

# FORCE ANALYSIS FOR SEGMENTAL GRINDING

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## Introduction

Due to the large variety of chemical, electrical, biological, and mechanical properties that ceramics presently exhibit, there are many social and industrial applications with ceramics. On the other hand, some of the desirable properties of ceramics also cause difficulties in machining them to a precise size and shape. Grinding is an enabling technology in the manufacture of ceramic components because it can produce accurate shapes deterministically.

Compared to other machining processes, grinding requires large energy per unit volume of material removed. In other words, for the same amount of material removed, grinding takes much more energy and force. High grinding forces mean higher temperatures that lead to more coolant usage. Both forces and temperatures influence the workpiece accuracy. High grinding forces also make the machining tools wear faster. Methods to reduce grinding forces are, therefore, desirable. For example, high speed grinding has been used to decrease grinding forces [1,2]. The threshold is about 80-180 m/s depending on grinding conditions and workpiece material. Also, in-process dressing sharpens the grinding wheel thus reducing grinding forces.

A number of researchers have demonstrated that segmental grinding is a promising approach to reduce grinding forces. Using a segmental wheel is a convenient way to accomplish intermittent grinding since the spacers of the wheel do not contact the workpiece. Lee et al. [3] explored the cutting force for ceramic face grinding using slotted diamond wheels and built a temperature model for face grinding. Brecker et al. [4] developed a segmental cup wheel to improve grinding performance when work traverse speed is low. He found that the interrupted cutting surface permitted improved cutting fluid effectiveness resulting in significantly lower friction forces, less power, and better surface finish. A.V. Gordeev [5] found that metal bonded segmental wheels wore more slowly than wheels with a continuous working surface.

This paper focuses on developing a force model for segmental wheel grinding. Based on the modeling analysis, optimal segmental wheel geometry will be identified.

## Grinding Force Modeling

The grinding force can be divided into normal and tangential components ( $F_z$  and  $F_x$  respectively). Each of these can be further subdivided into two parts: a cutting component and a rubbing component. The cutting component increases with material removal rate ( $MRR$ ) and the rubbing component is independent of  $MRR$ :

$$\begin{aligned} F_z &= k_z \cdot MRR^{m_z} + F_{z0} \\ F_x &= k_x \cdot MRR^{m_x} + F_{x0} \end{aligned} \quad (1)$$

$k_z, k_x, m_z, m_x, F_{z0}$  and  $F_{x0}$  are constants that depend on the workpiece material and grinding wheel.  $F_{z0}$  and  $F_{x0}$  are the rubbing components in the normal and tangential directions, respectively.

## MRR Analysis for Segmental Wheel Grinding

Segmental wheel grinding changes the contact pattern between the wheel and workpiece so that the instantaneous material removal rate is different from regular grinding. Based on it, the grinding forces for segmental wheel grinding can be predicted based on the instantaneous MRR change.

The cutting cycle of each segment can be divided into four stages: the previous segment leaving grinding zone, the current segment approaching grinding zone, the current segment entering grinding zone, and the current segment fully contacting the workpiece. The geometry of these four stages was analyzed, and equations for instantaneous MRR were derived based on wheel radius, wheel speed, table speed, depth of cut, and segment size and spacing. Figure 1 shows instantaneous MRR under a set of specific conditions for two segments of grinding, in which 1, 2, 3, and 4 correspond to the four stages respectively. In this plot the contact time between

the wheel and workpiece is a little more than a half cycle (56.8%), and the highest MRR happens in stage 3 when the segment enters to the grinding zone grind zone when the instantaneous depth of cut is highest too).

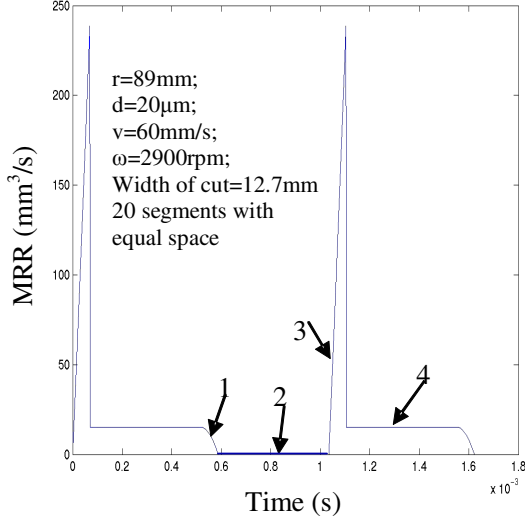


Figure 1: Instantaneous MRR for two segment cycles

### Model Calibration Tests

To find the  $k$ 's,  $m$ 's and  $F_0$ 's in Equation 1, a series of surface grinding tests were done with a regular wheel. The experiment setup is shown in Figure 2, and the grinding conditions are shown in Table 1. The wheel was trued with multiple passes to minimize the roundness error. Both normal force  $F_z$  and tangential force  $F_x$  were measured by a Kistler tri-axial force dynamometer. Then they were amplified and collected by a computer.

Workpiece Material	4140 Steel (50 x 5 x 10 mm)
Grinding Wheel	Aluminum oxide 32AR46-JV40 162 mm dia. x 6.4 mm
Wheel Speed	29.4 m/s
Feed Rate	45, 82, 114, 150 mm/s
Depth of Cut	5, 25, 50, 75, 100 $\mu\text{m}$
Coolant	No

Table 1: Regular grinding test conditions

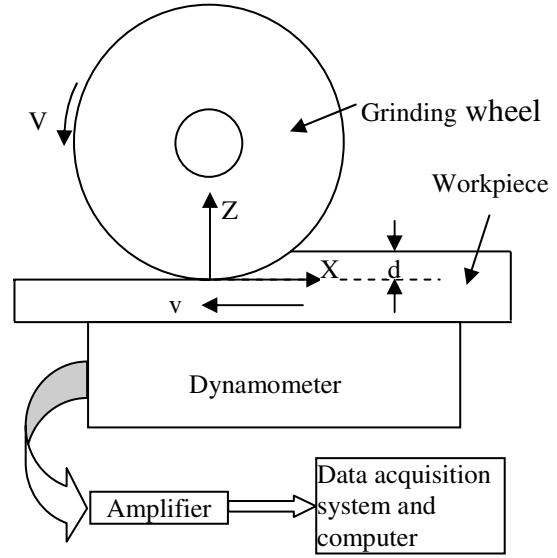


Figure 2: Grinding tests setup

The grinding forces change with depth of cut and table speed as shown in Figure 3 and 4. Every point in these figures is the average of three measurements.

The rubbing components  $F_{z0}$  and  $F_{x0}$  were measured at sparkout when no new material is removed.

Rubbing component measurements were taken for all the grinding conditions in Table 1. The rubbing components in both directions proved to be independent of table speed or depth of cut of previous passes. In this experiment,  $F_{z0}$  and  $F_{x0}$  were 0.74 and 0.43 newtons respectively.

Tests were done at five depths of cut and four table speeds for a total of twenty material removal rates.

The curves in Figure 5 are power trend lines fit to twenty points. When MRR is small, it takes more energy to grind material. From this figure, we can find  $k_z$ ,  $k_x$ ,  $m_z$ , and  $m_x$  in Equation (1). In this experiment, they are 4.13, 2.51, 0.77, and 0.81 respectively. So under these grinding conditions, the force model equation is:

$$\begin{aligned} F_z &= 4.13(MRR)^{0.77} + 0.74 \\ F_x &= 2.51(MRR)^{0.81} + 0.43 \end{aligned} \quad (2)$$

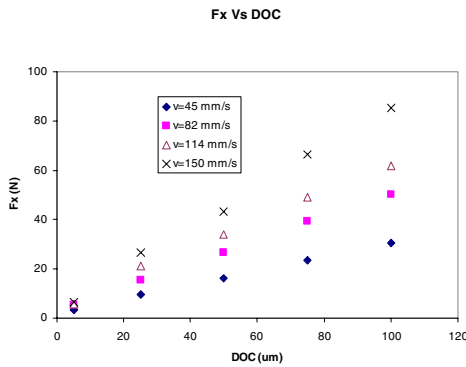
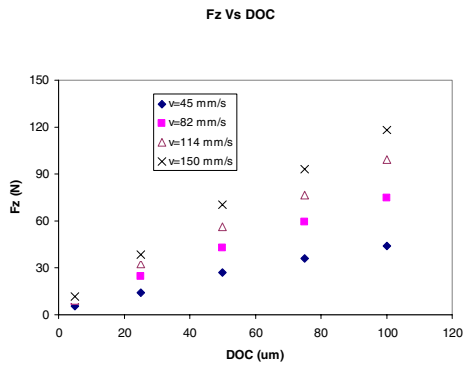


Figure 3:  $F_z$  and  $F_x$  Vs depth of cut

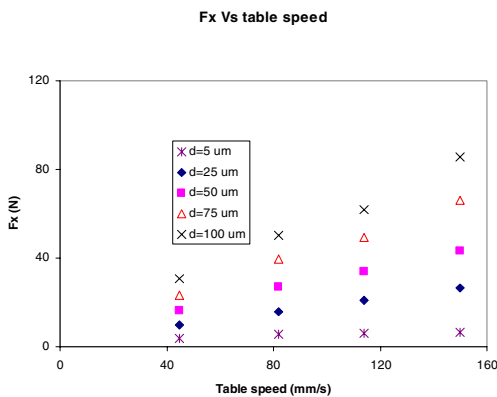
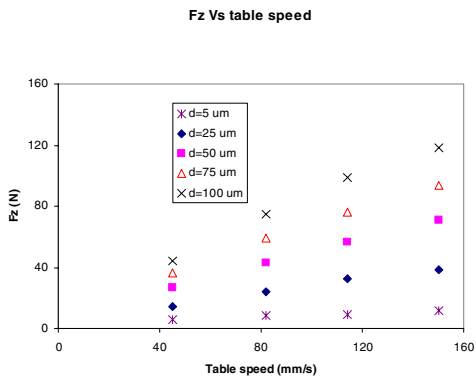


Figure 4:  $F_z$  and  $F_x$  Vs table speed

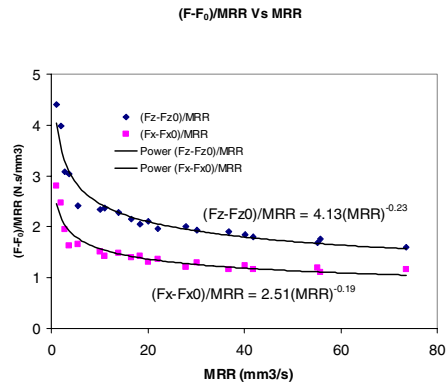


Figure 5: Cutting components Vs MRR

## Segmental Grinding Tests

With the instantaneous MRR (as illustrated in Figure 1), Equation 2 can be used to predict segmental grinding forces. Figure 6 depicts the segmental wheels used in experiments for validating the model. They were cut from regular aluminum oxide wheels. Segmental wheel No. 1 has forty teeth and its proportion of segment length to notch length is 1:1. Segmental wheels No. 2 and 3 have twenty segments while No. 4 has ten segments. Wheels No. 3 and 4 have segment to notch length of 3:1.

The experiments were done with these four segmental wheels according to Table 2.

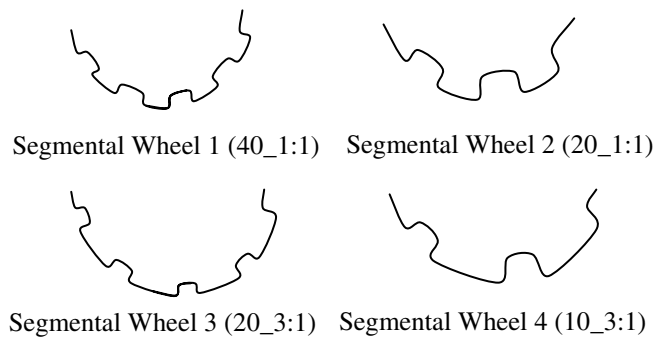


Figure 6: Segmental grinding wheels

Workpiece Material	4140 Steel (50 x 5 x 10 mm)
Segmental Wheels	Cut from aluminum oxide 32AR46-JV40 162 mm dia. x 6.4 mm
Wheel Speed	29.4 m/s
Feed Rate	40-150 mm/s
Depth of Cut	25 $\mu$ m
Coolant	No

Table 2: Segmental wheel grinding conditions

## Results and Discussion

Figure 7 compares model prediction from Equation 2 (continuous lines) and average (of three) measured forces (individual points). The error bar corresponds to the 95% confidence interval. For comparison, the modeled and measured forces for regular (no segments) grinding are shown.

The experiment results and model predictions match very well. These plots show that grinding forces reduce when using segmental wheels. Also, fewer segments lead to lower forces and larger segment spacing results in less force. According to MRR analysis, larger segment spaces and fewer segments increase material removed in Stage 3 and decrease that in Stage 1 and 4. Since MRR in Stage 3 is higher than the rest and specific energy is lower with larger MRR, this size effect will result in lower average forces.

## Conclusion and Future Work

Segmental wheels are an effective way to reduce grinding forces. However, there are still some concerns. As number of segments decreases, the finished surface roughness increases and the peak forces increase. Meanwhile, the segment is weakened if the space between them is too large.

Future work will focus on the optimal design of segment geometry that can balance following aspects: surface finish, average forces, peak force, subsurface damage and wheel wear.

## Reference

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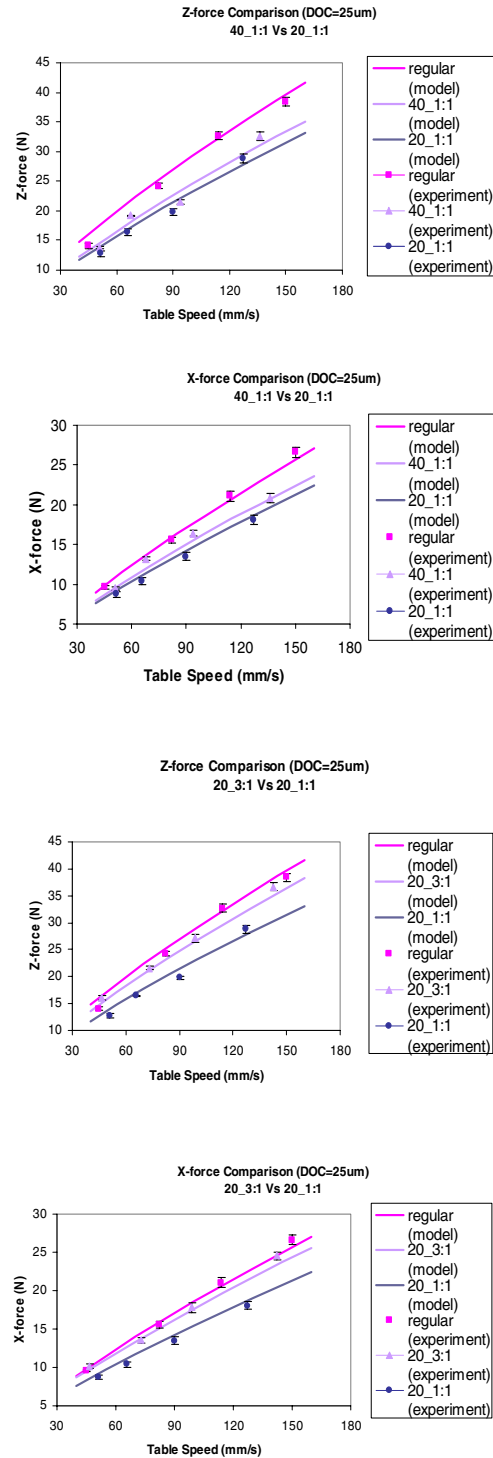


Figure 7: Forces Comparison with Segmental Wheels