Force Analysis for Segmental Grinding

Xiaorui Fan and Michele H. Miller
Michigan Tech University
Ways To Reduce Grinding Forces

1) Smaller depth of cut and/or table speed

2) In-process dressing

3) Better lubrication

4) Segmental grinding
Force Modeling

\[ F_z = F_{zc} + F_{z0} \]
\[ F_x = F_{xc} + F_{x0} \]

- Total force = cutting component + rubbing component
  - Cutting component depends on MRR
  - Rubbing component independent of MRR

\[ k_z \cdot MRR^{m_z} \]
\[ k_x \cdot MRR^{m_x} \]
Continuous Grinding

Segmental Grinding
\[ F = k (MRR)^m + F_0 \]
Estimated Instantaneous MRR

r=89mm;
d=25µm;
v=60mm/s;
ω=2900rpm;
Width of cut=12.7mm;
20 segments with equal space
Model Calibration

\[ F = k(MRR)^m + F_0 \]
Rubbing Component  \[ F = k(MRR)^m + F_0 \]

Average  \[ F_{zo} = 0.74 \text{ N} \]

Average  \[ F_{xo} = 0.43 \text{ N} \]
Cutting Component (z direction)

\[ F = k(MRR)^m + F_0 \]

- **v=45 mm/s**: Diamond markers
- **v=82 mm/s**: Square markers
- **v=114 mm/s**: Triangle markers
- **v=150 mm/s**: Cross markers

Variables:
- \( F_z \) (N) - Force in the z direction
- \( d \) (µm) - Depth of cut
- \( v \) (mm/s) - Cutting speed
Cutting Component (x direction)

\[ F = k(MRR)^m + F_0 \]

- \( \Delta \) v=45 mm/s
- \( \triangle \) v=82 mm/s
- \( \times \) v=114 mm/s
- \( \times \) v=150 mm/s

\( F_x \) (N) vs. \( d \) (\( \mu \)m)

- 100
- 90
- 80
- 70
- 60
- 50
- 40
- 30
- 20
- 10
- 0

- 120
- 110
- 100
- 90
- 80
- 70
- 60
- 50
- 40
- 30
- 20
- 10
- 0

- 0
- 30
- 60
- 90
- 120

\( d \) (\( \mu \)m)
Equation: $F = k(MRR)^m + F_0$

Curve Fit:

- $y = 4.13x^{0.77}$
- $y = 2.51x^{0.81}$

Graph:

- $F - F_0$ vs. MRR (mm$^3$/sec)

Equations:

- $F_z = 4.13(MRR)^{0.77} + 0.74$
- $F_x = 2.51(MRR)^{0.81} + 0.43$
Predicted Force

- $r=89\text{mm}$;
- $d=25\mu\text{m}$;
- $v=60\text{mm/s}$;
- $\omega=2900\text{rpm}$;
- Width of cut $=12.7\text{mm}$;
- 20 segments with equal space

Avg. force
Segmental Wheel Geometries

40 segments
1:1 ratio

20 segments
1:3 ratio

20 segments
1:1 ratio

10 segments
1:3 ratio
Alumina Wheel
Model Validation

\[ d=25 \, \mu m \]

as no. of segments goes down, force goes down
as space-to-segment ratio goes up, force goes down
Effect of Number of Segments (Simulated)

### Average Force

- **Fz**: 
  - 0 N at 0 segments
  - Increases linearly with number of segments
- **Fx**: 
  - 4 N at 0 segments
  - Increases linearly with number of segments

### Peak Force

- **Fz**: 
  - 400 N at 0 segments
  - Decreases exponentially with number of segments
- **Fx**: 
  - 300 N at 0 segments
  - Decreases exponentially with number of segments

**1:1 Wheels**
Explaining Segment Number Effect

- $F_{z} (N)$
- $F_{\text{Avg.}} = 16.66 N$
- $r = 89 \text{ mm}$;
- $d = 25 \mu \text{m}$;
- $v = 60 \text{ mm/s}$;
- $\omega = 2900 \text{rpm}$;

40 _1:1

- $F_{\text{Avg.}} = 15.75 N$
- $r = 89 \text{ mm}$;
- $d = 25 \mu \text{m}$;
- $v = 60 \text{ mm/s}$;
- $\omega = 2900 \text{rpm}$;

20 _1:1
Effect of Space-to-Segment Ratio (Simulated)

Average Force

Peak Force

20 Segment Wheels
Explaining Space-to-Segment Ratio Effect

- $F_{avg.} = 17.92\, N$
  - $r = 89\, \text{mm}$;
  - $d = 25\, \mu\text{m}$;
  - $v = 60\, \text{mm/s}$;
  - $\omega = 2900\, \text{rpm}$;
  - 20_1:3

- $F_{avg.} = 15.75\, N$
  - $r = 89\, \text{mm}$;
  - $d = 25\, \mu\text{m}$;
  - $v = 60\, \text{mm/s}$;
  - $\omega = 2900\, \text{rpm}$;
  - 20_1:1
Diamond Grinding on Glass

Ground by segmental wheel

Polished interface

Ground by continuous wheel

Grinding Direction
Homemade Diamond Wheels
Subsurface Damage

$\text{d}=2.5 \, \mu m$

$\text{d}=7.5 \, \mu m$

segmented wheels →

continuous wheels →

20 μm

50 μm
Illustration of Damage Measurement
Subsurface Damage Depth

- Maximum Depth (µm)

- 2.5µm 7.5µm 2.5µm 7.5µm
- Segmental Wheel Continuous Wheel

- d
Conclusions

• Grinding forces decrease using segmental wheels. A model has been developed that explains why.
• Fewer segments lead to lower average forces but higher peak forces.
• Larger segment spacing results in lower average forces but higher peak forces.
• In diamond grinding tests, segmental wheels produce lower surface roughness and shallower subsurface damage.
Future Work

• Identify segment shapes that produce optimal combination of peak force and average force.

• Investigate wear rates of segmental wheels.