Specific energy in grinding of tungsten carbides of various grain sizes

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\section*{A B S T R A C T}

The objective of this study is to investigate specific energy in grinding of tungsten carbides of various grain sizes. Through the construction of a mathematical model, the study demonstrates the correlation of specific energy with the grinding process parameters and the material property parameters for the tungsten carbides. The study also examines material-removal mechanisms and surface finish in grinding of such materials using scanning electron microscopy, X-ray diffractometry and energy dispersive spectrometry techniques, etc. The study concludes that specific energy is related not only to grinding process parameters, but also to the physical–mechanical properties of the workpiece material.

\section*{1. Introduction}

Grinding is an abrasive machining process in which material removal is realized through abrasive and workpiece interactions. Different than machining with well-defined tools, abrasives in grinding have irregular cutting edges. The interaction between the abrasive cutting edges and workpiece is highly dependent on grinding wheel surface topography, wheel and workpiece surface geometries, and relative motions between the wheel and workpiece. There are a number of approaches to studying the phenomena during abrasive–workpiece interactions. One of them is to examine the morphologies of grinding debris produced in the process so as to understand material-removal mechanisms, and another is to measure the grinding forces and/or power requirements under different conditions\cite{1}. Since the abrasive–workpiece interactions have to follow the law of energy conservation, an energy indicator can be utilized to quantify the amount of energy consumption and to measure the degree of abrasive–workpiece interactions during grinding. Specific energy is usually used as such an indicator.

In machining, specific energy generally includes energies consumed in chip formation, plowing, sliding, and elastic deformation of workpiece. Specific energy in grinding is roughly an order of magnitude higher than in turning or milling. The higher specific energy in grinding is mainly due to more specific surfaces produced in chips, as well as more material deformations (both plastic and elastic). On the other hand, under the same grinding conditions, specific energy also depends on the properties of the workpiece material, especially physical–mechanical properties. Specific energy in grinding can be mathematically modeled and used to predict grinding processes. In the previous research, Tönshoff and Malkin et al. analyzed the correlations between specific energy and material properties and grinding parameters, and proposed specific energy models\cite{2,3}.

Tungsten carbide (WC) materials have been widely used in the manufacturing industry for many applications, such as molds and dies, cutting tools and wear-resistant components and coatings, due to their high hardness and fracture toughness\cite{4}. Nanosstructured WC materials have been developed for thermal barrier coatings. They can be fabricated by sintering nanometer-scaled tungsten carbide powders with cobalt using the nano-composite technology. The nano-composite technology utilizes the size-effect to resolve the conflict between hardness and fracture toughness for the WC materials to obtain both higher hardness and higher fracture toughness\cite{4}. When subjected to grinding, the nanosstructured WC exhibits ductility similar to a metallic material, and meanwhile is as hard as ceramics. A study has shown that grinding forces on the nanostructured WC are related to workpiece material properties and grinding process parameters\cite{5}. Specific energy is proportional to grinding forces and should also be related to workpiece material properties and grinding process parameters.

\section*{2. Mathematical modeling}

According to its definition, specific energy in grinding is determined by the tangential grinding force. Based on the previous study on a grinding force model, the tangential grinding force per grit is given as\cite{5}:

\begin{equation}
F_{\text{tang}} = \left( k \frac{H}{K_c} \right)^{\gamma} \sigma_{\text{max}}^{2(1-\gamma)}
\end{equation}

where $H$ is workpiece hardness; $K_c$ is workpiece fracture toughness; $\sigma_{\text{max}}$ is the maximum undeformed chip thickness; $k = 10^{-6}$ m is a constant and is related to the physical–mechanical properties of the workpiece material; $\varepsilon$ and $\gamma$ are parameters that can be determined based on the workpiece material properties and grinding process parameters. Based in Eq. (1), tangential grinding
force $F_t$ can be obtained by integrating grit forces over the entire grinding zone:

$$ F_t = b \int_0^{l_s} F_{et}N_{dyn}(l) \, dl $$

where $l_s$ is the wheel-workpiece contact length in the grinding zone and is related to the equivalent wheel diameter and wheel depth of cut; $N_{dyn}$ is the number of active cutting grits in the unit width of the grinding zone, and is related to $l_s$ and the mean distance between the adjacent active cutting grits; $b$ is the effective width of the grinding zone. Because the number of active cutting grits in the grinding zone can be measured by the experimental method [6], Eq. (2) can be simplified as

$$ b \int_0^{l_s} N_{dyn}(l) \, dl = bl_c $$

where $c$ is the number of active cutting grits per unit grinding length, and is related to wheel dressing conditions and wheel parameters.

Because specific energy is defined as the energy expended in the unit volume of material removal [1], specific energy can be obtained by combining Eq. (1) through Eq. (3):

$$ \dot{u} = \frac{cV_c}{V_w} \sqrt{\frac{\alpha_v}{\alpha_r}} \left( \frac{kH^\gamma}{K_f^2} \right)^{1/2} $$

where $d_e$ is the equivalent wheel diameter; $\alpha_v$ is wheel depth of cut, $V_c$ and $V_w$ are wheel speed and worktable speed, respectively.

In the analysis of the abrasive–workpiece interactions, the active cutting grits are usually assumed to be evenly distributed over the wheel surface [1]. Based on kinematics of the abrasive–workpiece interactions, the maximum undeformed chip thickness is written as [1]:

$$ \tmax{\alpha} = \left( \frac{4V_w}{\pi V_c} \frac{\alpha_t}{d_e} \right)^{1/2} $$

where $r$ represents the ratio of chip width to chip thickness, and is usually in the range of 10–20 [7]. It is assumed to be 10 in this paper. With the utilization of Eq. (5), Eq. (4) can be further expressed as:

$$ \dot{u} = \frac{4}{r} \left( \frac{kH^\gamma}{K_f^2} \right)^{1/2} \left( \frac{\alpha_t}{\alpha_{\max}} \right)^{2r-1} $$

Eq. (6) correlates specific energy in grinding with the physical properties of the workpiece material and with grinding process parameters. Eq. (6) needs to be experimentally verified.

3. Experiment

Four WC samples of different grain sizes (from the submicrometer level to the micrometer level) were chosen for the experimental study. The WC samples had the same cobalt content of 10 wt%. Table 1 presents the microstructural details and the experimental data, specific energy in grinding of the YH6F sample can be represented by

$$ \dot{u}_{YH6F} = 272.45 \frac{d_s}{\alpha_{\max}}^{0.27} $$

While specific energies for the other WC samples, YL10, YF06, and YU06, are expressed in the following equations, respectively

$$ \dot{u}_{YL10} = 314.01 \frac{d_s}{\alpha_{\max}}^{0.22} $$

$$ \dot{u}_{YF06} = 342.92 \frac{d_s}{\alpha_{\max}}^{0.21} $$

$$ \dot{u}_{YU06} = 386.67 \frac{d_s}{\alpha_{\max}}^{0.19} $$

With an increase in the maximum undeformed chip thickness, the specific energies for all the WC samples show a decreasing trend. Eqs. (7)–(10) are obtained based on both the analytical and experimental methods, and can be used to predict specific grinding energies for the WC samples of the respective grain sizes. Eq. (6)

### Table 1
Physical properties of WC samples.

<table>
<thead>
<tr>
<th>Sample</th>
<th>Grain size (µm)</th>
<th>Bending strength $\sigma$ (MPa)</th>
<th>Hardness $H$ (GPa)</th>
<th>Fracture toughness $K_I$ (MPa m$^{1/2}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>YH6F</td>
<td>0.13</td>
<td>4200</td>
<td>21.5</td>
<td>9.5</td>
</tr>
<tr>
<td>YU06</td>
<td>0.30</td>
<td>3800</td>
<td>20.5</td>
<td>9.1</td>
</tr>
<tr>
<td>YF06</td>
<td>0.50</td>
<td>3800</td>
<td>18.0</td>
<td>8.8</td>
</tr>
<tr>
<td>YL10</td>
<td>1.70</td>
<td>3000</td>
<td>15.8</td>
<td>7.9</td>
</tr>
</tbody>
</table>

Comparison purposes, WC sample YL10 of a conventional grain size of 1.7 µm was also used. The average grain sizes for the other two WC samples were 0.30 and 0.50 µm, respectively. All the four WC samples were commercial products with highly stable microstructures and physical properties.

Moreover, straight-type diamond wheels of mesh numbers of #80, #600, and #2000 were adopted for the grinding experiment. The wheels were 200 mm in diameter, 12 mm in width, and 8 mm in the diamond layer. Prior to the grinding experiment, each wheel was trued with a break-controlled truing device and then dressed with alumina sticks. The grinding experiment was conducted on a precision surface grinder which was configured with a horizontal spindle. A WC workpiece of the dimensions 2.5 mm $\times$ 2.5 mm $\times$ 20 mm was fixed onto a table-type piezoelectric dynamometer. Up-grinding mode was used during the grinding experiment and no spark-out was arranged. The grinding wheel specifications and the grinding process parameters are list in Table 2.

In order to more effectively evaluate the ground WC samples in terms of their physical–chemical changes, such as material compositions and XRD power density spectrum, an unground WC sample was used for comparison. The unground WC sample was sectioned using the fracture technique. The fractured-sections of both the unground and ground workpiece samples were observed and analyzed with various experimental techniques which include scanning electron microscopy, energy dispersive spectrometry and X-ray diffractometry. Cu $K\alpha$, X-ray lines were used in the X-ray diffractometry with a diffraction angle ranging from 20° to 90°. Before being used for observations and analysis, the WC sample was ultrasonically cleaned in an acetone bath in order to remove the contaminants from the grinding coolant.

4. Results

4.1. Specific energy

The experimental specific energy can be calculated with the use of the grinding process parameters and the tangential grinding force measured in the grinding experiment. Fig. 1 shows that the experimental specific energy $\dot{u}_e$ monotonically decreases with an increase in the maximum undeformed chip thickness. With the application of the least squares curve-fitting technique to the experimental data, specific energy in grinding of the YH6F sample can be represented by

$$ \dot{u}_{YH6F} = 272.45 \frac{d_s}{\alpha_{\max}}^{0.27} $$

While specific energies for the other WC samples, YL10, YF06, and YU06, are expressed in the following equations, respectively

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the EDS analysis results of element contents in the ground surface and the base elements in all the workpiece samples. Table 3 presents the EDS analysis results of element contents in the ground surface.

Table 3

<table>
<thead>
<tr>
<th>Element</th>
<th>Fractured-section (wt.%)</th>
<th>Ground surface (wt.%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>C</td>
<td>8.81</td>
<td>10.70</td>
</tr>
<tr>
<td>O</td>
<td>9.71</td>
<td>4.33</td>
</tr>
<tr>
<td>Co</td>
<td>9.17</td>
<td>2.67</td>
</tr>
<tr>
<td>W</td>
<td>72.31</td>
<td>82.30</td>
</tr>
<tr>
<td>Gross</td>
<td>100.00</td>
<td>100.00</td>
</tr>
</tbody>
</table>

The EDS analysis results demonstrated that C, O, Co and W were the basic elements in the workpiece sample, however, it caused a slight decrease in the O and Co contents, whereas a slight increase in the W and C contents. The loss of Co in the ground workpiece surface is considered due to the “squeezing out” of the softer Co phase by the stress field induced during grinding. The YH6F sample ground with the SD2000N100V and SD80N100B wheels under the conditions of 10 μm wheel depth of cut and 30 mm/s worktable speed, as displayed in Lines 1 and 2, respectively. All the diffraction peaks are clear for both ground surfaces except for the metal cobalt. The diffraction peaks of the metal cobalt are nearly submerged in the background clutter. Compared to the unground fractured-section in Line 3, grinding caused a slight shift in the diffraction peaks to the left and an increase in the full width at half maximum (FWHM) of the peaks. For example, the FWHMs measured based on the (1 0 1) plane of the WC grains were 0.56°, 0.44° and 0.25°, respectively, for Lines 1, 2 and 3.

5. Discussion

In the previous research, it has been demonstrated the tangential grinding force per grit monotonically increases with the maximum undeformed chip thickness [5]. However, at a given material-removal rate, specific energy, which is also measured in grinding force work, monotonically declines with the maximum undeformed chip thickness. Researchers attempt to interpret the anomalous phenomenon in terms of the “size-effect” which states that the smaller the material unit removed by an abrasive grit, the lower the likelihood of defects involved in the material unit, and vice versa [8]. The small unit of material removal corresponds to a small undeformed chip thickness, and thus high material-removal stress in machining. According to Bragg’s law, for a distorted material lattice, its diffraction peaks are different and its FWHM changes accordingly [9]. The XRD results also demonstrated more lattice distortion in fine grinding than in coarse grinding, which confirms the higher stress level in fine grinding.

Grinding force is generated through the abrasive–workpiece interactions in the form of elastic–plastic deformation, chip formation and friction between abrasive, bond and workpiece. The total specific energy in grinding consists of energies for chip formation and friction between abrasive, bond and workpiece. Although material removal mostly occurs by chip formation, much of the grinding energy is expended by other mechanisms than chip formation. For example, wear flats on the abrasives slide against the workpiece surface without removing any material but consume energy through the frictional effect. Moreover, plowing is due to material flow in the form of plastic deformation and/or pulverization [10]. Material flow due to abrasive scratching can be in the direction of machining or other directions, such as the side directions. It forms scratches, ridges or pile-ups in the machined workpiece surface.

Generally, deformation of the WC samples in grinding is described in terms of elastic and inelastic material responses. While the elastic deformation is usually small and in most cases negligible, the inelastic deformation constitutes the major material deformation during grinding, which may include plastic deformation, microcrack formation, fracture and chipping, void collapse, etc. [10]. Since all the sample materials contained 10% Co binder phase, the Co phase could be squeezed out of the ground workpiece.
surface. A part of the “squeezed out” Co was found to smear over the ground surface which also formed ridges and pile-ups along the grinding scratches. The “squeezing out” effect caused a decrease in the concentration of the Co phase in the ground workpiece surface, which resulted in the weaker diffraction peaks of the power density spectrum in the XRD results.

Under the same grinding conditions, the WC samples of different grain sizes exhibited different specific energies. This is because the physical–mechanical properties are different for the WC samples of different grain sizes. The material flow caused by an abrasive grit is governed by the stress–strain state in the material response to the abrasive–workpiece interactions. Under an external loading condition, the WC samples may deform elastically and then plastically, and may further fracture or crack. The material deformation behavior is also governed by the stress–strain state exerted to the material [4]. In the WC samples, there exist hard WC phase and soft Co phase. Generally, the former provides hardness and wear resistance while the latter provides strength and toughness to the material. In the nanostructured WC samples, the mean free path of the Co phase is reduced due to the reduced grain size, which greatly enhances the solubility of Co in the WC samples. The enhanced solubility in turn increases the strength and hardness of the WC samples.

The existing research shows that fracture mainly occurs at the grain boundaries of a WC sample in the form of Co phase separation. Very few intragranular fracture cases are found in the WC samples [4,11]. In addition, fracture may also preferably be formed around the pre-existing voids and/or defects in the WC samples. The pre-existing voids and/or defects decrease as the average grain size result in lower specific energy, and vice versa.

Plastic deformation occurs during grinding of the WC samples. Under a given grinding condition, the WC samples with a smaller average grain size result in lower specific energy, and vice versa. Plastic deformation occurs during grinding of the WC samples. It is mainly due to the soft Co phase which is found to be “squeezed out” due to abrasive–workpiece interactions. The “squeezing out” causes the Co phase to smear over the ground workpiece surface, forming ridges and/or pile-ups along the grinding scratches.

6. Conclusions

The study proposed a mathematical model to predict specific energy in grinding of tungsten carbides of various grain sizes and arrives at the following conclusions:

- The model prediction is well verified by the grinding experiment and is proven to be viable.
- The grain size of the WC samples has an obvious effect on specific energy in grinding and surface topography of the ground WC samples.
- Under a given grinding condition, the WC samples with a smaller average grain size result in lower specific energy, and vice versa. Plastic deformation occurs during grinding of the WC samples. It is mainly due to the soft Co phase which is found to be “squeezed out” due to abrasive–workpiece interactions. The “squeezing out” causes the Co phase to smear over the ground workpiece surface, forming ridges and/or pile-ups along the grinding scratches.

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References