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Force characterization of micro grinding in zirconia

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Abstract
This study explores the viability of mapping certain machining parameters to measured normal force in zirconia grinding. The work is specifically focused on very low material rate grinding in which the rubbing and plowing components of grinding force are significant compared to the actual cutting force. A design of experiments is performed to see how the machining parameters relate to the measured normal force. It is determined that cutting length best scales with grinding force. Using this and the equivalent chip thickness, the data reveal a power regression relationship that estimates the grinding force within the design space of the tested parameters.

Grinding, force measurement, manufacturing, micromachining

1. Introduction

The literature contains many successful efforts to build models capable of estimating grinding force. The past work includes a comprehensive range of experimental work used to inform and verify several grinding force models. One of the very clever and useful breakthroughs in the development of these models was the introduction of an equivalent chip thickness that may be used to compare and often generalize results obtained by different research groups.

In this work, we sought to revisit the specific niche of grinding at very low material rates, as characterized by micron-level depths of cut and conspicuously slow feed rates (often limited by tool breakage considerations). Such small cuts tip the balance of the components of grinding force away from actual cutting towards rubbing and plowing. This added force doesn't result in the removal of material but does interact with the machine compliance to cause a relatively more significant difference between programmed and actual depth of cut (DOC). In general, the actual DOC is smaller than the programmed DOC because of compliance in the machine tool. In circumstances requiring a small amount of material to be removed from a workpiece, the geometry may more quickly converge upon the correct form by knowing something about the grinding force and its interaction with the machine compliance. This paper discusses early work to model grinding force in zirconia in preparation for the larger task of predictive CNC programming to achieve a particular workpiece geometry.

2. Equivalent chip thickness

The equivalent chip thickness is known to be a convenient and accurate predictor of grinding force, as first suggested by Snoeys and Peters [1]. They demonstrated how the equivalent chip thickness or h_{eq} is critical to comparing grinding data collected under differing grinding parameters. Rowe and others later introduced the contact length and deflected contact length to further parameterize grinding parameters [2].

3. Methodology

A number of low material removal rate grinding experiments were carried out on a Moore Nanotechnology Systems UPL 450 lathe. The grinding spindle was a Professional Instruments ISO 50 000 RPM ultra-precision air bearing spindle. The wheel was Ø10 mm diameter, 320-grit vitreous metal-bonded diamond. The zirconia was mounted to a Kistler dynamometer and both the high speed wheel and zirconia were trued and dressed in assembly. A design of experiments (DOE) was carried using a large range of grinding parameters with the depth of cut (DOC), the stepover (*st*) and feedrate (v_w) as the independent grinding parameters.

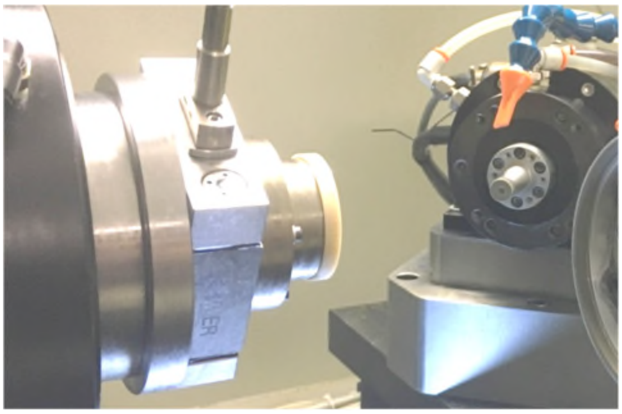

Figure 1. Setup for grinding samples in the Moore Nanotech 450 UPL. [Left] Professional Instruments ISO 5.5 work spindle with zirconia and dynamometer assembly. [Right] Professional Instruments 60kRPM grinding spindle and wheel.

4. Results

The data were analyzed by plotting the force per unit volume versus the material removal rate (MRR). The results demonstrate the increased force per unit volume in the smaller range of the observed MRRs. This can be attributed to the increased rubbing of the wheel relative to the material removed.

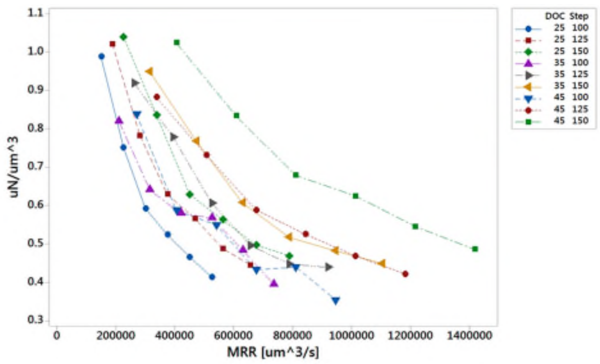

Figure 2. Plot of force per unit volume vs MRR grouped by the DOC and stepover. The feedrates in each group increase from left to right.

Analysis confirmed the well-known relationship between DOC, stepover, and force. Therefore, the plots can be further improved by taking the force per unit volume and further normalizing by the theoretical contact length l_c. This results in the quantity described as force per unit volume by contact length against the equivalent chip thickness per stepover.

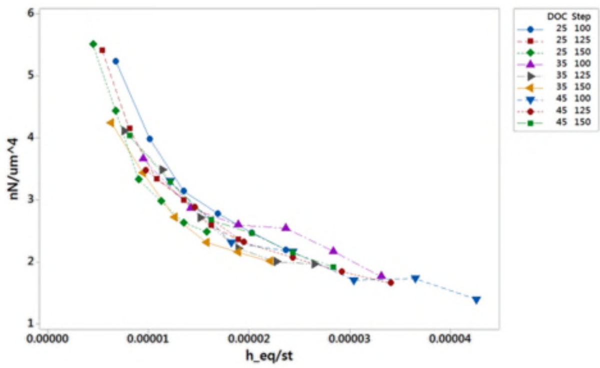

Figure 2. Plot of normalized grinding force vs normalized equivalent chip thickness grouped by the DOC and stepover. The feedrates in each group increase from left to right.

The normalized data plotted in Figure 2 fall close to a simple power relationship with nicely satisfying integer and rational powers. Further agreement can be had by allowing slight changes in the coefficients. In fact, if the normalized equivalent chip thickness is raised to the 0.65 power (instead of unity) the measured force data fall into line, as shown in Figures 3 through 5. This model has not yet been tested with other coolants, grinding wheels or workpiece materials.

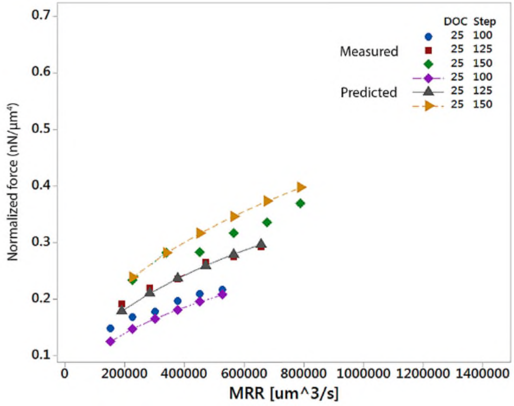

Figure 3. Predicted and measured normalized force at DOC = 25 um.

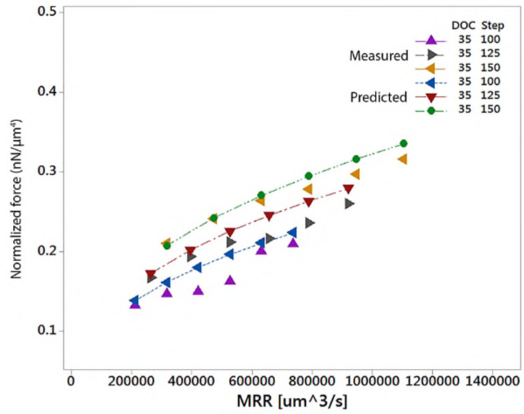

Figure 4. Predicted and measured normalized force at DOC = 35 um.

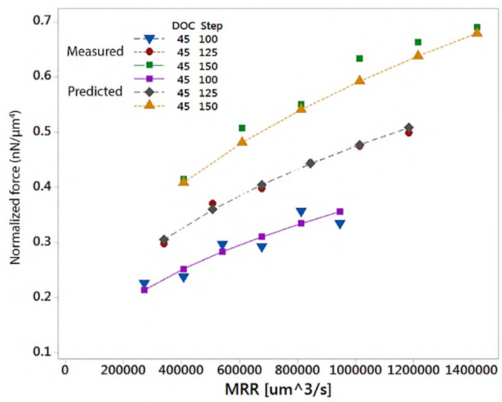

Figure 7. Predicted and measured normalized force at DOC = 45 um.

5. Conclusion

A slightly modified grinding force model may provide expanded predictive capability when grinding at very low material removal rates. Such a model may be useful in such cases where rubbing and plowing friction contribute significantly to the measurable normal grinding force. Substantial work remains to explore the accuracy of the model in a wider range of machining parameters and materials. Of course, the model does require preliminary tests for any given combination of workpiece and wheel and does not approach the utility of more general grinding models previously reported in the literature. That said, the work shown here suggests that at least some predictive capability may be possible in cases of the lightest cuts in lowest material removal rates.

References

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