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Effects of machine compliance in micro-grinding

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Abstract
This work seeks to identify, model, and compensate for machine compliance in tungsten carbide mould manufacturing. The machine compliance, including the spindle and tool, is characterized by direct measurement as well as cutting trials. This information will be used to create a grinding force model that may be used in the manufacturing of moulds with complex geometry.

This task is complicated by the fundamentally three-dimensional nature of the mould geometry. An adequate compliance model must capture the full 3D characteristics of the machine/tool compliance in order to achieve some measure of success. Furthermore, the relationship between cutting force and material removal is decidedly nonlinear at micron-level depths of cut. This must also be captured to control workpiece form error.

This work approaches the modelling task using observations made in a series of micro-grinding trials that span a wide swath of the cutting parameter space for micro grinding. We also will collect data on the role of machine/tool compliance. These results will guide the formulation of a model for compensating for machine compliance using cutting force as the primary monitoring signal.

Grinding, process modelling, precision machining

1. Background

Tungsten carbide mould manufacturing is a process that involves a small radius grinding tool and extremely long machining time. Creation of a machine compliance model for this process have far reaching implications, but requires extensive cutting tests. Additionally, comparison of the results of various grinding parameters to characterize precision manufacturing processes is nontrivial. The analysis of these conditions especially when using a small-radius grinding tools, requires scrutiny of in situ and post machining data. There is also significant lack of literature regarding small radius grinding and exploration in the area is largely based off of qualitative observation. Research in the area is limited to the expense of creating the small radius tools as well as the increased potential for breaking the tools while testing. Characterization of the grinding process is the first step to identifying the compliance during manufacturing. The results of this study can lead to drastically decreased manufacturing times as well as an increase accuracy.

2. Testing and Equipment

The Machine Dynamics Research Lab (MDRL) at Penn State is uniquely suited to conducting the tests required to build a compliance model for small radius grinding. The cutting tests are conducted on a Moore Nanotech 350+ UPL (Ultra-Precision Lathe), instrumented with a specialized dynamometer for measuring small forces. The cutting tool is mounted on a high-speed ultra-precision Professional Instruments 50k air-bearing spindle. For the purpose of this study, a wide breadth of grinding parameters need to be considered. To accomplish this, a Design of Experiments (DOE) is conducted to explore the effects of various parameters on the in situ and post machining results. The features produced are sequential patches of increasing depth of cut (DOC) and each set of patches is utilizes a different combination of wheel rotational speed, traverse speed or feed (linear pass of the wheel) and stepover (distance between passes of the wheel). For these tests the wheel speed is 30k – 45k rpm, the traverse speed is 5 – 20 mm/m, and the step over is 15 um to 45 um; all conducted at cuts ranging from 1 to 20 um. Each of these parameters largely result in varying of the material removal rate (MRR). The machining set up is shown in Figure 1.

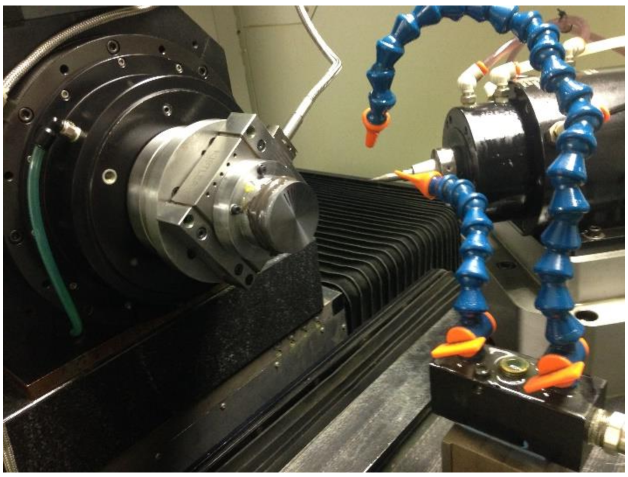

Figure 1. Workpiece with dynamometer and high speed spindle.

3. Normalization

To compare the in situ forces between varying grinding parameters, an "equivalent chip thickness" must be determined. This is a means of normalizing the data. While there is much documentation on the equivalent chip thickness for cylindrical grinding processes, there is little on small radius grinding processes. Normalizing data for cylindrical grinding processes is simplified because of the geometry and comparatively large features involved. To normalize the data, requires precise knowledge of the MRR, which, for the geometries and grinding parameters, is nontrivial. To illustrate the MRR of a set of cutting parameters per revolution of the wheel while grinding a detailed CAD illustration is provided in Figure 2. The volume of the "scallop" shown in the figure can then be determined using a series of numerically evaluated surface integrals, each with parameters specific to the conditions of the individual grind. The grinding parameters are normalized with the resulting MRR (Equation 1) resulting in a quantity with the units of volumetric impulse.

$$Volumetric_{Impulse}\left[\frac{mNs}{um^3}\right] = \frac{Force_{normal}[mN]}{VRR\left[\frac{um^3}{s}\right]} \quad (1)$$

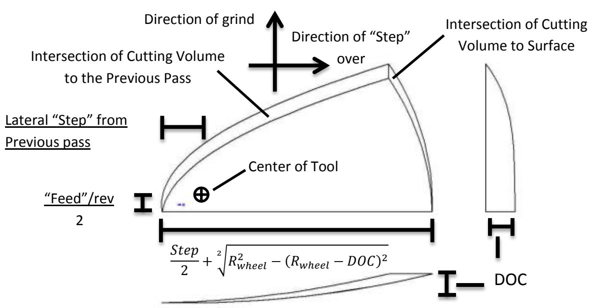

Figure 2. Detailed view of the material removed per revolution

4. Results

When comparing the force traces for each individual pass, there is a very large scatter without regular patterns between the grinding parameters, except for the nonlinearly increasing normal force as the DOC increases. However, when the data is normalized, the volumetric impulse for each set approach similar values as the MRR increases, despite different grinding parameters. These values, for the larger MRRs, are analyzed by the interaction plot shown in Figure 3.

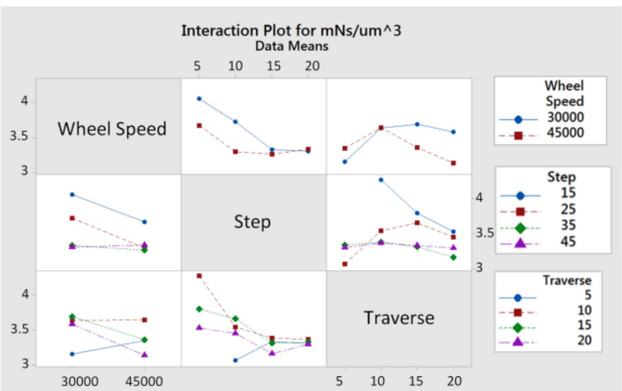

Figure 3. Interaction plot of grinding parameters at high MRR (>25k um^3/s)

For small DOC's, the rubbing interaction between the wheel, the workpiece and the cutting fluid becomes significant and the results of the grind become imprecise. For that purpose, those values were excluded in the creation of Figure 3. Despite the drastic differences in grinding parameters between the sets, the volumetric impulse of the passes are largely grouped within a small range ~3 – 4 mNs/um^3. This demonstrates the relative invariability of the volumetric impulse with the differing parameters at the higher MRRs.

To examine the accuracy of each grind, the depth of the cut was compared with the real programmed depth of cut, resulting in a parameter, d (or deviation from the programmed DOC). To analyze these results statistically, this value was then divided by the square root of the real DOC. This created a composite value that was independent of the DOC and allowed the separate data sets to be compared. These values are then interpreted using an interaction plot shown in Figure 4.

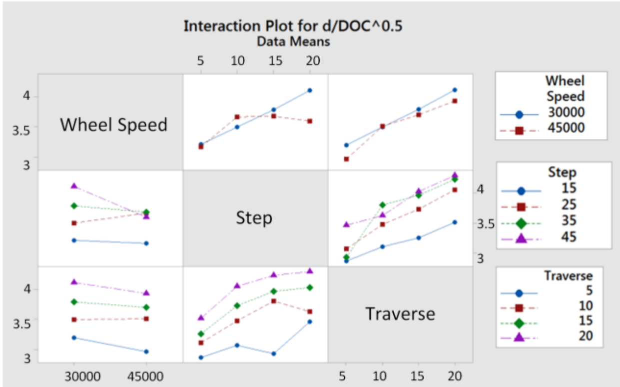

Figure 4. Interaction plot of deviations at high MRR (>25k um^3/s)

Intuitively, these trends are normal. Looking at the interaction of the traverse, the deviation increases as the traverse increases in all cases. There is some increase of the data means as the step increases as well. It is interesting to note that there is little difference in the data means as the speed of the wheel is changed.

5. Conclusion

These results lay the groundwork for the characterization of a machine compliance model for the small radius tool grinding. It is exciting that the results corroborate previous qualitative observations regarding smaller DOCs and poor, unpredictable results. It is also encouraging to see that the MRR can be increased without increasing the normalized normal grind force (volumetric impulse), which could allow for the drastic decrease in manufacturing times. It is also encouraging that the parameters affect the deviation of the grind in a predictable manner. Further research will result in applying these results to the results of machine compliance to evaluate the effects on accuracy and quality of surface.

References

[1] R. Snoeys and J. Peters 1984 The significance of chip thickness in grinding