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Prediction of surface generation in microgrinding of ceramic materials by coupled trajectory and finite element analysis

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ABSTRACT

This study investigates numerical modeling of surface generation in microgrinding of ceramic materials by coupled trajectory and finite element analysis. The resultant surface generation from both ductile flow mode grinding and fracture mode grinding is modeled in microgrinding of alumina. In the ductile flow mode grinding, the surface generation is simulated by trajectory analysis. In the fracture mode grinding, the surface generation is estimated from the fully damaged subsurface depth by cohesive zone method (CZM) based FEA simulation. The simulated surface profile matches well with the experimental result in the arithmetic average surface roughness. However, larger error is observed in the root mean squared surface roughness at high feed rate. It is suspected that this is caused by the increased vibration in microgrinding at high feed rate, which increases the complexity in the ground surface.

1. Introduction

In the past decade, the demand for ceramic micro-components has been on the rise for their many attractive properties, such as high strength, wear resistance and good chemical stability. Conventionally, grinding is widely used to fabricate ceramic components, as it provides not only precise dimensional control but also superior surface finish. In micro-level manufacturing, miniaturized tool based grinding has been investigated to overcome the tool size constraint in traditional grinding. Several studies have been done in microgrinding of ceramic materials by using electroplated microgrinding tools [1,2]. However, it is observed that their tool life is too short for practical applications. To resolve this problem, Zhang et al. used a sintered metal-bonded microgrinding tool for grinding high strength ceramic materials [3]. Different from the electroplated tool, which only has a single layer of diamonds, the sintered metal-bonded tool has diamonds mixed inside. With proper truing and dressing, its tool life is much longer [3]. Therefore, tool life is no longer the major obstacle for microgrinding of ceramic materials. It is highly desirable to be able to predict surface finish in the selection of microgrinding process parameters for better quality and efficiency.

Many studies have been done in modeling surface finish in grinding in the past. Early research efforts have been focused on developing various empirical or semi-empirical methods to predict surface roughness in grinding. However, due to the empirical nature, their accuracy is sensitive to the changes in the grinding process and the environment. To overcome this problem, some numerical approaches employ measured actual grinding wheel profiles to model surface generation in grinding, such as cutting edge trajectory analysis [4], Monte-Carlo simulation [5] and statistical derivation [6]. These methods often assume an effective material removal, i.e., all the workpiece materials that are swept by the cutting edge are considered to be removed. Hence, these methods are not suitable to account for surface chipping/crack phenomena in grinding ceramic materials [7], which result from the brittle nature of ceramic materials. In practice, surface chipping will affect not only surface finish indexes, such as arithmetic average surface roughness (*Ra*) and root mean squared surface roughness (*Rq*), but also have an impact on the strength of the ground parts. Hence, it is crucial to incorporate the influence of surface chipping in modeling surface finish in grinding ceramic materials.

It is generally accepted that there are two types of material removal mechanisms in grinding brittle materials: fracture mode grinding and ductile flow mode grinding [7]. As shown in Fig. 1, the fracture mode grinding involves micro-level fracture due to crack propagating within grains (Cleavage) or along grain boundaries (Brittle Intergranular Fracture). The ductile flow mode grinding occurs along with micro-level fracture in the plastic region [8], and it results in very little material removal. Through moving indentation studies, it has been observed that cracks generated in micro-level fracture can be classified as: median/radial cracks or lateral cracks [9,10]. The median/radial cracks are produced inside workpiece, while the lateral cracks branch onto the workpiece surface and cause surface chipping. In order to predict the surface chipping, Bifano et al. proposed a critical depth of cut for surface chipping initiation based on energy balance

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between machining energy, surface energy and plastic deformation energy [8]. However, as this approach mainly focuses on the initiation of surface chippings instead of their profile, a direct application of this method for surface roughness modeling is difficult. In the past, surface chipping was mainly investigated by experimental study, in which total chipping areas and average chipping depth were measured by 3D interferometer. It has been found that surface roughness (*Ra*) is closely related to surface chipping depth [11].

By recognizing the importance of surface chipping on surface finish in grinding, it is desirable to predict them for modeling overall surface roughness. However, this is very difficult in the grinding, not only due to complex material removal mechanisms, but also because of the challenge in accounting for numerous irregular diamonds on a conventional grinding wheel. By contrast, the microgrinding provides a unique opportunity for studying this problem. As there are much less diamonds on a microgrinding tool, individual diamond profile can be well-captured by 3D profile measurement, such as white light interferometer. This reduces the error of assuming all diamonds follow a spherical or pyramid shape. With this advantage, the objective of this study is to explore modeling of surface finish in microgrinding of ceramic materials based on actual diamond profile and detailed material removal mechanisms.

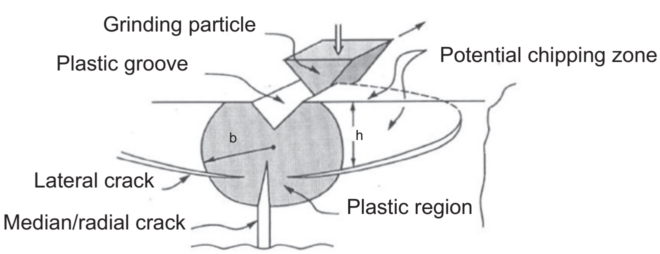
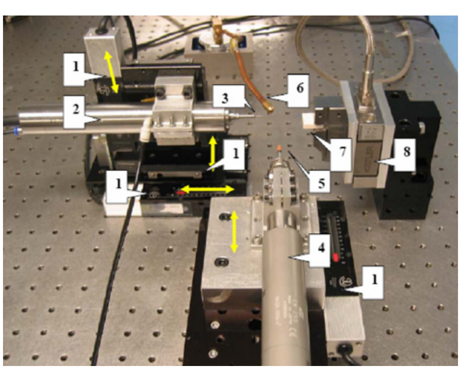


Fig. 1. Material removal mechanisms in grinding ceramic [7].



Legend

1. Linear slides
2. Grinding spindle
3. Microgrinding tool
4. Truing spindle
5. Truing wheel
6. Coolant Mist
7. Workpiece
8. Dynamometer

Fig. 2. Microgrinding experimental setup.

2. Experimental setup and pretest

A meso-scale grinding system is developed to conduct microgrinding in this study. As shown in Fig. 2, this system consists of four DC motor-driven linear slides, a high speed electrical spindle for grinding, an electrical spindle for truing and a mist generating device (COLUBRICATOR, UNIST Inc.). The DC motor-driven linear slides have a maximum load capacity of 133 N in the traveling direction. Its positioning resolution is 0.1 μm, and its positioning error is within 1 μm, calibrated by a laser interferometer. The runout of the grinding spindle and the truing spindle is within 1 μm. An oil based coolant (Coolube 5500) is sprayed onto the workpiece at 0.198 cc/min by the mist generating device during grinding.

A sintered nickel–copper bonded microgrinding tool is used in this study (see Fig. 3). Its diamond grit is 240, and the diamond concentration is 100. The microgrinding tool was trued to 850 μm in diameter by a ∅7.8 mm, 120 grit rotary diamond wheel. The spindle speed for the truing wheel was set at 20,000 rpm and the microgrinding tool was running at 60,000 rpm during truing process. Then, the end face of the microgrinding tool was trued at 5000 rpm to ensure end flatness. During dressing process, the microgrinding tool was dressed by a 220 grit alumina dressing stick to expose diamonds. Alumina (AD94 from Coorstek) is selected as workpiece material in this study, and its material properties are summarized in Table 1. Before microgrinding experiment, the workpiece was flattened by a ∅7.8 mm, 120 grit metal-bonded diamond grinding wheel at 70,000 rpm. During the experiment, straight slots are ground on the Alumina workpiece, as shown in Fig. 3(b). These slots are 6.35 mm in length and 0.85 mm in width.

In order to determine a proper methodology for modeling surface finish in microgrinding of ceramic materials, the ground Alumina surface texture is inspected by a scanning electron microscope. The sample Alumina workpiece is ground at 2 μm depth of cut, 90 mm/min feed rate, 60,000 rpm spindle speed and the total grinding depth is 24 μm. As shown in Fig. 4, the ground ceramic surface is composed of surface chipping region and ductile flow region. In the ductile flow region, there are visible cutting marks generated from cutting edge trajectories. The topography of the ground surface is inspected by a white light interferometer. As shown in Fig. 4, surface chipping has caused

Table 1
Properties of Alumina (AD94).

Property	
Elastic modulus (GPa)	303
Poisson's ratio	0.21
Density (gm/cm^3)	3.70
Hardness (GPa)	11.5
Tensile strength (MPa)	139
Fracture toughness K_{IC} (MPa m$^{1/2}$)	4–5

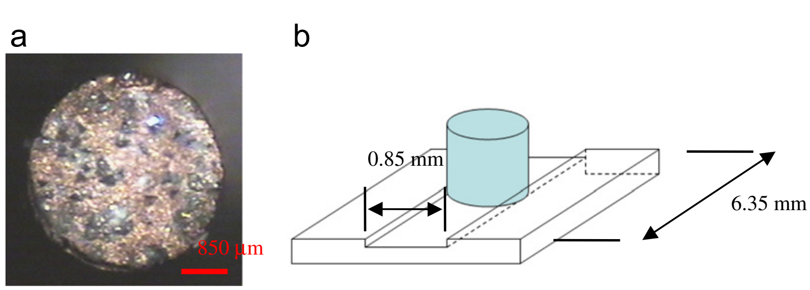


Fig. 3. Microgrinding operation (a) top view of the microgrinding tool and (b) end grinding configuration.