Advanced and Refractory Ceramics for Energy Conservation and Efficiency
Contents

Preface ix

ADVANCED CERAMICS AND COMPOSITES FOR GAS TURBINE ENGINES

Damage of Ceramic Matrix Composites (CMCs) During Machining Operations
R. Goller and A. Rösig 3

CMCS: The Key for Affordable Access to Space
Johannes Petursson and Luis Gonzalez 11

Numerical Determination of Effects of Temperature on Infiltration Dynamics of Liquid-Copper and Titanium/Solid-Carbon System
Khurram Iqbal 21

Oxidation and High Temperature Resistance of SiC/SiC Composites by NITE-Method
Daisuke Hayasaka, Hirotatsu Kishimoto, Joon-Soo Park, and Akira Kohyama 29

High Performance SiC/SiC Component by NITE-Method and Its Application to Energy and Environment
A. Kohyama, D. Hayasaka, H. Kishimoto, and J. S. Park 37

Ceramic Matrix Composites: Concurrent Development of Materials and Characterization Tools
G. Ojard, I. Smyth, Y. Gowayed, U. Santhosh, and J. Ahmad 53

Fabrication of EBC System with Oxide Eutectic Structure
Shunkichi Ueno, Kyosuke Seya, and Byung-Koog Jang 65
ADVANCED REFRACTORY CERAMIC MATERIALS
AND TECHNOLOGIES

The Use of Advanced Ceramic Materials in Oil and Gas Applications 75
Richard A. Clark and Andrew J. Goshe

Microstructure and Elastic Properties of Highly Porous Mullite Ceramics Prepared with Wheat Flour 83
E. Gregorová, W. Pabst, and T. Uhlířová

The Use of Advanced Refractory Ceramic Materials to Address Industrial Energy Efficiency Challenges 95
J. G. Hemrick

An Approach for Modeling Slag Corrosion of Lightweight $\text{Al}_2\text{O}_3$-$\text{MgO}$ Castables in Refining Ladle 101
Ao Huang, Huazhi Gu, Zou Yang, Lvping Fu, Pengfei Lian, and Linwen Jin

Microstructure, Elastic Properties and High-Temperature Behavior of Silica Refractories 113
W. Pabst, E. Gregorová, T. Uhlířová, V. Nečina, J. Kloužek, and I. Sedlářová

Cement Free Magnesia Based Castables versus Magnesia-Spinel Bricks in Cement Rotary Kilns 125
Jérôme Soudier

Evaluation of Reoxidation Tendency of Refractory Materials in Steel Metallurgy by a New Test Method Based on Carrier Gas Hot Extraction 139
Almuth Sax, Lisa Redecker, Stephan Clasen, Peter Quirmbach, and Christian Dannert

Ceramic and Metal-Ceramic Components with Graded Microstructure 149
U. Scheithauer, E. Schwarzer, C. Otto, T. Slawik, T. Moritz, and A. Michaelis

ENERGY EFFICIENT WEAR RESISTANT MATERIALS

High Speed Formation of Fine Ceramic Layers by Nanoparticles Filler Rod Thermal Spraying 163
Soshu Kirihara and Kazuto Takai

Development of Silicon Nitride Bearing Components by Powder Injection Molding using a Novel Binder System 169

vi · Advanced and Refractory Ceramics for Energy Conservation and Efficiency
ADVANCED COATINGS

Stability of $\alpha$-Alumina Photonic Structures Formed at Low Temperatures Utilizing Chromia-Seeding
Robert M. Pasquarelli, Martin Waleczek, Kornelius Nielsch, Gerold A. Schneider, and Rolf Janssen

Polymer Derived Glass Ceramic Layers for Corrosion Protection of Metals
Milan Parchovianský, Gilvan Barroso, Ivana Petriková, Gunter Motz, Dagmar Galusková, and Dušan Galusek

Author Index

179
187
201
Preface

The global challenges we face require innovative thinking and sustainable technology to meet increased demands for energy, clean water, and infrastructure. Research of materials, specifically ceramic materials, continues to provide solutions to everyday challenges such as environmental protection, energy supply and generation, and healthcare. The 11th International Symposium on Ceramic Materials and Components for Energy and Environmental Applications (11th CMCEE), held June 14–19, 2015 at the Hyatt Regency Vancouver in Vancouver, B.C., Canada, identified key challenges and opportunities for ceramic technologies to create sustainable development.

This Ceramic Transactions volume contains papers submitted from the following five symposia held in Track 2: Ceramics for Energy Conservation and Efficiency:

- Advanced Ceramics and Composites for Gas Turbine Engines
- Advanced Refractory Ceramic Materials and Technologies
- Advanced Ceramic Coatings for Power Systems
- Energy Efficient Advanced Bearings and Wear Resistant Materials
- Advanced Nitrides and Related Materials for Energy Applications

After a peer-review process, 19 papers were accepted for inclusion in this proceedings volume. The editors wish to extend their gratitude and appreciation to all the symposium co-organizers for their help and support, to all the authors for their cooperation and contributions, to all the participants and session chairs for their time and efforts, and to all the reviewers for their valuable comments and suggestions. We also acknowledge the organization and leadership provided by the meeting chairs, Mrityunjay Singh, Tatsuki Ohji and Alexander Michaelis.

We hope that this proceedings will serve as a useful resource for the researchers and technologists in the field of energy conservation.

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Advanced Ceramics and Composites for Gas Turbine Engines
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.-%.
OFC-P1 is also a 2d laminate based on woven $0/90^\circ$ fabrics of 3M™ Nextel™ alumina ($\text{Al}_2\text{O}_3$) fibers. The investigated composite consists of a lay-up of twelve $0/90^\circ$ 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.

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

![Fig. 1 Test machine DMG Ultrasonic 55-5 linear with basic parameters](image)

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

![Fig. 2 Machining set up for drilling experiments](image)
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 reinforce 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 Aicona](image)

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

\begin{align*}
F_{\text{Chip, L}} &= \frac{V_{\text{Chip, L}}}{V_{0, L}} \\ 
V_{\text{Chip, L}} &= \sum_{i=1}^{n} A_{\text{Chip, i}} \ t_{\text{Chip, i}} \\ 
V_{0, L} &= A_{0} \ t
\end{align*}

$A_{\text{Chip, i}}$  Single sheet element area
$A_{0}$  Nominal hole area
$t$  Specimen thickness
$t_{\text{Chip, i}}$  Thickness of single sheet elements
$V_{0, L}$  Nominal hole volume
$V_{\text{Chip, L}}$  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:
Damage of Ceramic Matrix Composites (CMCs) During Machining Operations

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.

<table>
<thead>
<tr>
<th>Run</th>
<th>Machining parameters</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Feed [mm/rev]</td>
</tr>
<tr>
<td>2</td>
<td>Speed [m/min]</td>
</tr>
</tbody>
</table>

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.
Damage of Ceramic Matrix Composites (CMCs) During Machining Operations

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 $F_{\text{Chip,L}}$ 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
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.

![Image of cutting speed effects on fiber fraying for OFC-P1](image)

**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.
Damage of Ceramic Matrix Composites (CMCs) During Machining Operations

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.

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

<table>
<thead>
<tr>
<th>Speed [m/min]</th>
<th>Feed [mm/rev]</th>
<th>C-SiC Chipping</th>
</tr>
</thead>
<tbody>
<tr>
<td>175</td>
<td>0.01</td>
<td>Low</td>
</tr>
<tr>
<td>300</td>
<td>0.01</td>
<td>Moderate</td>
</tr>
<tr>
<td>425</td>
<td>0.01</td>
<td>Plenty</td>
</tr>
</tbody>
</table>

Advanced and Refractory Ceramics for Energy Conservation and Efficiency 9
Damage of Ceramic Matrix Composites (CMCs) During Machining Operations

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

The authors thank Hufschmied GmbH, Bobingen for providing the tools and the machining capacity, Schunk Group for offering the C-SiC material and University of Bayreuth for offering Ox-Ox material.

LITERATURE


