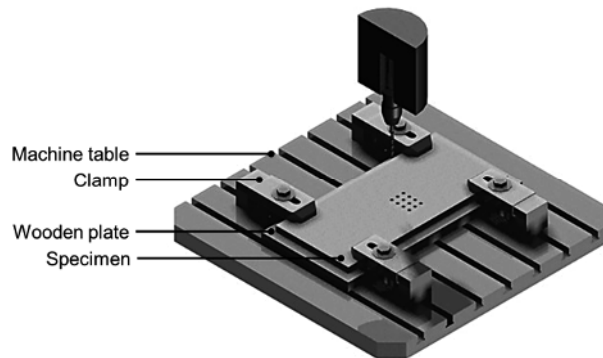


Fig. 2 Machining set up for drilling experiments

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EVALUATION WITH FOCUS VARIATION AND IMAGE PROCESSING

Digital image analysis to determine delamination after drilling composites was applied by Davim et.al. [6] on fibre reinforced plastics. In our case the method of focus variation, which describes a procedure, where a microscope is scanning in 3 axis the surface of a specimen was applied on CMCs. The digital pictures of single stacks were arranged by a special software tool to create a 3d digital image. These images represent the surface and the surface near zones, which could be reached by the microscope and from these pictures surfaces and volumes were calculated. In Fig. 3 the measurement and digital imaging process is explained.

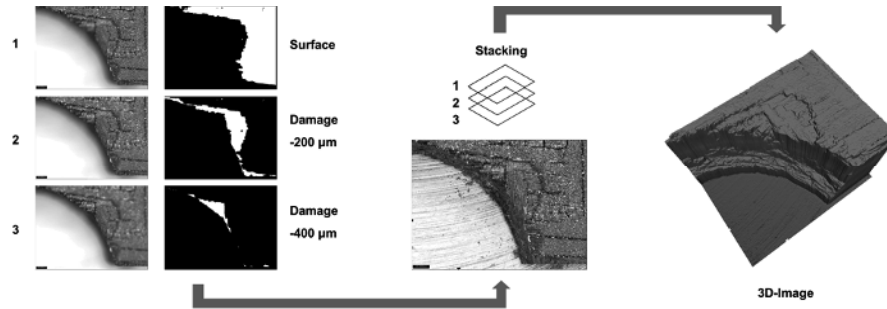


Fig. 3 Analyses with focus variation from Alicona

The introduction of the dimensionless chipping factor $F_{Chip,L}$ is described in a previous paper [7]. Eq. 1-3 describe the calculation of the edge chipping factor $F_{Chip,L}$.

$$F_{Chip,L} = \frac{V_{Chip,L}}{V_{0,L}} \quad (1)$$

$$V_{chip,L} = \sum_{i=1}^n A_{Chip,i} t_{chip,i} \quad (2)$$

$$V_{0,L} = A_0 t \quad (3)$$

$A_{Chip,i}$	Single sheet element area
A_0	Nominal hole area
t	Specimen thickness
$t_{Chip,i}$	Thickness of single sheet elements
$V_{0,L}$	Nominal hole volume
$V_{Chip,L}$	Calculated chipping volume

To evaluate the OFC-1 material the chipping factor could not be used, because the damage did not show any chipping, but fraying. The quantitative evaluation of fraying length or fraying area did not show any consistent result. Therefore it was decided to use a qualitative evaluation. The problem of this evaluation method is that it depends on the experience of the observer's eye. Nevertheless 3 levels of fraying have been defined:

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Plenty = the whole area shows fraying traces
 Moderate = only partial fraying
 Low = very little or no fraying

RESULTS

As a result of the drilling operation 2 fundamentally different damage mechanisms were seen. While the C-SiC material showed brittle fracture behavior in the case of Ox-Ox a kind of fiber pull-out was observed. In the microscopic pictures of Fig. 4 the two mechanisms are compared. We called the brittle behavior “edge chipping” and the fiber pull out (non cut fiber residuals respectively) “fiber fraying”. This leads to the hypothesis, that the different fiber/matrix bonding of the two materials causes also different cutting behavior. In the C-SiC case much better bonding than in the OFC case. At the same time density (matrix porosity respectively) can be related to the inter-laminar shear/tensile strength (ILS). Especially the porous Matrix properties of the Ox-Ox lead to low ILS [8]. Looking at the resulting images the link between porosity, fiber content and machining behavior can be explained. To further find out, if there is also an influence of the machining parameters on chipping and fraying intensity, these were varied according to Tab. 1.

Tab. 1 Machining parameters

Run	1	2	3	4	5	6
Feed [mm/rev]	0.01	0.01	0.01	0.05	0.10	0.20
Speed [m/min]	175	300	425	175	175	175

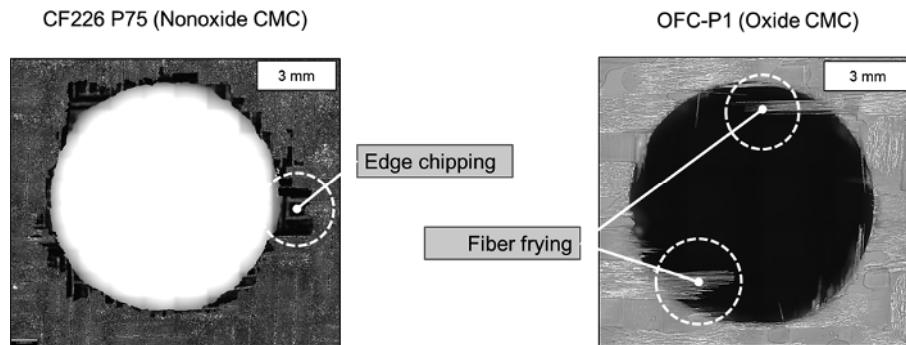


Fig. 3 Comparison of the mechanical damage characteristics when drilling - Left side: 2d-C-SiC - Right side: OFC-1 CMC

In Figure 5 the effect of feed rate on the edge chipping factor $F_{Chip,L}$ of the 2d-C-SiC shows that increasing feed rate increases the chipping. At 0,2 mm/rev the chipping factor is with 2 % two times the value at 0,01 mm/rev. The scatter also increases significantly.

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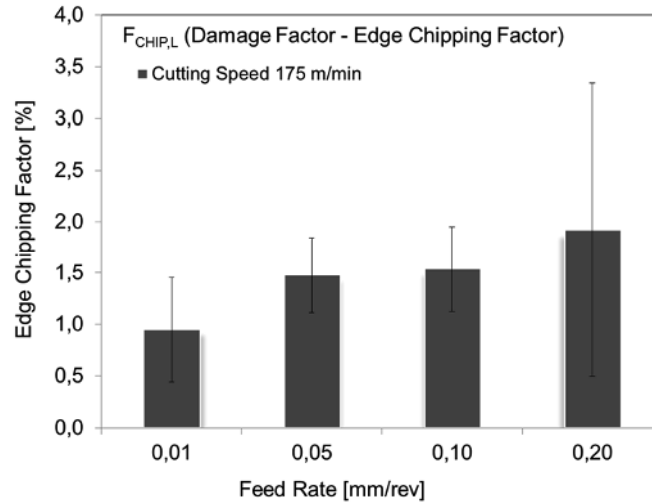


Fig. 4 Effect of feed rate on the Edge chipping factor for CF226 P75

Keeping the feed rate at a lowest point (with lowest chipping result), the increase of cutting speed shows, that $F_{CHIP,L}$ depends much more on the cutting speed (Fig. 6). At 175 m/min cutting speed the chipping factor was only at 1%. At 300 m/min an increase to 8% was observed and the worst result showed the experiment at 425 m/min with a factor of 32%.

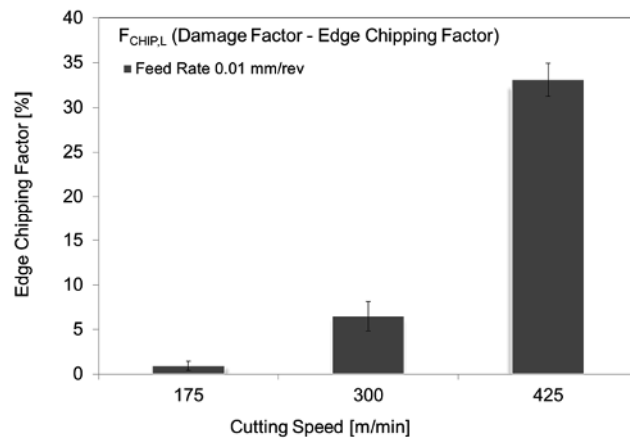


Fig. 5 Effect of cutting speed on the Edge chipping factor for CF226 P75

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In Fig. 7 the qualitative analysis of OFC-P1 material shows, that the combination of low constant speed of 175 m/min and low feed rate gives lowest fraying. Increasing feed rate increases the fraying. In all cases fraying occurs mostly at the hole exit, which also can be seen in the images below.

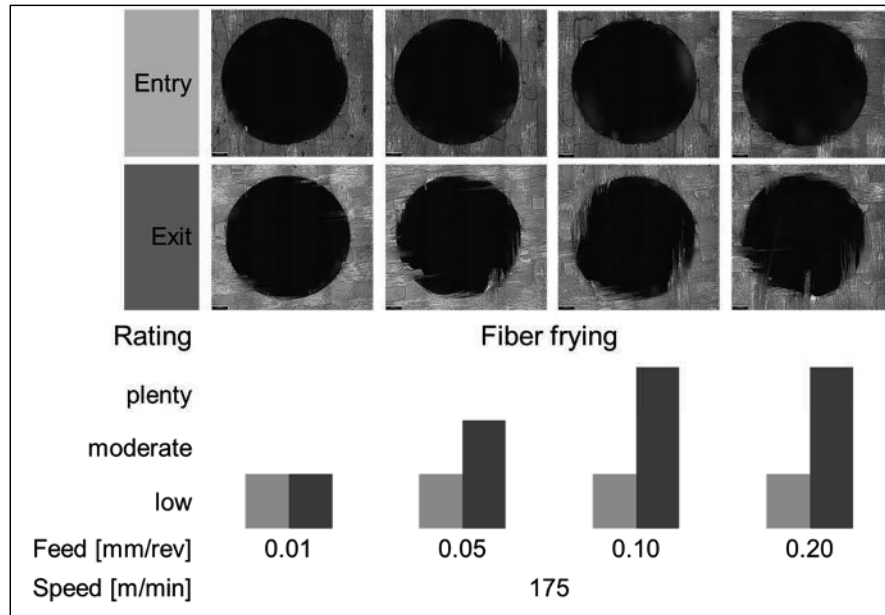


Fig. 6 Effect of feed rate on fiber fraying for OFC-P1

On the other hand cutting speed seems not to have a strong influence on fraying in the case of the OFC-P1. The results in Fig. 8 do not show significant differences between low and high speed. Also entrance and exit of the hole show no difference in this case.

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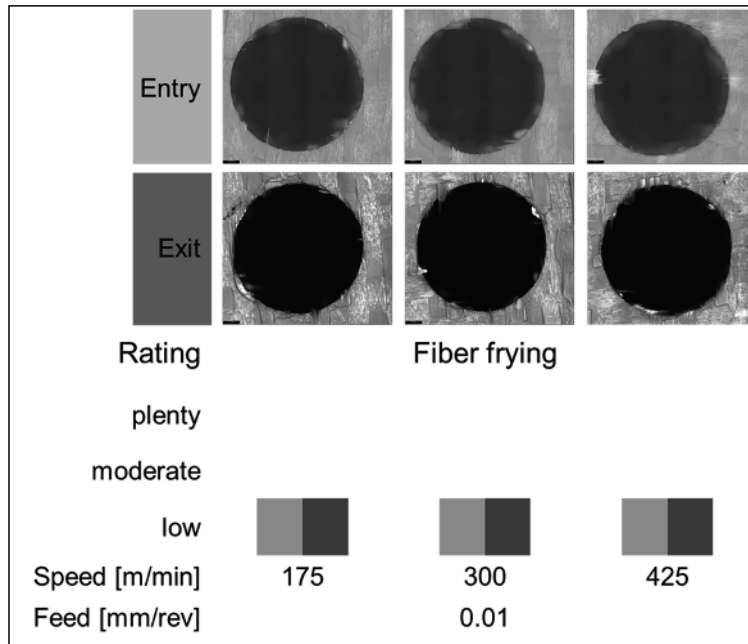


Fig. 7 Effect of cutting speed on fiber frying for OFC-P1

CONCLUSION

Two ceramic composite materials have been investigated regarding their damage behavior through a drilling operation using diamond tipped tools with defined cutting edges and varying feed rate and cutting speed.

The results show two different damage mechanisms of the two materials. Where C-SiC shows chipping of edges in surface and volume, the Ox/Ox Composite shows fiber fraying mainly at the exit of the holes.

C-SiC shows a small increase of chipping with increasing feed rate, at constant cutting speed. However a strong effect of cutting speed on chipping can be observed. One explanation for this behavior could be the strong fiber/matrix bonding of the C-SiC and the micro cracked micro-structure of this laminate. This leads to the chipping of material from the matrix. At higher speed more cutting power is introduced into the material and leads therefore to more damage. Depending on the final requirements this is a clear indication that the cutting speed cannot be increased over a certain limit, which is on the one hand given by the tool stability and on the other hand by the micro structural bonding of fiber and matrix.

In contrast to the chipping of the 2d-C-SiC, the Ox-Ox material behaves completely different. In this case no chipping but fraying of alumina fibers can be observed. One explanation could be the much lower fiber matrix bonding between alumina fibers and alumina matrix, which leads to more fiber pull out. No direct influence of the cutting speed but significant more fraying by increasing the feed rate. Low feed rate give in this case low fraying even at high cutting speed.

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The experiments and investigations will be continued to find out, how the damage will influence the mechanical performance of the part and to find an optimum tool/machine/parameter configuration. As inter-laminar damage can be expected, further research has to be done on shape, type and detection of those damages.

ACKNOWLEDGEMENT

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