ELID Fine Grinding of Sapphire Rollers with Emphasis on Roughness and Material Removal Rate

Omar T. Bafakeeh¹, Ahmed B. Khoshaim² and Ioan D. Marinescu¹

¹The University of Toledo, Toledo, USA
²Umm Al-Qura University, Makkah, Saudi Arabia
albafakeeh@gmail.com, abkhoshaim@yahoo.com, Ioan.Marinescu@utoledo.edu

Abstract

The demand for sapphire (α-Al₂O₃) has significantly increased due to its reliable properties. Sapphire is known for its high hardness and high brittleness. Sapphire has excellent properties such as optic, mechanical and physical properties, which can be maintained even if machined in high temperatures. Due to these properties, sapphire has been used in many different applications such as aerospace, optics, and electronics as well as other industries. Machining of Sapphire is challenging due to its high hardness and brittleness. Fine grinding can be preferable over conventional grinding when machining ceramics because of the ability to provide a flat surface. However, the manufacturing cost for such materials is very high because of high tool wear and longtime machining. In addition, most of the grinding process is followed by a lapping process. Elimination of lapping process can be accomplished using many techniques, one of which is the use of electrolytic in process dressing (ELID). Therefore, the use of fine ELID grinding will reduce the machining time which in turn reduces the manufacturing cost. Part of the solution also investigates the influence of different variables on the workpiece surface finish. This paper presents the influence of four parameters with three level each: different pressures, different eccentricities, different spindle speeds, and different wheel speed ratios. A full factorial design, for both roughness (Ra) and material removal rate (MRR) conducted to present mathematical models which predict future results. The kinematics of the process will be investigated based on the effect of different eccentricity. The mesh size of the diamond grinding wheel used in this experiment is #400.

Keywords: Sapphire, Fine Grinding, Electrolytic in Process Dressing; ELID
1 Introduction

Machining ceramic materials is a big challenge for manufacturing companies due to its high hardness and brittleness. Grinding ceramic materials accounts for up to 80% of the total manufacturing cost. Therefore, companies have been forced to find cheaper approaches to machine ceramic materials, such as casting, hot pressing, injection molding…etc. However, these processes are not able to provide parts with the desired precise dimensional tolerance and with high surface finish. Finishing process such as lapping and polishing are required [B.P. Bandyopadhayay, H. Ohmori, A. Makinouchi 2006]. In single side grinding with lapping kinematics, the workpiece will be in contact with the grinding wheel during the whole process with constant pressure [Doi, T., Uhlmann, E., & Marinescu, I. D. (Eds.) 2014]. What distinguishes single side grinding from lapping is that lapping is a three-body abrasive process while single side grinding is a two-body abrasive process. The abrasive in single side grinding are bonded to the grinding wheel. Therefore, the grinding wheel must be dressed frequently to assure having fresh sharp abrasive during the grinding process. In grinding, choosing the right parameters is essential in order to achieve the optimum desired result. The aim of this experiment is finding models which can predict the roughness and material removal rate result. In this experiment there are different parameters, three levels each, that have been examined in order to determine the significant parameters that affect the results of roughness and material removal rate. These parameters are eccentricity, pressure, spindle speed, and wheel speed. This project is a part of a bigger project with three grit sizes wheels, #400, #1000 and #2000. The #400 part shows that the MRR is very good as well as the Ra. This paper presents the results of #400 only.

1.1 Eccentricity

The workpieces will be held in workpiece holders. Each workpiece holder holds three workpieces at once. This will assure better flatness and increase the accuracy of the results. The workpiece holder will be mounted in a spindle. Three workpiece holders have been designed with different eccentricities, 17, 13 and 9mm, which is the leaner distance from the center of the workpiece holder to the center of the workpiece “ec”. The experiment will examine the influence of these eccentricities on the result of the roughness and material removal rate. Figure 1 illustrates the eccentricity.
2 ELID technology

The electrolytic in process dressing (ELID) technique is a new technique which was discovered by Muraya in 1985. It was enhanced in 1990 by Hitoshi Ohmori [Lim, H. S., Fathima, K., Kumar, A. S., & Rahman, M. 2002]. This technique allows the grinding wheel to be dressed during the grinding operation without the need to stop it. This technique can be applied to any ordinary grinding machine without the need for special equipment. It uses a conventional grinding machine, an electrode made out of stainless steel or copper (copper not recommended), an electrolyte, and DC electrical pulse source. The negative pole will be connected to the electrode, while the positive pole connected to the grinding wheel via a smooth brush [Ohmori, H., Marinescu, I. D., & Katahira, K. (2015)]. The electrode will cover one sixth of the active area of the grinding wheel with a gap between 0.1 to 0.3 mm [Lim, H. S., Fathima, K., Kumar, A. S., & Rahman, M. 2002]. This technique will allow the removal of the metal bond by using electrolyte. This technique requires a preparation stage which is known as a pre-dressing process. In this stage, the electrical DC current will applied on to the rotating grinding wheel, and by the presence of the electrolyte, the electrical circuit will complete. The electrolysis will allow ion to transfer from the grinding wheel to the electrode and this will form an oxide layer of $Fe_2O_3$ on the grinding wheel. This layer work as an electrical isolator. Therefore, the accumulation of the oxide layer will increase the wheel electrical resistivity therefore, the current will reduce. When the system reaches equilibrium, the grinding process can start. During the grinding process, the oxide layer will wear out which in turn will reduce the electrical resistivity of the grinding wheel. Therefore, the current will increase and form another oxide layer [Ohmori, H., Marinescu, I. D., & Katahira, K. (2015)].

Figure 1: workpiece holders with different eccentricities, from the left 9, 13, 17mm
2.1 ELID electro aspects

In the pre-dressing process, the current is at its highest level and the voltage at its lowest level between the grinding wheel and the electrode. After a few minutes, the electrolysis will remove the cast iron which allow the ions to transfer mostly as \(Fe^{2+}\). These ions will react with the fluid forming \(Fe(OH)_2\) or \(Fe(OH)_3\). The following chemical equations are the basis of these reactions:

\[
\begin{align*}
Fe & \rightarrow Fe^{2+} + 2e^- \\
Fe^{2+} & \rightarrow Fe^{3+} + e^- \\
H_2O & \rightarrow H^+ + OH^- \\
Fe^{2+} + 2OH^- & \rightarrow Fe(OH)_2 \\
Fe^{3+} + 3OH^- & \rightarrow Fe(OH)_3
\end{align*}
\]

The oxide iron will form \((Fe_2O_3)\) on the active area of the grinding wheel which will reduce the current, due to the increases in the electrical resistivity of the grinding wheel. This accure because of the forming of the oxide layer until the system reaches equilibrium [Marinescu, I. D. (Ed.)2006]. Figure 2 presents the pre-dressing stage:

**Figure 2:** Mechanism of ELID grinding [Bandyopadhyay,Ohmori, H.Makinouchi,2006]
3 Experiment

The parameters in this experiment are:
1- workpiece holders with different eccentricities 17, 13, and 9 mm
2- spindle speed 150, 175, and 200 rpm
3- wheel speed ratio 1/2, 1/4, and 1/8 of the spindle speed
4- pressures (load) 10, 15, and 20 kg

Table 1 below illustrates the combination of the above parameters.

<table>
<thead>
<tr>
<th>Eccentricity</th>
<th>Spindle Speed</th>
<th>Wheel speed</th>
<th>Wheel speed</th>
<th>Wheel speed</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>a. 150 rpm</td>
<td>b. 175 rpm</td>
<td>c. 200 rpm</td>
<td></td>
</tr>
<tr>
<td>a. 75 rpm</td>
<td>rep</td>
<td>rep</td>
<td>rep</td>
<td>rep</td>
</tr>
<tr>
<td>b. 38 rpm</td>
<td>rep</td>
<td>rep</td>
<td>rep</td>
<td>rep</td>
</tr>
<tr>
<td>c. 19 rpm</td>
<td>rep</td>
<td>rep</td>
<td>rep</td>
<td>rep</td>
</tr>
<tr>
<td>a. 88 rpm</td>
<td>rep</td>
<td>rep</td>
<td>rep</td>
<td>rep</td>
</tr>
<tr>
<td>b. 44 rpm</td>
<td>rep</td>
<td>rep</td>
<td>rep</td>
<td>rep</td>
</tr>
<tr>
<td>c. 22 rpm</td>
<td>rep</td>
<td>rep</td>
<td>rep</td>
<td>rep</td>
</tr>
<tr>
<td>a. 100 rpm</td>
<td>rep</td>
<td>rep</td>
<td>rep</td>
<td>rep</td>
</tr>
<tr>
<td>b. 50 rpm</td>
<td>rep</td>
<td>rep</td>
<td>rep</td>
<td>rep</td>
</tr>
<tr>
<td>c. 25 rpm</td>
<td>rep</td>
<td>rep</td>
<td>rep</td>
<td>rep</td>
</tr>
</tbody>
</table>

Table 1: Experiment parameters combinations

The combinations of the parameters in table 1 repeated with different loads.
The electrolyte used in this experiment was (TRIM® C270). The grinding machine used was the double sided Lapping/Fine Grinding Melchiorre machine (210-3P). This machine was designed for double sided grinding; therefore, some modifications have been applied to make it suitable for single side grinding.

Figure 3 illustrates the electrical behavior of the experiment during the pre-dressing stage.
After the pre-dressing stage, the grinding process will start according to the parameters combinations in table 1. There are two data collected in this experiment roughness (Ra) and material removal rate (MRR). These were collected in four time cycles: after 5, 10, 20, and 30 minutes. All collected data have been applied in full factorial design to be analyzed and to identify the significant factors among the chosen parameters. The interaction of the variables is neglected due to their low significance. Figure 4 illustrates the ELID single side grinding. Figure 5 presents the whole system connected.
Figure 4: ELID single side grinding

Figure 5: complete system
3.1 Experimental-based model

The fixed parameters in the current experiment are as follows:

1. DC electrical source 75 V, 2μs, IP8
2. Grinding wheel (#400) outer diameter 211 mm, and inner diameter 114 mm
3. Workpiece diameter 13 mm and thickness 13 mm
4. Fluid TRIM C270 with 5% concentration
5. The gap between the electrode and the grinding wheel 0.2 mm

4 Experiment result

After conducting a full factorial design, results show some parameters significantly affected the roughness whereas some parameters significantly affected the material removal rate. However, the effect of the load on the roughness is not significant and can be neglected.

The significant factors for roughness are:

- The spindle speed
- The load (not significant)
- The eccentricity

While the significant factors for the material removal rate are:

- The wheel speed ratio
- The load
- The eccentricity
Figure 6 changes in roughness with time with different eccentricities.
Figure 7 changes in roughness with speeds with different eccentricities.
Figure 8 changes in MRR with time with different eccentricities
5 Trajectory

Understanding the grain path of the grinding wheels will help understanding some of the experiment results. In this experiment there are two rotations, spindle rotation and grinding wheel rotation, these rotations are combined together. Each one rotate with different speed and direction, which result in a unique profile. The result of a study titled “Influence of Kinematics on the face Grinding Process on Lapping Machine” showed that different path with different spindle speed ration and wheel speed will affect the roughness and MRR in addition to flatness [Uhlmann, E., Ardelt, T., & Spur, G. 1999]. In this experiment there are three spindle speed, three wheel speed ration in addition to three different eccentricities, this compensation create unique paths. This combinations gave twenty seven runs. Each run has its own path. Keeping in mind that the wheel speed is a ratio of the spindle speed, there is a similarity in each ratio. In other word, there are three main trajectories. The spindle and the grinding wheel both have circular motion, as the grinding process continued, the workpieces in the holder will have contacted the whole area of the grinding wheel. Figure 10 presents different trajectory with different speed ratio (1/2,1/4,1/8) and eccentricity (17,13,9mm).
6 Model and calculations

The main goal of this section is to find the exponents for the proposed equations for Ra and MRR. Each equation has four exponents (C, α, β, γ) [Dorin and Marinescu 1981]. The measurement devise used for Ra is “Pocket Surf III”. It is a portable surface roughness gage by Fedral Products Company. This devise can measure roughness range from 0.03-6.35 micron. Calculating MRR is by measuring the weight of the workpiece before and after the grinding operation. The difference in weight will provide the weight of the material removed. That different will be divided by the density which is (3.98)

The volume of the material removed = the weight change/the density
The proposed equation for the roughness is:

\[ Ra = C \cdot V^x \cdot F^\beta \cdot e_c^\gamma \] 

(1)

The proposed equation for the material removal rate is:

\[ MRR = C \cdot V_r^\alpha \cdot F^\beta \cdot e_c^\gamma \] 

(2)

Where \( V \) is spindle speed, \( F \) is force, \( e_c \) is eccentricity, and \( V_r \) is speed ratio.

The time in the experimental result was constant, which gives 81 proposed equations. Multi-Correlation theory was used to fit all the data into four equations [Khoshaim, A. B. 2014].

6.1 (Ra) modeling

\[ \sum_{i=1}^{81} \log(Ra) = n \log(C) + \alpha \sum_{i=1}^{81} \log(V) + \beta \sum_{i=1}^{81} \log(F) + \gamma \sum_{i=1}^{81} \log(e_c) \] 

(3)

\[ \sum_{i=1}^{81} \log(V) \log(Ra) = \log(C) \sum_{i=1}^{81} \log(V) + \alpha \sum_{i=1}^{81} [\log(V)]^2 + \beta \sum_{i=1}^{81} \log(V) \log(F) + \gamma \sum_{i=1}^{81} \log(V) \log(e_c) \] 

(4)

\[ \sum_{i=1}^{81} \log(F) \log(Ra) = \log(C) \sum_{i=1}^{81} \log(F) + \alpha \sum_{i=1}^{81} \log(V) \log(F) + \beta \sum_{i=1}^{81} \log(F)^2 + \gamma \sum_{i=1}^{81} \log(V) \log(F) \log(e_c) \] 

(5)

\[ \sum_{i=1}^{81} \log(e_c) \log(Ra) = \log(C) \sum_{i=1}^{81} \log(e_c) + \alpha \sum_{i=1}^{81} \log(V) \log(e_c) + \beta \sum_{i=1}^{81} \log(F) \log(e_c) + \gamma \sum_{i=1}^{81} \log(V) \log(e_c)^2 \] 

(6)

Applying all the data on the four equations results to the final model:

\[ Ra = \frac{0.07624 \cdot V^{0.1303} \cdot e_c^{0.1481}}{F^{0.0061}} \] 

(7)

6.2 (MRR) modeling

\[ \sum_{i=1}^{81} \log(MRR) = n \log(C) + \alpha \sum_{i=1}^{81} \log(V_r) + \beta \sum_{i=1}^{81} \log(F) + \gamma \sum_{i=1}^{81} \log(e_c) \] 

(8)

\[ \sum_{i=1}^{81} \log(V_r) \log(MRR) = \log(C) \sum_{i=1}^{81} \log(V_r) + \alpha \sum_{i=1}^{81} [\log(V_r)]^2 + \beta \sum_{i=1}^{81} \log(V_r) \log(F) + \gamma \sum_{i=1}^{81} \log(V_r) \log(e_c) \] 

(9)

\[ \sum_{i=1}^{81} \log(F) \log(MRR) = \log(C) \sum_{i=1}^{81} \log(F) + \alpha \sum_{i=1}^{81} \log(V_r) \log(F) + \beta \sum_{i=1}^{81} \log(F)^2 + \gamma \sum_{i=1}^{81} \log(V_r) \log(F) \log(e_c) \] 

(10)

\[ \sum_{i=1}^{81} \log(e_c) \log(MRR) = \log(C) \sum_{i=1}^{81} \log(e_c) + \alpha \sum_{i=1}^{81} \log(V_r) \log(e_c) + \beta \sum_{i=1}^{81} \log(F) \log(e_c) + \gamma \sum_{i=1}^{81} \log(V_r) \log(e_c)^2 \] 

(11)
Applying all the data on the four equations results to the final model:

\[ MRR = 0.0016642 \times V_r^{0.4417} \times F^{1.169} \times e_c^{1.1305} \]  \hspace{1cm} (12)

7 Conclusions

In the current experiment, the effect of several variables on roughness and material removal rate has been investigated. The experiment was conducted using a diamond grinding wheel with mesh size #400. Multiple conclusions can be drawn:

1. The force applied has no significant effect on the roughness, therefor it can be neglected. However, in the presented (Ra) module the effect of the force is included in the module just for explanation and understanding purposes, even though it effect can be neglected in the model as mentioned. It is known that the force is proportional to roughness, but in our case it has inverse proportional to the result of the roughness, although it is not significant. The explanation for this can be that, the increasing of the force is breaking (crushing) the grains which lead to get better roughness instead of bad roughness. As the force increases the diamonds are breaking in smaller particles, as a result the roughness is getting better. The regime is not as important as the normal force which has a good effect.

2. The mechanism of removing material is a hybrid one, as some particles are freed from the wheel (or crushed) and they will act as lapping particles. We name this mechanism lap-grinding process, which is specific for ELID grinding and more evident for smaller grits. The lap-grinding mechanism is not the main subject of this paper, as we emphasize more at macro/micro level and applications.

3. The valid load for this model are loads within the specified and tested loads for this experiment.

4. Decreasing the eccentricity will result in better surface roughness. Based on the trajectory, the larger the eccentricity, the material will be exposed to more fresh grains compared to smaller eccentricity. Therefore, larger eccentricity results in high material removal rate but not better surface roughness.

5. Increasing the spindle speed will increase the surface roughness, since it is a significant factor that affect the roughness result and it is proportional with roughness. While wheel speed ratio, which is the significant factor that affect material removal rate, is proportional with material removal rate. Increasing the wheel speed ratio will increase the material removal rate because of the trajectory. The higher the wheel speed ratio the workpiece will travel and cover more grains on the grinding wheel.

6. These models are effective only within the range of the variable used in this experiment. The eccentricity cannot exceed 17mm and cannot be less than 9mm because of the size of the grinding wheel used.

7. The model is a pleiotropic model and it is not general for this specific case. After using #1000 and #2000 grit we will attempt to establish a more general model.
References


