Collaborative Working Group on Hybrid Processes

Investigation of the Tool Life and the Process-Material Interaction in Ultrasonic Assisted Grinding of SiSiC Ceramic Materials

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January 26th, 2011
## Outline

1. Hybrid Machining of SiSiC
2. Scratch Test
3. Experimental Tests on Ultrasonic Assisted Grinding
4. Summary/Outlook
Hybrid machining using ultrasonic vibrations

Ultrasonic assisted grinding:

trajectory \( s(t) \) of a single grain

\[
s(t) = \begin{bmatrix} x(t) \\ y(t) \\ z(t) \end{bmatrix} = \begin{bmatrix} v_w \cdot t - (r_s \cdot \sin(\omega_s \cdot t)) \\ r_s \cdot \cos(\omega_s \cdot t) \\ A_{US} \cdot \sin(2\pi \cdot f_{US} \cdot t + \varphi_0) \end{bmatrix}
\]

\( v_w \) … velocity of workpiece
\( r_s \) … radius of grinding tool
\( \omega_s \) … angular velocity of grinding tool
\( A_{US} \) … amplitude of ultrasonic vibration
\( f_{US} \) … frequency of ultrasonic vibration
\( \varphi_0 \) … angular phase shift of ultrasonic vibration

Ultrasonic assisted grinding:

\[ A_{US} = 0.2 \, \text{µm} \ldots 10 \, \text{µm} \]
\[ f_{US} = 13.7 \, \text{kHz} \ldots 22.5 \, \text{kHz} \]
\[ v_c = 2 \, \text{m/s} \]
\[ v_{US,max} = 0.4 \, \text{m/s} \ldots 0.7 \, \text{m/s} \]

angle of penetration \( \rho = 18.6^\circ \)

\[ \rho = \arctan \frac{v_{US,max}}{v_c} \]

Interpretation of Hybrid Machining:

Hybrid machining processes comprise manufacturing technologies using a planned and controlled interaction of two or more process mechanisms, which are separately energy supported and executed in a temporal and local interaction.
## Workpiece and material properties of SiSiC

- reaction-bonded, silicon infiltrated SiC (SiSiC)
- ca. 70% silicon- and 30% carbon-proportion
- ca. 85% up to 94% SiC and 15% down to 6% metallic Si

<table>
<thead>
<tr>
<th>Material properties</th>
<th>Units</th>
<th>SSiC</th>
<th>SiSiC</th>
</tr>
</thead>
<tbody>
<tr>
<td>Type of material</td>
<td></td>
<td>SSiC</td>
<td>SiSiC</td>
</tr>
<tr>
<td>Density</td>
<td>g/cm³</td>
<td>3,07</td>
<td>3,11</td>
</tr>
<tr>
<td>Vickers hardness HV</td>
<td>2500</td>
<td>2650</td>
<td>HV0,5</td>
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<tr>
<td>Elasticity modulus E</td>
<td>GPa</td>
<td>370</td>
<td>360</td>
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<tr>
<td>Flexural strength σ₄₅₅</td>
<td>MPa</td>
<td>280</td>
<td>300</td>
</tr>
<tr>
<td>Compressive strength σ₂₅₂</td>
<td>MPa</td>
<td>2500</td>
<td>3200</td>
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<tr>
<td>Poisson ratio µ</td>
<td>-</td>
<td>0,16</td>
<td>0,19</td>
</tr>
<tr>
<td>Fracture toughness Kᵢₒ</td>
<td>MPa·m₁/₂</td>
<td>3,8/3</td>
<td>3,2</td>
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<tr>
<td>Thermal conductivity λ</td>
<td>W/m·K</td>
<td>100</td>
<td>110</td>
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<tr>
<td>Coefficient of thermal stress R₁=σ₅·(1-µ)/(α·E)</td>
<td>K</td>
<td>210</td>
<td>140</td>
</tr>
<tr>
<td>Thermal expansion coefficient α bis 1000°C</td>
<td>10⁻⁶ K⁻¹</td>
<td>4,3</td>
<td>4,5</td>
</tr>
</tbody>
</table>
Scratch test

- specimen
- sonotrode
- membrane
- piezo-actuator
- housing

Ø 100 mm
84 mm

Grain: 50 µm

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Result of scratch test

radius of flywheel $r_s = 84 \text{ mm}$
rotational speed $n = 250 \text{ rpm}$
cutting speed $v_c = 2,2 \text{ m/s}$
period length $T_{11,5kHz} = 193 \text{ µm}$

arise: depth of scratch $h_{cu,max} = 1,5 \text{ µm}$

with ultrasonic vibration $T_{19,3kHz} = 113 \text{ µm}$

no ultrasonic vibration $50 \text{ µm}$

ultrasonic vibration

$h_{cu,max} = r_s - \sqrt{r_s^2 - \left(\frac{L_R}{2}\right)^2}$

profile of scratch ground
Machining center for US assisted grinding

Gildemeister Ultrasonic 70 linear

- main spindle
- stator of inductively coupled power transmission
- rotor of power transmission
- housing of piezo - actuator
- tool clamping
- grinding tool
Vibration absorption by tool clamping torque

Influence of tool clamping torque on vibration amplitude:
Grinding tool: mounted point with hollow shaft, Ø 5.5 mm

Amplitude [µm]

- Tool clamping torque 50Nm
- Tool clamping torque 30Nm
- Tool clamping torque 10Nm

Frequency [kHz]

Recommended frequency adjustment: Tool clamping torque

\[ f_{US} = 19.691 \text{ Hz} \]
Process – material interaction

Tool:
mounted point with hollow shaft, electroplated
grain size (blocky)       diamond D 91
grain concentration       C 200
thickness of plating      1,5 mm
diameter $d_S =           5,5 mm$
length of shaft $L =      45 mm$
n_S = 8.000 rpm           $v_W = 400 \text{ mm/min}$
$A_{US} = 2,8 \mu\text{m}$ $f_{US} = 17,63 \text{ kHz}$
without coolant

Workpiece material: SiSiC

Tool:

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US-influence on process force in Z-axis

**Tool:**
- mounted point with hollow shaft, electroplated
- grain size (blocky) diamond D 107
- grain concentration C 200
- thickness of plating 1,5 mm
- diameter $d_S = 5,5$ mm
- length of tool $L = 45$ mm
- $n_S = 8,000$ rpm $v_W = 360$ mm/min

**Workpiece material:** SiSiC

<table>
<thead>
<tr>
<th>Amplitude</th>
<th>Frequency</th>
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<tbody>
<tr>
<td>0 μm</td>
<td>0 kHz</td>
</tr>
<tr>
<td>0,25 μm</td>
<td>20,8 kHz</td>
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<tr>
<td>3 μm</td>
<td>18,3 kHz</td>
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</tbody>
</table>

**Coolant:** Aral Sulnit CC5, 7,9 mm²/s, 6 μm filtration

**Graph:**
- $F_Z [N]$ vs. $a_p [μm]$
Tool wear and tool lifetime

Grinding ratio $G$:

Average tool abrasion:
- With US: 14 mm³/grain
- Without US: 3.5 mm³/grain

Mounting point:
- Ø 2 mm without US
- Ø 2 mm with US
- Ø 4 mm with US

Graph showing the grinding ratio $G$ with $V_s$ in mm³ as the y-axis and $V_w$ in mm³ as the x-axis.
Summary/Outlook

- Increase of material removal rate in machining SiSiC using ultrasonic assisted grinding
- Significant increase of tool life with ultrasonic vibration
- Improvements in chip flushing
- Tool-workpiece interaction shows significant influence on dynamic coupling of US vibration
- Active control of vibration amplitude is recommended

Continuative research work:
- Use in machining of metallic materials
- Optimization of active amplitude control
- Multi-axes activation of workpiece