Structured Surfaces Damping Enhancements at Mechanical Interfaces

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The development of high-power, high-speed machine tools has lead to a practical need to predict, enhance and control regenerative chatter. While techniques such as tool tuning have been used to significantly enhance machining stability in high-speed machining, increasing system damping is a more effective means of enhancing the overall stability of the machining system. However, the damping properties of machine structures are extremely difficult to predict or control because it depends strongly on the microscopic contact conditions at the mechanical interfaces in the system. We aim to design structured surfaces that intentionally create contact conditions that enhance the damping and the dynamic repeatability of the mechanical connections in a machine tool without compromising the kinematic repeatability and accuracy. This will result in increased stability, productivity and machine utilization.

Determining the cause of the variation in dynamic stiffness between nominally identical unaltered toolholders presents a significant challenge in itself. In order to better understand the spindle – toolholder dynamic interactions, three toolholders were placed into a control group and analyzed. Two toolholders were AT-4 fit class and one toolholder was AT-5. The Frequency Response Functions (FRF) of the two AT-4 toolholders, nicknamed Frick and Frack, were compared from impact modal tests in the Spindle Test Stand (STS) with a 34.1 kN drawbar load.

These two toolholders, Frick and Frack, which look nominally the same, differ in weight by less than 0.01 %, and differ in natural frequency by less than 0.6 %, differ in damping ratio by more than 54 %. Their dynamic stiffness also differs by around 52 %. Small changes in damping ratio yield large changes in dynamic stiffness. Since no alteration was made to the contact surface of the toolholders and they were both tested in the same spindle nose with the same drawbar load, the difference in dynamic stiffness must come from the geometry of the toolholders themselves. The geometry of the tapers of the two toolholders was measured, revealing lobing of the taper consistent with parts that were OD ground. Since the toolholders can be inserted into the test stand in two orientations (at 0 degrees and rotated 180 degrees) dynamic measurements were taken in both orientations. Both toolholders proved to have preferred orientations in the spindle test stand resulting in more repeatable results across consecutive measurements than their alternate insertion orientations.

Additionally, an AT-5 fit class toolholder was tested to establish its baseline FRF and then its tapered surface was altered on a micro level using a fine grit sandblast. The surface was iteratively sandblasted and surface texture and FRF measurements were taken three times. The sandblast resulted in a change in surface texture measured by an 18% increase in Ra, 11% increase in Rq, 4.8% increase in Rmax, 6.5% increase in Rz, and a 42% more negative skew than the original surface. A two factorial experiment was designed to test the effects of drawbar load, orientation, and surface (before and after sandblasting) on the first natural frequency (cantilever bending mode) and damping ratio. The experiment showed qualitatively that the drawbar load had a statistically significant effect on the natural frequency. The experiment also showed qualitatively that the drawbar load had an effect on the damping ratio. These experiments again showed a preferred orientation of the toolholder in the spindle resulting in more repeatable results across consecutive measurements. These results statistically verify the earlier work of Smith and Jacobs (2000).

Table 1. AT-4 CAT 40 toolholders.

<table>
<thead>
<tr>
<th>Toolholder</th>
<th>Natural Frequency</th>
<th>Damping Ratio</th>
</tr>
</thead>
<tbody>
<tr>
<td>Frick</td>
<td>2100.0 Hz</td>
<td>0.46 %</td>
</tr>
<tr>
<td>Frack</td>
<td>2089.5 Hz</td>
<td>0.72 %</td>
</tr>
</tbody>
</table>

Figure 1. CAT 40 toolholder with altered contact surface.
Fabrication of structured surfaces and evaluation of the contact between two surfaces is difficult enough without the added complexity of the two surfaces comprising the spindle-toolholder interface being conical. In order to simplify this problem, it was decided to investigate the effects of structured surfaces on the contact interaction of two flat, parallel surfaces. In essence, this simplified configuration gives a cut-away look at the spindle-toolholder interface during the experiments. Once candidate surfaces have been identified and their effects documented in the 2-D test stand, they can then be replicated on toolholders and tested in the STS and machines.

The 2-D surface test stand was designed to focus on the contact interaction be the two surfaces while mimicking the conditions seen in the spindle-toolholder interface in a machine tool. In a machine tool, toolholders are placed in the spindle and held in place with a drawbar. This introduces a load that elastically deforms the surface of the toolholder. We chose to replicate the contact pressure at the interface between the spindle – toolholder combination. To do so, the area and loading method were designed so that these contact pressures could be easily replicated using a loading bolt as shown in Figure 2. Another important loading consideration was uniformity of the loading. We hypothesize that the cause of the increased dynamic stiffness seen with the original altered toolholder was that the surface had somehow enhanced, exaggerated, or caused the onset of stick-slip friction at the interface. If this is true, then non-uniformity in the loading would change the behavior of the interface and not isolate the effects of the structured surface.

Choice of material was also driven by the interface we were trying to replicate. Toolholders and spindle noses are commonly made from AISI 8620 steel case hardened at 58 – 60 HRC to 1.5 – 2.0 mm deep. The surface samples and test stand therefore were made from AISI 8620 steel. Case hardening of the entire flexure was not desirable since it would make future machining for fixturing extremely difficult and would cause non-uniform deflection of the arms with load application since the shell of the arms would be harder than the core. Therefore, the contact portion of the flexure was cut first with the wire EDM (WEDM), and the remainder of the flexure was coated with copper to prevent carbon from leaching into surfaces that were not intended to be hardened. The flexure was then carburized, hardened, and final WEDM of the flexure was completed. The rest of the features were machined and a final pass was made on the contact surfaces with the WEDM. This resulted in a completed test stand with a case hardened contact area.

Loading and unloading of samples also made it necessary for the test stand to actuate. Since we planned to characterize the surfaces with dynamic excitation, we also needed a way to load the samples in nominally the same location every time and have no contact interfaces besides the one under consideration in the metrology loop. All these considerations led us to a flexure design for the surface test stand, dubbed the Flexural Test Stand (FTS). A flexural design allowed for uniaxial actuation with no interfaces in the test stand thus fulfilling all the requirements set earlier. A picture of the FTS is shown in Figure 2 below.

Measuring the load applied to the sample is done with a strain gage load cell. Since the load cell could not be placed between the clamping arms of the test stand and the sample, a calibration had to be done between the load it measures through the flexure and the load actually applied to the sample. A second strain gage load cell was calibrated to the one used in the test stand in a separate fixture. The load cell was placed in the test stand and the second load cell was placed in the contact area. The output of the first load cell was then calibrated to the output of the second load cell. In this way, the output of the load cell in the test stand is calibrated to reflect the load actually applied to the samples. The calibration curve is show in the figure below.

The experimental surfaces being tested range from macro geometric features with size scales on the order of millimeters, to micro texturing with size scales on the order of micrometers characterizable in terms of surface finish. The operating assumption

![Figure 2. Flexural Surface Test Stand.](image)
of this project is that a given surface exists, which may be a combination of surface finish and macro geometry, resulting in a maximum dynamic stiffness, for a given clamping load, in the frequency range of interest. Several test surfaces have been fabricated with macro geometric feature sizes from 10 millimeters to 1 millimeter.

The samples all have surface roughness of approximately 0.3 microns Ra. A stitched surface roughness scan of one of the samples from a white light interferometer is shown in the figure above. This sample is the 2-D version of the surface applied to the toolholder in figure 1. A 6 millimeter diameter ball-nose end mill was used to create dimples 1 millimeter deep in the surface of the sample.

Alteration of the contact surface in the spindle – toolholder interface has been proven to effect the dynamic stiffness of the system. During the last year, the focus has been on determining the optimum surface for damping enhancement at the spindle – toolholder interface.