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Section A of

The Book of GRINDING

Introduction
Vitrified-Bonded Wheel

Porosity

Bond Bridge

Abrasive Grain

Dressed Vitrified-Bonded Al₂O₃ Wheel

0.200 mm
0.008”

Sample Version
Worn Metal-Bonded Diamond Wheel

0.500 mm
0.020”

80-mesh grit

150-mesh grit

320-mesh grit

Drawn to Scale, Relative Sizes of Chips & Different Grit Sizes

Sample Version
The same scratch from the rear.

Repeated plowings and piling up along the sides facilitate the eventual formation of a chip to the side of one of the plow marks.
Why Do Forces Matter?

Depth of Dress
= 0.005 mm
= 0.0002”

High normal forces cause chatter and dimensional problems.

High tangential forces cause high heat and burn.

Depth of Cut = 5 mm; Wheel Speed= 31 m/s; Feedrate = 6600 mm/min; Coolant: 4% Solution; Workpiece = EN31 @ 736 HV; Wheel = WA60HV; Dressing: Blade, 0.2 mm/rev @ Three Depths. Source: J. Badger, Ph.D. Thesis, Trinity College, Dublin.
As you increase material-removal rate, you increase grinding forces.

\[ y = 4.23x^{0.86} \]
\[ y = 1.566x^{0.91} \]


Grinding of Silicon Nitride with a 320-mesh, 100-concentration, resin-bonded wheel with friable diamond after truing and sticking.

SEM figures of wheel taken here, after trueing & dressing... and here, after grinding.

Grits plucking out of the bond material.

As wheel wears, grits previously below the dressing line now getting into the action.

Grinding of Silicon Nitride with a 320-mesh, 100-concentration, resin-bonded wheel with friable diamond after truing and sticking.

Total number of grits visible
Active grits in the grinding action

Grit Density

0
50
100
grits/mm²

material removed, V, (mm³/mm/mm)

2
4
6
8

1. Data taken from: T.W. Liao, K. Li, S.B. McSpadden Jr. “Wear mechanisms of diamond abrasives during transition and steady stages in creep-feed grinding of structural ceramics,” Wear 242, 2000, page 35, figure 3. 2. V = material removed in mm³ per mm wheel width per mm wheel circumference. 3. SD320-R100B99-1/8, RVG diamond. 4. 37C220-KVK truing wheel; 5. NMVC400-H5VCA stick. 6. after grinding 2.0 mm³/mm/mm.

Grit Size: It's All About Sieves

46-mesh: 46 wires per inch
60-mesh: 60 wires per inch
80-mesh: 80 wires per inch

Why Does Size Go Down as Mesh Number Goes Up?
### Practice Assignment – Specific Energy

<table>
<thead>
<tr>
<th>Operation</th>
<th>Details</th>
</tr>
</thead>
<tbody>
<tr>
<td>a) Plunge</td>
<td>1.0 mm/min.</td>
</tr>
<tr>
<td>b) Dwell</td>
<td>4.0 s, then</td>
</tr>
<tr>
<td>c) Wipe</td>
<td>25 mm/min.</td>
</tr>
</tbody>
</table>

**Specific Material Removal Rate (MRR)**

- **Specific Material Removal Rate (MRR) = Plunge speed (inches/min) \times \pi \times workpiece diameter (inches) \left\{ \frac{\text{in}^2}{\text{min}} \text{ or } \frac{\text{in}^3}{\text{min}} \right\}**

- **Specific Material Removal Rate (MRR) = \text{plunge speed (mm/s)} \times \pi \times \text{workpiece diameter (mm)} \left\{ \frac{\text{mm}^2}{\text{mm}} \text{ or } \frac{\text{mm}^3}{\text{s}} \right\}**

For more info, see supplementary section on Cylindrical Grinding.
Power is Increasing in Each Pass, But the MRR is the Same

Power increasing somewhat rapidly, so wheel probably dulling. Indication that we're not getting good self-sharpening.

Dress before grinding

Grinding of HSS with SG wheel, 4 flutes

The Grindometer ©
G-ratio Trends

<table>
<thead>
<tr>
<th>Feedrate (mm/s)</th>
<th>0</th>
<th>50</th>
<th>100</th>
<th>150</th>
<th>200</th>
<th>250</th>
<th>300</th>
<th>350</th>
</tr>
</thead>
<tbody>
<tr>
<td>100/120 mesh</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>140/170 mesh</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>200/230 mesh</td>
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<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Change in part dimension (mm)

<table>
<thead>
<tr>
<th>Parts ground after dressing</th>
<th>0</th>
<th>4</th>
<th>8</th>
<th>12</th>
<th>16</th>
<th>20</th>
<th>24</th>
<th>28</th>
<th>32</th>
</tr>
</thead>
<tbody>
<tr>
<td>+0.060</td>
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<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>+0.050</td>
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<td></td>
<td></td>
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<tr>
<td>+0.040</td>
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<td></td>
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<td></td>
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<tr>
<td>+0.030</td>
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<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>+0.020</td>
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<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>+0.010</td>
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<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>+0.000</td>
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<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Part ground after dressing:
- no burn
- slight burn
- heavy burn

Feedrate:
- $v_w = 600$ mm/min
- $v_w = 780$ mm/min
- $v_w = 960$ mm/min
What’s the Root Cause of Residual Stress?

6) Therefore, the hot material will be under compressive stress (as it wants to be larger than it is allowed to be)

Type 4: Rehardening burn

Heat-treating your material – not in the furnace but in the grinding machine!
Type 4: Rehardening Burn

T4

~ 860°C ~ 1580 F

Rehardening burn after cutting/polishing & nital etching

White part is rehardening burn

Dark grey part is overtempering

Ground surface
Sample Version

Group Assignment 1

Fundamentals: Wheel Wear, Power, Heat & Dressing
Group Assignment 1

Conflict in the Grinding Factory
Drama in Real Life

Rex the Production Manager, Joe The Grinder and Lefty the grinding-wheel salesman

Joe The Grinder is form-grinding 50 Rc hardened bearing steel with an aluminum-oxide wheel. Joe’s 55 years old, ready to retire and doesn’t like change.

Joe’s been having on-again-off-again problems with burn. He’s got to hold a 0.150 mm (6 thou) corner radius and sometimes it breaks down. He also needs to get a surface finish of Ra=0.4 \( \mu \text{m}=16 \mu \text{inches} \).

Joe’s currently using a Norton 57A80JVS wheel and dressing it with a single-point diamond 0.005 mm (0.0002”) every third part. His wheel is running at 3000 RPM during dressing and it takes 10 seconds to dress the wheel, which has a width of 25 mm (1”). He then takes a dressing pass with no in-feed.

Joe’s supervisor, Rex, comes in with the grinding-wheel salesman, Lefty.
Section H

Dressing Overview

Overview of dressing tools

- Single-Point
- Cluster
- Blade & Blade Fliesen
- Diamond Roll
- Form Roll Disk
- Rotary PCD Form Roll

Updated from Suzanne's 5/2012
Red points for depth=7.7%, softer material (34 Rc) from Malkin’s “Comparison of single-point and rotary dressing of grinding wheels” from Lindsey and Bhateja’s book.

Malkin’s chip-formation energy for steel of 13.8 J/mm³

This point after grinding V''=0.035 mm³/mm. Initial specific energy estimated at 15 J/mm³.

This point after grinding V''=0.035 mm³/mm. After grinding of material, specific energies rise as high 600J/mm³.

Typical values between 2 and 10

Specific energy for dressing depths of 7.5% to 12.5% of grit diameter

Whack Number, U

dressing overlap ratio

Sample Version
But if the ratio is not an integer, for example:

\[
\text{Dressing Roll Ratio} = \text{RATIO2} = \frac{\text{RPM}_{\text{diamond roll}}}{\text{RPM}_{\text{wheel}}} = 4.287
\]

Then the roll picks up in a different location every time it traverses one wheel revolution – and all the waves are obliterated out.
Group Assignment 7

The Grinding Doc’s Book of Grinding

Superabrasives, Part B
Hank the grinder has to remove 3 mm of steel with his CBN wheel. He decides to try it several different ways to see what will happen.

<table>
<thead>
<tr>
<th>Test</th>
<th>depth</th>
<th>wheel diameter</th>
<th>feedrate</th>
<th>wheel speed</th>
<th># of passes</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>3.0 mm</td>
<td>400 mm</td>
<td>500 mm/min</td>
<td>50 m/s</td>
<td>1</td>
</tr>
<tr>
<td>2</td>
<td>1.5 mm</td>
<td>400 mm</td>
<td>1000 mm/min</td>
<td>50 m/s</td>
<td>2</td>
</tr>
<tr>
<td>3</td>
<td>0.3 mm</td>
<td>400 mm</td>
<td>5000 mm/min</td>
<td>50 m/s</td>
<td>10</td>
</tr>
<tr>
<td>4</td>
<td>0.3 mm</td>
<td>400 mm</td>
<td>2500 mm/min</td>
<td>25 m/s</td>
<td>10</td>
</tr>
</tbody>
</table>

1. Calculate the specific material-removal rate, aggressiveness and length of the arc of cut for each set of conditions.
2. Do any of these have the same metal-removal rate?
3. If any have the same metal-removal rate, do they also have the same aggressiveness? Which ones are higher? Why are they higher (or, more aggressive)?
4. Which set of parameters will wear the most?
5. Which set of parameters will self-sharpen the wheel best?
6. Which set of parameters will give the biggest risk of burn?
7. Which set of parameters will result in more heat going to the coolant? Why?
Group Assignment 9

Ceramic Abrasives
Group Assignment 9

1. When we increase the feedrate 20%, does the power also increase by 20%? By how much? Is it more or less? Why?

2. Is this true for both the SG and Cubitron wheels?

3. Wheel wear is lowest at 120% feedrate for the SG wheel. Where is it lowest for the Cubitron wheel?

4. Where is the Sweet Spot for the SG wheel?

5. Where is the Sweet Spot for the Cubitron wheel?

6. Define the blunting region, sweet-spot region and bond-fracture region for the SG wheel.

7. Define the blunting region, sweet-spot region and bond-fracture region for the Cubitron wheel.
## Two Types of Chatter

### Type 1 chatter: Forced
- **Description:** Something banging or vibrating that shouldn’t be banging or vibrating.
- **Frequency:** The source of the banging/vibration.
- **Examples:** Imbalanced wheel, out-of-true wheel, bad bearing, belt, lose fitting between adaptor and wheel.

### Type 2 chatter: Unforced
- **Description:** The wheelhead/workpiece just starts bouncing around.
- **Names:** Unforced chatter, self-excited chatter, regenerative chatter.
- **Frequency:** The natural frequency (also called resonant frequency) of the system, using higher than forced chatter.
Those forces are oscillating up and down at 652 Hz. What's the natural frequency of the spindle on a Jones & Shipman 540 grinder*? 650 Hz.

Chatter frequency (Hz) =

\[
\text{Number of chatter marks on one revolution of the workpiece} \times \frac{\text{Workpiece RPM}}{60} \div \frac{\text{chatter marks/revolution}}{\text{revolutions/second}}
\]

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by The Grinding Doc

Chatter Wavelength Obliteration

Sample Version

Section 1 of The Grinding Doc’s Book of Grinding

Ceramic Abrasive
Two passes: 1 roughing pass, one finish pass. Four flutes per part. SG wheel, 4 grinds/part, depth = 1.6 mm, table speed = 400 mm/min, wheel speed = 50 m/s, wheel diameter = 200. Aggressiveness400 = 12 (not very aggressive for SG wheel)
The Book of Grinding
by The Grinding Doc

Sample Version

Section Y
of
The Grinding Doc’s
Book of Grinding
New Developments
Bob decides he's got coolant problems. He decides to get rid of all his nozzles and use just three small, round nozzles (each has an opening of 3.125 mm (1/8"). His wheel is running at 60 m/s (11800 SFPM). He wants to match this wheel speed. Bob's grinding with oil.

1. What pressure does Bob need at the outlet?
2. What is the total orifice area of the three nozzles?
3. What flowrate can he expect from these three nozzles to match the wheel speed?
4. What size pump does he need?

Bob sticks on his new pump with his three nozzles. He still doesn’t have a pressure gauge, so he uses the ol’ bucket-&-stopwatch technique. He fills up an 80 liter (21 gallon) bucket in 68 seconds.

5. Is Bob’s coolant velocity close enough to his wheel speed?
Fred the grinder is thread-grinding 16 mm diameter taps on a Drake multi-rib thread grinder. The thread-pitch is 11 threads per inch. He checks the recommended wheel specification and finds a recommended grit size of 180 mesh. He's using 220 mesh.

His grinding parameters are as follows:

<table>
<thead>
<tr>
<th></th>
<th>Wheel speed</th>
<th>Workspeed</th>
<th>depth</th>
<th>% of total</th>
<th>Relative aggressiveness*</th>
<th>Dressing depth</th>
<th>plunge speed</th>
<th>Ratio</th>
<th>Dwell</th>
<th>Wheel RPM</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rough 1</td>
<td>14000 SFPM</td>
<td>400 ipm</td>
<td>0.0400”</td>
<td>29.4%</td>
<td>5.7</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Rough 2</td>
<td>14000 SFPM</td>
<td>400 ipm</td>
<td>0.0300”</td>
<td>22.1%</td>
<td>4.9</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Rough 3</td>
<td>14000 SFPM</td>
<td>400 ipm</td>
<td>0.0300”</td>
<td>22.1%</td>
<td>4.9</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Rough 4</td>
<td>14000 SFPM</td>
<td>400 ipm</td>
<td>0.0220”</td>
<td>16.2%</td>
<td>4.2</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Rough 5</td>
<td>14000 SFPM</td>
<td>400 ipm</td>
<td>0.0120”</td>
<td>8.8%</td>
<td>3.1</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Dress 1</td>
<td>.0012”</td>
<td>.00008”/rev</td>
<td></td>
<td>+0.4</td>
<td>2000</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Finish 1</td>
<td>8000 SFPM</td>
<td>180 ipm</td>
<td>.0010”</td>
<td>0.7%</td>
<td>0.7</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Dress 2</td>
<td>.0012”</td>
<td>.00008”/rev</td>
<td></td>
<td>+0.4</td>
<td>2000</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Finish 2</td>
<td>8000 SFPM</td>
<td>180 ipm</td>
<td>0.0010”</td>
<td>0.7%</td>
<td>0.7</td>
<td>0.1360”</td>
<td>100.0%</td>
<td>0.7</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

*Because this is a multi-rib operation, the aggressiveness depends on the depth of each rib. Therefore, we've calculated a relative aggressiveness as

Relative Aggressiveness = 1000 x (workspeed/wheelspeed) X square root (depth of cut)