Superabrasive Grinding Process Optimization through Force Measurement

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Abstract

Several obstacles complicate the task of optimizing a particular superabrasive grinding process. Grinding wheel manufacturers provide valuable guidance in setting up a new process; however, there are numerous issues requiring better insight into machine setup and wheel selection. This paper presents a promising approach to investigating grinding brittle materials with superabrasives. In this work, a grinding machine is used with a specially designed air bearing spindle featuring embedded sensors calibrated for measuring grinding forces. The sensor output provides valuable feedback and is especially valuable in configurations that are not easily instrumented by other methods (such as ID, OD, and rotary grinding). In this article, an example is presented along with a brief review of the technical approach.

Introduction

The motivation for developing and building instrumented spindles is found in the many challenges facing the precision grinding community. Difficult materials, complex part geometries, and a wide variety of abrasive wheel types and coolants are found in every industry. Grinding process development is facilitated through the use of modern instrumentation and analysis tools [1-3]. Unfortunately, some of the most common grinding configurations, such as ID or OD grinding are difficult to instrument because of the rotation of both the workpiece and abrasive wheel. New commercial offerings of rotating cutting force dynamometers are available to measure the relatively large forces of milling (hundreds of Newtons), but there remains a need for a system suited to the light forces of precision grinding [4].

The instrumentation described in this article addresses the need for a precision grinding feedback system through the use of a spindle with embedded non-contact sensors that measure the relative axial motion between the rotor and stator. The advantage of using specially-calibrated displacement sensors to estimate grinding force is that the displacement is measured without introducing a compliant element into the structural loop. Using the known stiffness of the grinding spindle, force is computed without increasing the compliance of the machine.

This instrumentation approach allows efficient study of the grinding process with the benefit of an accurate and stiff machine tool. The air bearing spindles offer several additional characteristics favorable to grinding brittle materials including high speeds, high damping, and minimal synchronous and asynchronous error motions [5].

With this custom machine tool it is possible to measure and analyze a number of parameters critical to successful grinding with superabrasive wheels. It can also provide insight on the effect of a variety of operating parameters including wheel type, condition, and speed; dressing and coolant; workpiece properties; and machine characteristics including stiffness and damping. The instrumented spindle also detects the onset of grinding contact and grinding vibration, including chatter, and may offer valuable insight into mechanism of material removal during grinding.
Precision Grinding Machine and Spindles

Figures 1 and 2 show the plain way Moore grinding machine used in this testing. The grinding machine is outfitted with two Professional Instruments 10,000 RPM, motorized air bearing spindles. Customizable spindle mounting hardware allows a variety of grinding operations to be run, and both straight and cup wheels can be tested (typically 100 mm to 200 mm diameter superabrasive wheels are used).

![Figure 1. Instrumented Moore grinding machine.](image1)

The work spindle has embedded Lion Precision capacitance gages that sense relative motion between the spindle rotor and stator. The complications due to coolant and swarf contamination that arise when using capacitance gages are eliminated by sensing in the high pressure air film of the spindle. Figure 3 shows the important design features of the instrumented spindle used in this testing. The capacitance gages are embedded in the stator and target the thrust plate. The spindle features a spherical piloting wheel mount that allows interchanging of workpieces and grinding wheels with a repeatability of 0.1 microns. This allows for convenient off-line preparation and truing of workpieces and wheels, which can later be reliably mounted on the spindles for grinding. The piloting mounts are also used for interchanging wheels between grinding tests without the need for re-balancing.

![Figure 3. Instrumented spindle with lapped carbide piloting mount.](image3)

![Figure 4. Error map of the lapped spindle thrust plate.](image4)
Figure 4 shows the error map of the thrust plate that is removed from the capacitance gage output for calculation of the force measurement. The static stiffness of the spindle, along with the measured relative displacements between rotor and stator are used to estimate the grinding forces. The first structural resonance of the machine occurs at 300 Hz, so the usable bandwidth of the force measurement is approximately 75 Hz (one-fourth of the resonant frequency).

**Experimental Results**

Figure 5 shows the results of plunge rotary grinding a 150 mm silicon wafer with a 200 mm superabrasive cup wheel. The wheel spindle is running at 5825 RPM (62 m/s) and workpiece is running at 600 RPM with an infeed of 170 nm/s. Because of the alignment of the spindles, the forces steadily increase to 500 mN where the wheel is in contact with half of the wafer. The spectral content of the force measurement before contact of the wheel and workpiece (a) and during the grind (b) is shown in Figure 6. The waterfall plots clearly show workpiece speed (10 Hz) and its harmonics during the grind.

![Figure 5: Normal force and infeed while grinding silicon.](image1)

![Figure 6: Spectral content a) before contact and b) during grind.](image2)
In order to determine the quality of the surface finish obtained during the test, the specimen was examined with a Nomarski microscope and an SEM. A surface finish with grinding marks typical of those produced with rotary grinding were found on the specimen [6]. The surfaces shown in Figures 7 and 8 had an average roughness of $Ra = 18\ nm$.

![Figure 7. Nomarski microscopy picture of ground surface.](image1)

![Figure 8. SEM picture of ground surface.](image2)

**Conclusion**

This paper describes an instrumented grinding machine that features an air bearing spindle with embedded capacitance probes used to measure grinding forces in applications that cannot be instrumented with traditional techniques. The machine is well suited for grinding model verification because the instrumentation is tightly coupled to a high performance spindle and machine tool. This combination allows measurement of subtle, yet high frequency phenomena in the grinding process.

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**References**