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Parametric experimental study and design of experiment modelling of sapphire grinding

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ABSTRACT

This study investigates and models the grinding process of single crystal sapphire. Five parameters: the wheel speed, the feed speed, the vertical feed, the ultrasonic assistance and the crystallographic direction were considered via a design of experiments (DoE) approach. The responses were multiple but can be divided in three groups: the process, the machine and the grinding quality. DoE results revealed that the parameters interact in a complex manner and depends on the responses. Therefore, to gain a better understanding of the grinding process of sapphire, the interactions between parameters have also to be taken into consideration. It was found that three main parameters have the largest influences on the tangential grinding forces: the wheel speed, the feed speed and the vertical feed. In contrast, the median defect area is mainly impacted by the quadratic effects of the wheel speed and vertical feed followed by various interactions. After an optimization procedure, the second optimum for the tangential forces was found to be very close to the best optimum for the median defect area. The optimum solution is: a wheel speed of 7′500 rpm, a feed speed of 60 mm/min, a vertical feed of 12.5 μm/pass, no ultrasonic assistance and grinding along the *c*-axis. This set of parameters was validated with additional and repeated tests on both Verneuil and Kyropouloas sapphire. Finally, it came out that the optimum solution has also a very good productivity.

1. Introduction

This paper presents an investigation of the grinding of narrow (approximately 0.45 mm wide × 0.45 mm deep) grooves in sapphire by means of a parametric experimental approach using the Design of Experiments (DoE) methodology. To guarantee the functional suitability of the finished product, the process of grinding these grooves in sapphire must meet the imposed geometrical and dimensional specifications; in particular it must preserve the sharpness of the surface edges of the groove and minimize any other collateral damage, such as median or lateral cracks at the bottom of the groove. To help meeting these requirements, while still achieving economically acceptable material removal rates, the effect of superimposed ultrasonic vibrations was also considered in this study.

To meet these requirements while achieving economically acceptable grinding times, we performed grinding experiments with a modified CNC 3-axes milling machine. The samples with ground grooves were analyzed using an image analysis program specifically developed to quantify various types of encountered defects. The quantified defects were then used to develop several semi-empirical models based on a 2^{5-1} fractional factorial DoE. The models served to characterize and optimize the grinding process in terms of groove quality and process efficiency. The set of optimized process parameters were validated on the basis of independent experiments. We also discussed the process models and the established optimum process parameters on the basis of contact and fracture mechanics principles to gain a more fundamental understanding of the sapphire grinding process.

Grinding is one of the oldest processes for processing/shaping hard materials and has been the subject of numerous investigations (Groover, 2010; Malkin, 1989). Yet, the influence of the many parameters affecting the process still remains poorly understood and

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modeled. The first attempts at characterizing the material removal rate (*MRR*) during grinding involved purely geometric/kinematics modelling for estimating the maximum chip thickness. The kinematics model of (Groover, 2010; Malkin, 1989) considers dependencies between the grinding wheel microstructure, the amplitude of the wheel-work piece relative motions, and the geometry of the grinding wheel. Although this is a simplified and idealized approach, it plays a major role in predicting surface quality (Agarwal and Rao, 2010; Mayer and Fang, 1995) and evaluating the material removal efficiency of the process (Agarwal and Rao, 2010). Because grinding involves material deformation and fracture and because some of its parameters unavoidably evolve with time, grinding models must consider the effect of applied forces and of tool wear, which significantly adds to their complexity. More advanced models assume that material removal occurs by microcracking (median and lateral cracks) and generation of chip fragments (Evans and Marshall, 1981; Malkin and Hwang, 1996; Marinescu et al., 2000). Energy considerations such as those first proposed by Preston in (1927) provide another approach for developing simple grinding models. Inasaki (1987) suggested using the specific grinding energy, *E*, as a characterizing parameter. In his model, which also incorporates a geometric/kinematics model, the specific grinding energy is expressed in terms of the tangential grinding force, the peripheral velocity of the grinding wheel, the workpiece translational velocity, the depth of cut and the width of the grinding wheel.

During the past decade, industrial needs have prompted many efforts in mechanistic modelling, simulation and even probabilistic modelling of grinding processes (Brinksmeier et al., 2006; Stepien, 2009). Unfortunately, none of these models is detailed and reliable enough to allow a model-based optimization of the industrial grinding process.

Ultrasonic assistance (USA) significantly changes the grinding mechanisms activated during the cutting process (Uhlmann and Spur, 1998). USA superimposes a vibratory motion on the conventional grinding kinematics. Benefits of USA to grinding include:

- A reduction of loads on the grinding tool and consequently of its wear rate (Brehl and Dow, 2008).
- A better surface quality for the workpiece with less sub-surface damages (Qu et al., 2000).
- An increased material removal rate (Pei et al., 1995).

Grinding is a process best suited for hard materials. The nature of the material of the workpiece greatly influences the mechanisms of chip formation and the resulting surface quality of ground parts (Tönshoff et al., 1992). Although numerous studies have been conducted to understand and model the behavior of brittles solids, such as glasses and polycrystalline ceramics, the literature is less comprehensive for single crystal sapphire. Experiments were performed on single crystal sapphire and showed a strong correlation between the Preston's coefficient and the workpiece roughness (Funkenbusch et al., 1998). More recently, classical types of surface deformations induced by abrasive machining, such as lattice deformation, strain and scratch were studied on sapphire wafer (Wen et al., 2008). Kim et al. (2003) demonstrated that maintaining the feeding force constant, instead of the feeding rate, allows minimizing defects in sapphire. Fundamental characterization of the material in (Inkson, 2000) highlighted peculiar behaviors during twinning or microcracking in Al_2O_3. These focused studies for specific materials do not provide a comprehensive understanding of the effect on grinding of various properties such as anisotropy of the sapphire, Young's modulus (*E*), fracture toughness K_{Ic}, and strength (σ_c), and sapphire production methods (Verneuil, EFG, and Kyropulos).

Section 2 of this paper presents the experimental procedure used for the investigation (USA grinding set-up, material used, defect analysis procedure), the DoE quadratic model, as well as the various responses analyzed.

Section 3 discusses the correlation between the process parameters; grinding forces and finished groove quality are selected as key process indices and the corresponding DoE models are then proposed and optimized. The two optimized models serve to determine the best optimum for the process parameters. We show that the optimum in terms of grinding force and material quality are very similar. Finally, the optimum model is validated by performing additional tests and comparing the new results to the results of all experiments. The validation is performed not only for the grinding forces and material quality but also for the specific material removal rate and the total processing time.

Section 4 discusses the models and their optimization based on contact mechanics and fracture mechanics principles.

Section 5 summarizes the findings of the investigation and shows that optimized grinding parameters can be selected that satisfies both surface quality and material removal rate requirements.

2. Experimental procedures and materials tested

2.1. Experimental setup and procedure

Fig. 1 shows the experimental set-up used in the investigation, a modified CNC 3-axes milling machine. In this set-up, the spindle with the grinding disk has the three translational degrees of freedom *x*, *y* and *z*, whereas the workpiece is stationary (Fig. 1a). An asynchronous electric motor drives the precision spindle by means of pulleys and a belt at speeds ranging from 1′000 to 22′000 rpm.

Experiments can be carried out with or without ultrasonic assistance (USA). The machine includes the following instrumentation:

1) Rotary encoders on the motors of the axes, from which the *x*, *y* and *z* motions can be derived;
2) An encoder to measure the rotational speed of the spindle;
3) A torque meter, mounted by means of two balanced flexible couplings between the spindle and the belt-and-pulley transmission to measure the grinding torque;
4) A waterproof dynamometric table to measure the thrust grinding force, from now on referred to as normal force[2].

Fig. 1b shows the arrangement used in experiments with USA. The specimen is glued on a holder mounted directly on the tip of the sonotrode generating the ultrasonic axial motion[3]. The US actuator consists of a Branson piezoelectric converter excited by an ultrasonic generator (Branson type 2000 b/bdc). The converter generates an axial sinusoidal motion with a controlled frequency of 20 kHz and is coupled to a booster designed to have a zero axial displacement node at the resonant frequency of 20 kHz and an amplification factor of 1,48. The displacement node on the booster permits mounting of the sonotrode system without transmission of deleterious vibrations to the rest of the CNC machine. This arrangement achieved a peak to peak maximum displacement of

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[2] Forces are measured with three subminiature sensors (XCF 205R from Measurement Specialties) placed in a triangular pattern underneath the platen of the table. Each sensor provides a measurement range between 0 and 20 N and a high rigidity of $9 \cdot 10^6$ N/m.

[3] The holder is mounted to the sonotrode with a bolt that allows an appropriate preload to avoid interface separation. A high strength glue is required to avoid spalling off of the specimen from the holder.