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Simulating the Effect of Modulated Tool-Path Chip Breaking on Surface Texture and Chip Length

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Abstract

One method for creating broken chips in turning processes involves oscillating the cutting tool in the feed direction utilizing the CNC machine axes. The University of North Carolina at Charlotte and the Y-12 National Security Complex have developed and are refining a method to reliably control surface finish and chip length based on a particular machine's dynamic performance. Using computer simulations it is possible to combine the motion of the machine axes with the geometry of the cutting tool to predict the surface characteristics and map the surface texture for a wide range of oscillation parameters. These data allow the selection of oscillation parameters to simultaneously ensure broken chips and acceptable surface characteristics. This paper describes the machine dynamic testing and characterization activities as well as the computational method used for evaluating and predicting chip length and surface texture.

Introduction

Continuous chips are problematic in nearly all types of turning applications by causing a loss in productivity, surface degradation, and safety hazards. Glove box materials, such as depleted uranium, are especially hazardous since they are pyrophoric which causes a fire hazard when a tangled nest forms from long, stringy chips. Controlling the chip length with these materials is not only important due to the previously mentioned reasons but also vital to the safety of the operator and surrounding workers. With modulated tool-path turning operations, broken chips can be obtained by choosing parameters that create varying chip thickness along the cut and allowing thickness to reach a zero value, which creates a chip breaking tool-path (Smith 2009). The parameters that influence the chip length are spindle speed, global feed rate (fr), the number of oscillations of the tool per work piece revolution (OPR), and the ratio of the oscillation amplitude of the tool compared to the global federate (R_{af}). When the oscillation of the tool is phased correctly with the revolution of the spindle, there will be a point where the chip thickness reaches zero. If the correct parameters are not chosen, the tool-path can align to the same position as the previous rotation of the spindle and will create a continuous chip. Figure 1 below, shows examples of two sets of chip breaking parameters. The blue line, oscillating at 4.5 hertz is phased correctly where the chip thickness reaches zero, creating a broken chip. The red line is a modulated tool-path at 5 hertz; however, it still creates a continuous chip.

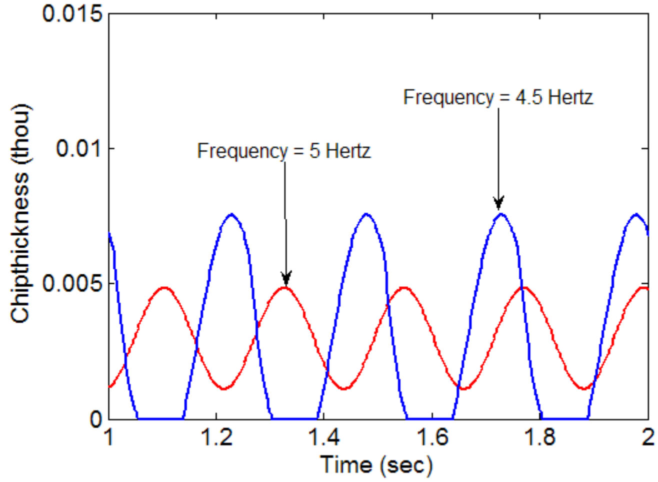

Figure 1: Chip Thickness vs. Time

Chip Length Simulations

By determining the amount of time that the tool is engaged in the cut, the chip thickness, and the feed rate, the resulting chip length can be derived for any set of oscillation parameters. A simulation was developed utilizing MATLAB that can predict the resulting chip length based on oscillation amplitude, OPR, and the diameter of the material for each cut. This simulation is shown in Figure 2.

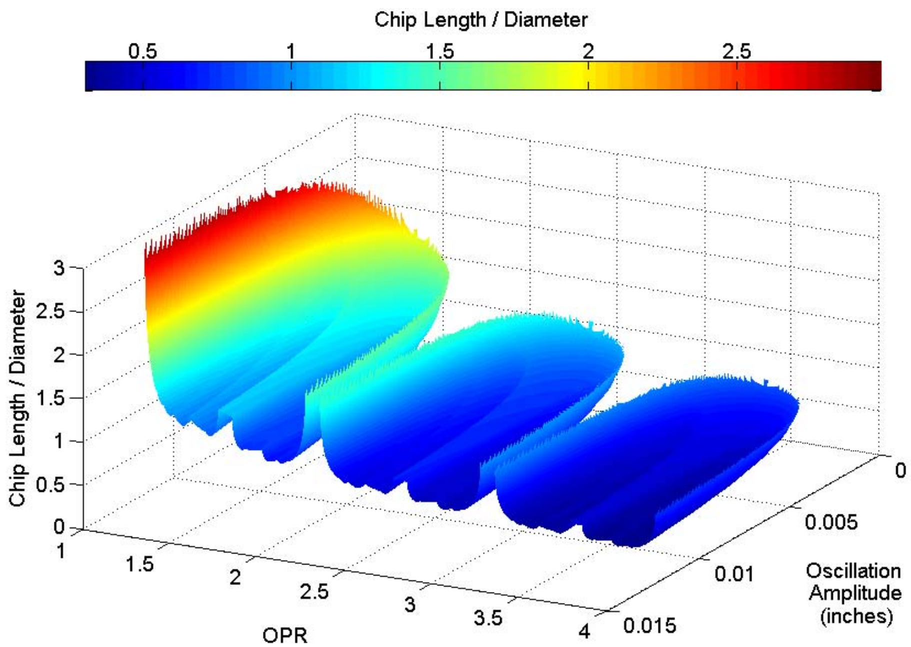

Figure 2: Three Dimensional Chip Length Simulation

Each point on the graph represents a single set of parameters that can be used for a chip breaking tool-path. To determine the chip length, the Z axis value on the graph needs to be multiplied by the diameter of the material that is being cut. When viewing the simulation from the top, as shown in Figure 3, it is apparent that the chip length has a mirror trend at every integer value of OPR, but with decreasing chip length values as the OPR increases. The white areas in the graph are the parameters where the phase shift of the tool oscillations and the spindle revolutions are aligned so that the chip thickness does not reach zero and a continuous chip is formed.

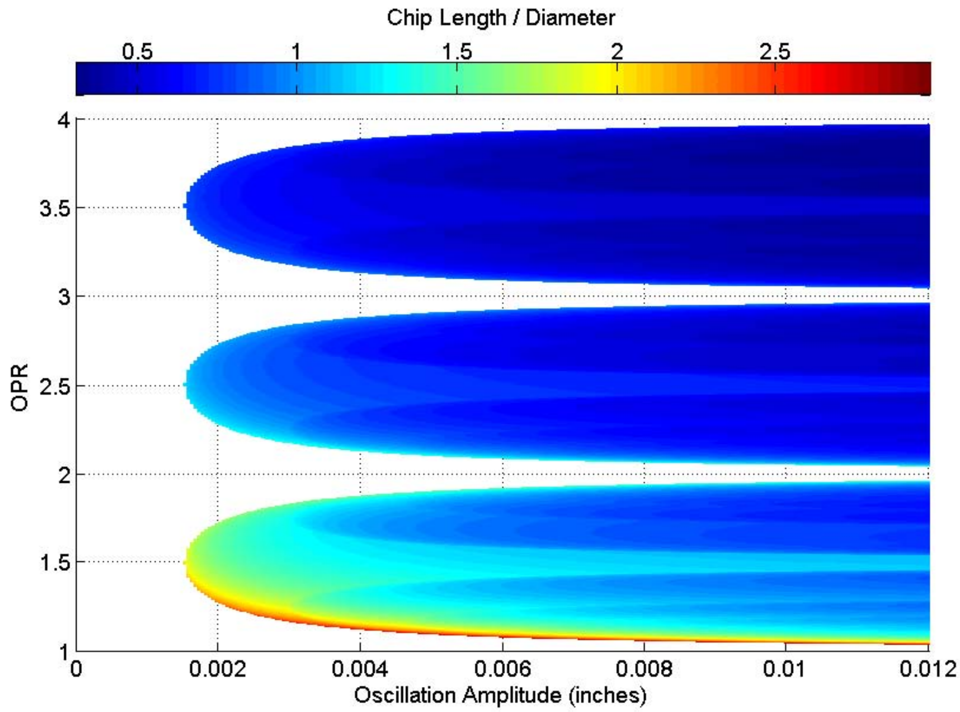

Figure 3: Top View of Figure 2.

Surface Simulations

Using a computer simulation developed with MATLAB, it is possible to predict surface characteristics generated from a modulated tool-path in turning applications. In order to simplify the simulation, it was assumed that the machine tool does not experience any backlash/reversal errors, out of plane errors, or deflections due to cutting forces. Although these errors exist in real machines and can significantly affect the surface finish, the simulations still provide a reasonably close representation of the measured physical parts. Each cutting parameter in a modulated tool-path, including oscillation amplitude, the number of oscillations per work piece revolution (OPR), global feed rate, and tool geometry all directly affect the resulting surface finish. OPR is a combination of spindle speed and oscillation frequency and can be expressed by the following

$$\text{OPR} = 60\omega/n \qquad \text{(EQUATION 1)}$$

where ω is the oscillation frequency in Hz, and n is the spindle speed in revolutions per minute. Depending on the oscillation parameters selected, it is possible to create an extremely wide range of different surface geometries. An example of one particular surface type generated from modulated tool-path chip breaking is shown in Figure 4. The predicted surface profile of the hemisphere is shown in Figure 5.

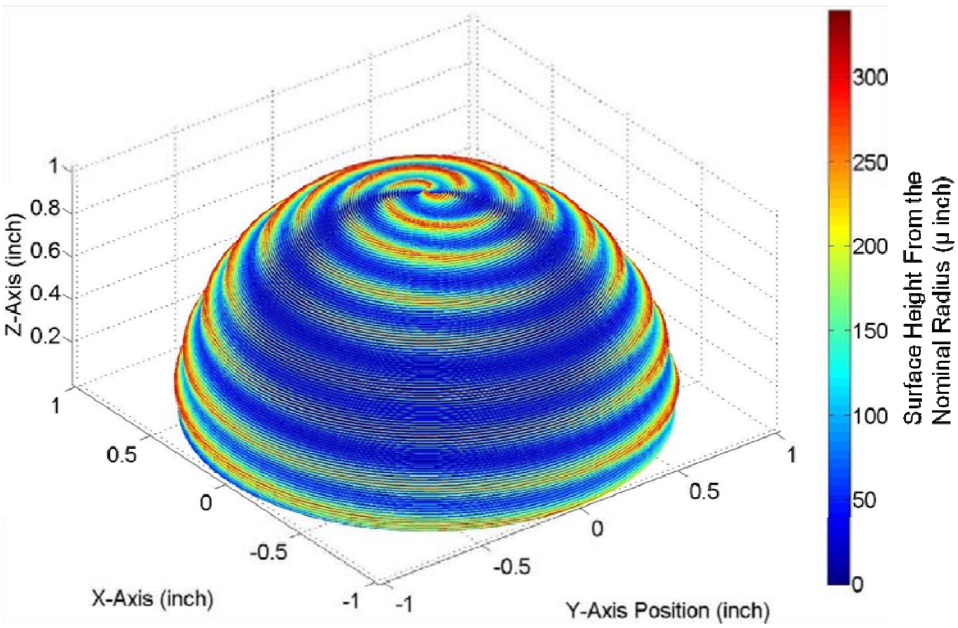

Figure 4: Three Dimensional Surface Model of a Hemisphere with Surface Features Exaggerated, and Color Coded for Clarity.

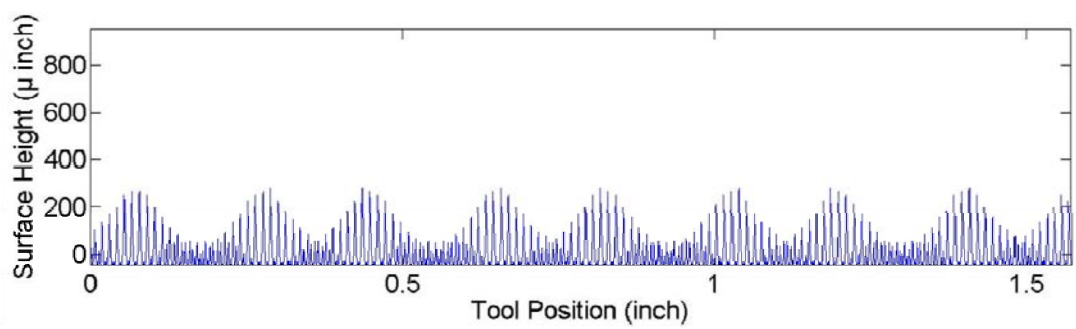

Figure 5: Predicted Surface Profile of Figure 4 Hemisphere Measured From Equator to Pole.

Due to the nature of modulated tool-paths, nearly all surfaces generated have a raised thread-like spiral similar to that shown by the red portions in Figure 4. This results in characteristic wave features as shown in the predicted surface profile of Figure 5. Despite a max peak-to-valley height of over 300 µin, the surface texture is only 44 µin (for the context of this paper, surface texture is the absolute arithmetic mean of the surface height normal to the nominal part surface). The work piece quality is determined by the magnitude and wavelength of the perturbations in the work piece surface.

Therefore it is necessary to understand the impact of different combinations of modulated tool-path process parameters on the work piece profile and surface texture.

The computer simulation is also used to analyze the theoretical surface texture values for an array of different oscillation parameters. For a given global feed rate and tool geometry, the surface texture is plotted versus OPR and oscillation amplitude. These plots help to show the correlation between an array of individual oscillation parameters and their resulting surface texture values. Figure 6 displays the surface texture correlation for oscillation amplitudes ranging from 0.000 inches to 0.012 inches, an OPR ranging from 0.0 to 3.0, a global feed rate of 0.003 inches per revolution, and a tool nose radius of 0.031 inches.

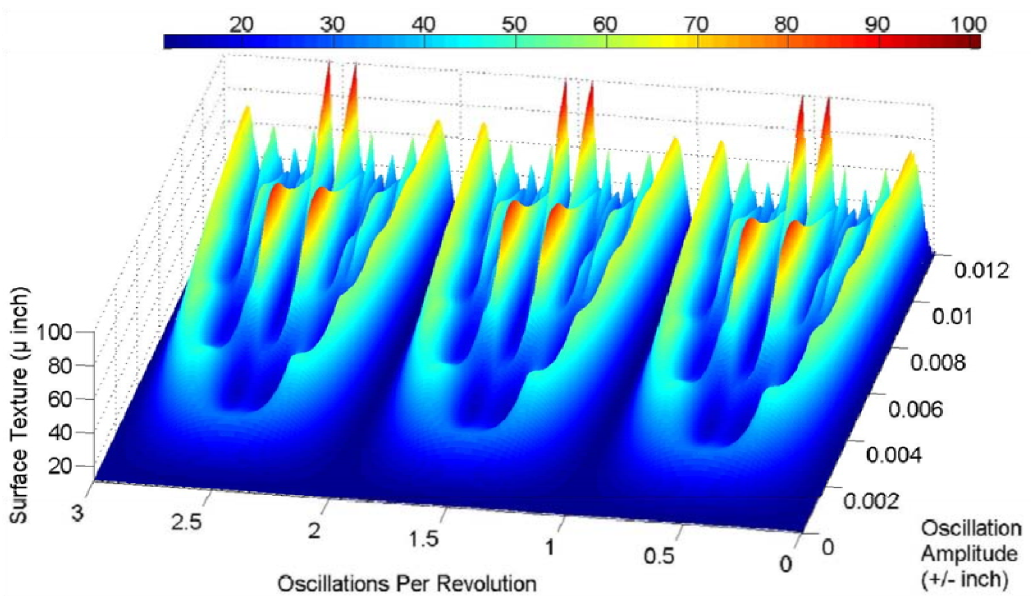

Figure 6: Surface Texture Versus OPR and Oscillation Amplitude.

The correlation of surface texture to the oscillation parameters determined using the computer simulation reveals some very interesting phenomena. The surface from 0.0 OPR to 0.5 OPR in Figure 6 is exactly reproduced every subsequent half integer of OPR. This is particularly important for applications that are not concerned with very short chip lengths, whereas shorter chip lengths occur at higher OPR. For such applications, it is only necessary to choose oscillation parameters from 0.0 OPR to 0.5 OPR. Any surface texture value that can be obtained with higher frequencies can be obtained within this small range of oscillation parameters. In related applications using external oscillating devices such as (Moriwaki 1991), the oscillation frequencies may be much higher than those described in this paper (reaching 40 kHz and higher). For spindle speeds less than 1000 RPM, the required oscillation frequencies in the range of 0.0 OPR to 0.5 OPR are less than 10 Hz. Figure 7 shows a top view of a section of Figure 6.

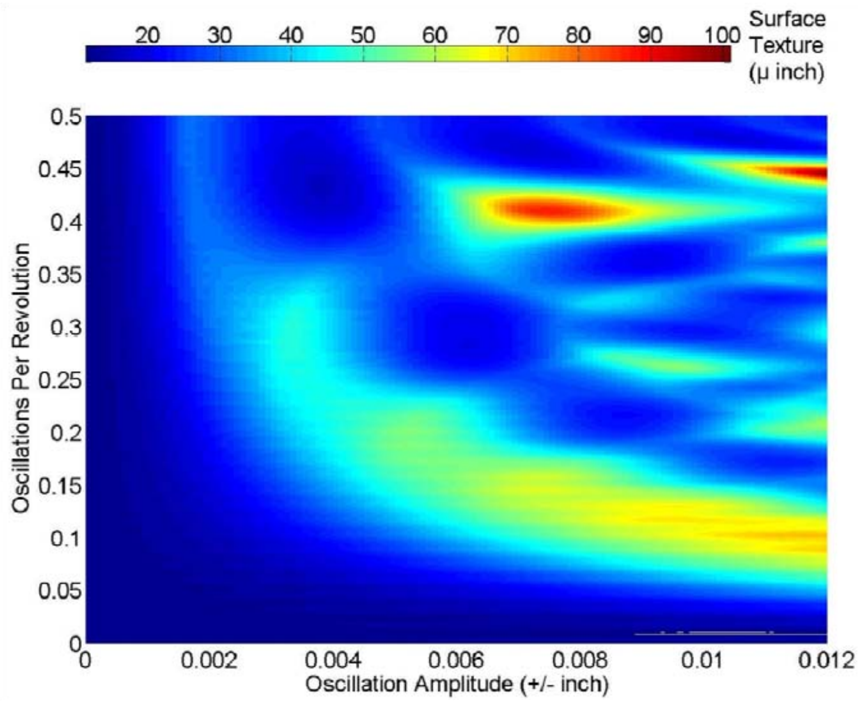

Figure 7: Top View of a Section of Figure 6.

The lowest surface texture values occur in the dark blue regions of Figure 7. In this case, the darkest blue regions are in the left and lower edges of the figure, and are areas where the OPR and/or oscillation amplitude is so small that chip breaking does not exist. Essentially, these regions represent the surface texture value obtained from traditional turning methods. This figure shows that with modulated tool-path chip breaking, it is possible to choose oscillation parameters that will obtain surface textures which nearly match, but never surpass, surface textures obtained from traditional turning methods.

Experimental Validation of Surface Simulations

Several diamond turning tests were conducted to experimentally validate the computer simulations. Typical diamond turning applications utilize very low feed rates; however, this experiment was intended to replicate the finishing passes for conventional tool room CNC lathes and was conducted with a feed rate of 0.0025 inch feed per revolution. With the diamond turning machine, it was possible to minimize the surface affects associated with machinability issues and positioning errors and therefore a greater similarity was observed between the predicted models and the experimental results. The experiment also utilized a constant spindle speed of 300 RPM, a 6061 aluminum work piece, and a diamond tool with a 0.020 inch nose radius. Two distinctly different sets of oscillation parameters were chosen for testing. The first set was intended to validate the predictions of several distinctly structured surface finishes, while the second set of oscillation parameters was intended to validate various low surface texture predictions. The test surfaces were measured using a stylus type profilometer, and they show agreement with the predictions. The mean deviation from predicted texture values over 14 tests was only 3.93 µin. Figure 8 shows the results obtained by inspecting the face, tapered, and cylindrical sections of the work piece. Figure 9 shows the predicted and measured surface profiles obtained by inspecting one cylindrical section of each work piece.

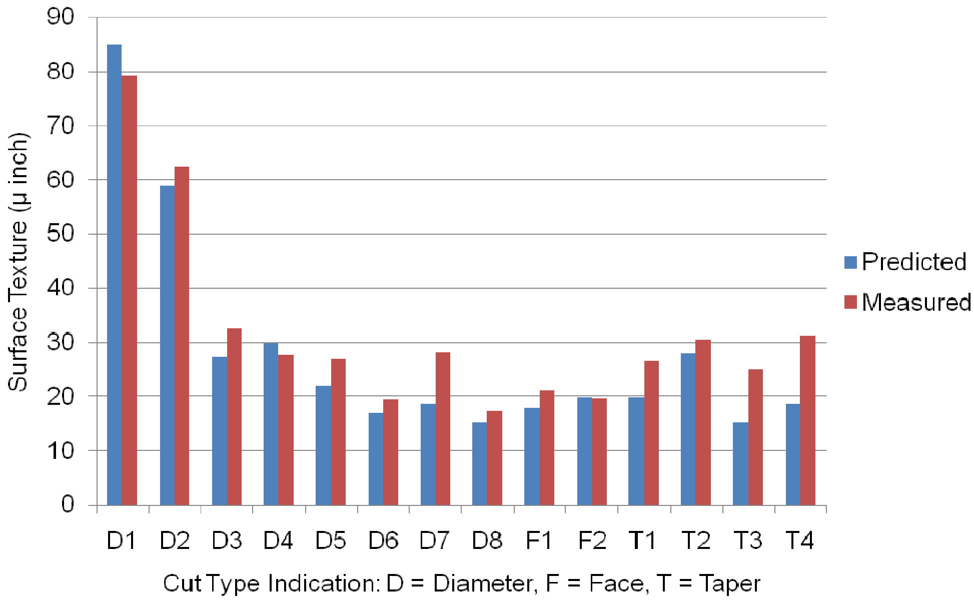

Figure 8: Comparison of Predicted and Measured Surface Texture Values From the Diamond Turning Tests. D1 – D4 are the Distinctly Structured Surface Types.

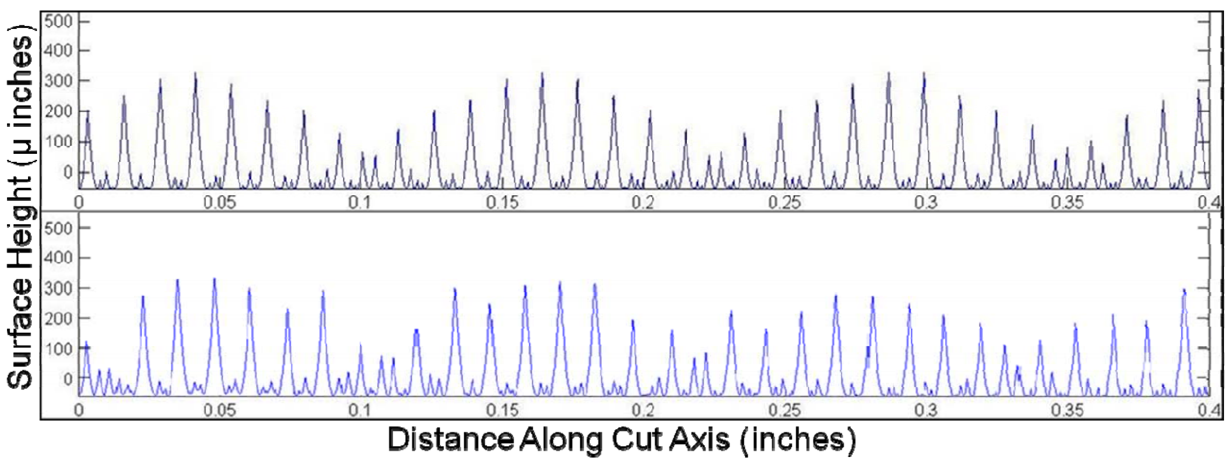

Figure 9: (Upper) Predicted Surface Profile of D2. (Lower) Measured Surface Profile of D2.

Continued experimentation to validate the surface simulations has been conducted using a Heidenhain grid plate. In this experiment, the grid plate is attached to the ways of a CNC lathe center and while performing modulated tool-path motions, an encoder measures the true position of the machine axes. By post processing the collected data through the aforementioned computer simulation, it is possible to compare the real machine positions with demanded positions and extract the errors associated with the motions in the X and Z axes. Although the experimental results are still preliminary, future work will provide important information regarding the errors of specific machines while performing modulated tool-path motions. Knowledge of these errors will help in generating programs that more accurately predict resulting surface finishes. Figure 10 shows the experimental setup of the machine grid plate testing.

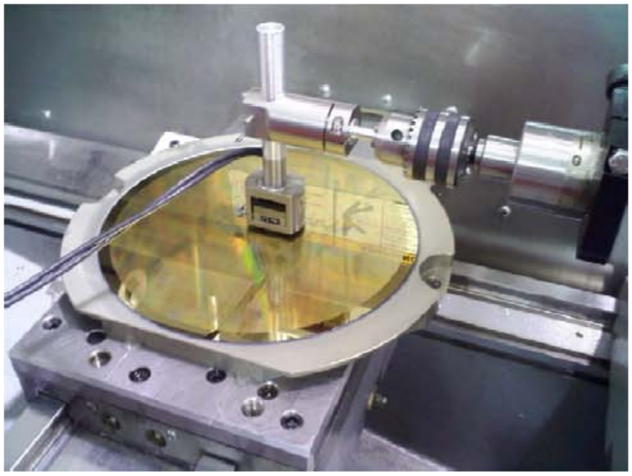

Figure 10: Experimental Setup of the Machine Grid Plate Testing.

Tool Wear Testing

In turning applications with difficult to cut materials, such as depleted uranium, tool wear is an issue that is constantly being addressed. Two of the largest influencing factors in tool wear are the temperature of the tool and the feed rate. During a chip breaking tool-path, the tool leaves the cut while making the oscillations required to break chips. The removal from the cut, allows the tool to cool and not reach a maximum temperature as seen in conventional turning operations (Palmai 1987, Stephenson 1992). This cooling cycle can be seen below in Figure 11.

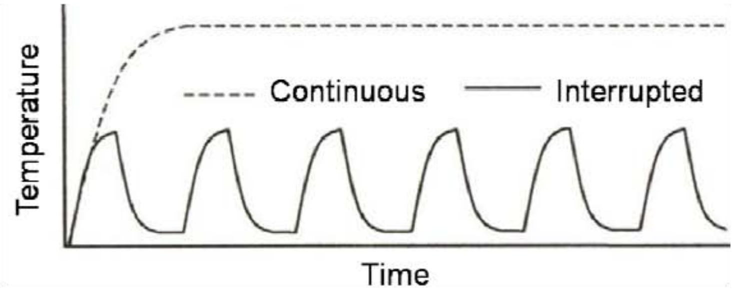

Figure 11: Temperature Change in Interrupted Cutting (Danley 2000)

Through the use of thermal imaging cameras, previous work has been done to show that lower temperatures can be seen on the face of the tool during chip breaking operations. To maintain the same metal removal rate (MRR) as a conventional turning operation, the instantaneous feed rate of a chip breaking cut must be increased in order to perform the oscillations along the tool-path. With higher feed rate, a greater amount of tool wear is generally seen (Miller 2003, Tlusty 2000). To determine whether the tool temperature or higher feed rate had a greater influence on the tool wear during chip breaking operations, a series of tests were performed to evaluate the wear seen on the inserts. Three separate tests were performed that all had similar cutting conditions. High Speed Steel (HSS) inserts were used to make facing cuts along 1018 steel with the following parameters: 100 SFM, 600 Max RPM, 4"OD material, 0.025" depth of cut per pass, 0.005 inches per revolution global feed rate and a total depth of 2" was cut from the material. Coolant was used for all three tests. There was a conventional turning pass compared to two chip breaking passes that had R_{af}s of 2.5 and 1.23, while both had an OPR of 0.431. The machining setup can be seen in **Error! Reference source not found.** (left). Two digital microscopes were setup to view the tool wear, one viewing the face of the tool and the other focused on the flank, as seen below in Figure 12 (right).

Figure 12: (Left) Tool Wear Testing (Right) Digital Microscope Cameras

In order to position the cameras to view both the flank and face wear, the tool had to cut from the center of the part to the outside diameter. The flank wear seen on the tests appears on the inserts as denoted by the green section in Figure 13. The wear seen on the profile and face of the tool is denoted by the yellow area.

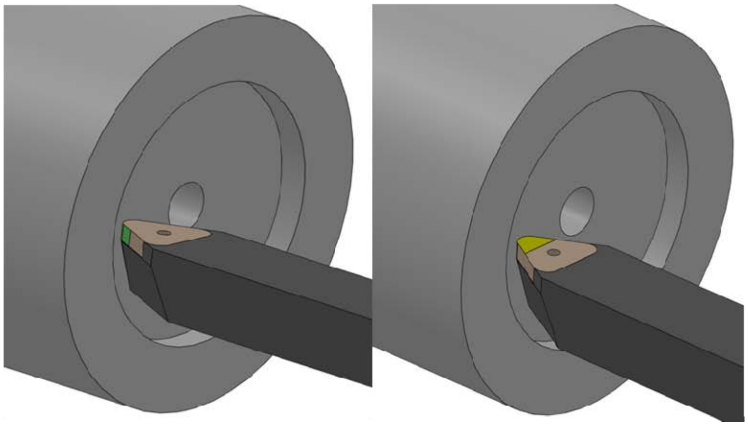

Figure 13: (Left) Flank Wear (Right) Profile and Crater Wear

To perform the tests, a picture was taken of the flank and face after every four passes at 0.025" depth of cut per pass. A total of 80 passes were completed on each set of parameters. Figure 14 through Figure 16 show the wear along the profile and face of the insert, while Figure 17 through Figure 19 show the wear along the flank of the inserts.

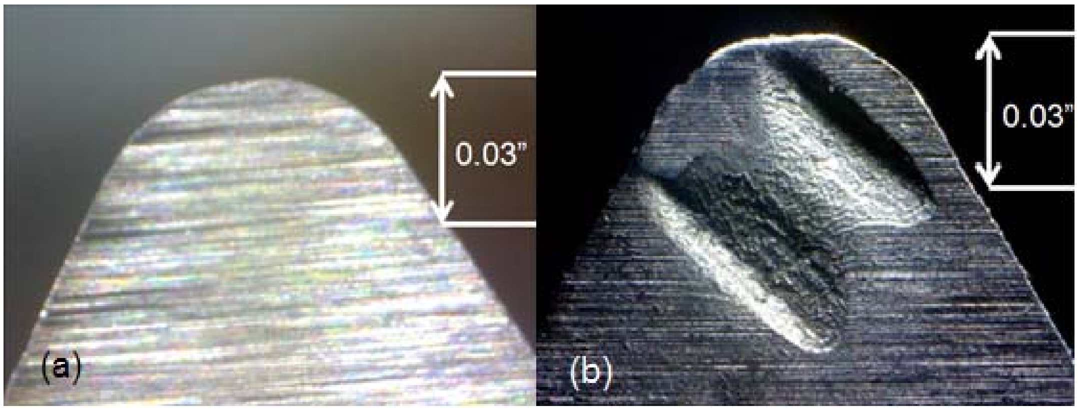

Figure 14: Conventional Cut (a) Original insert (b) Worn Insert

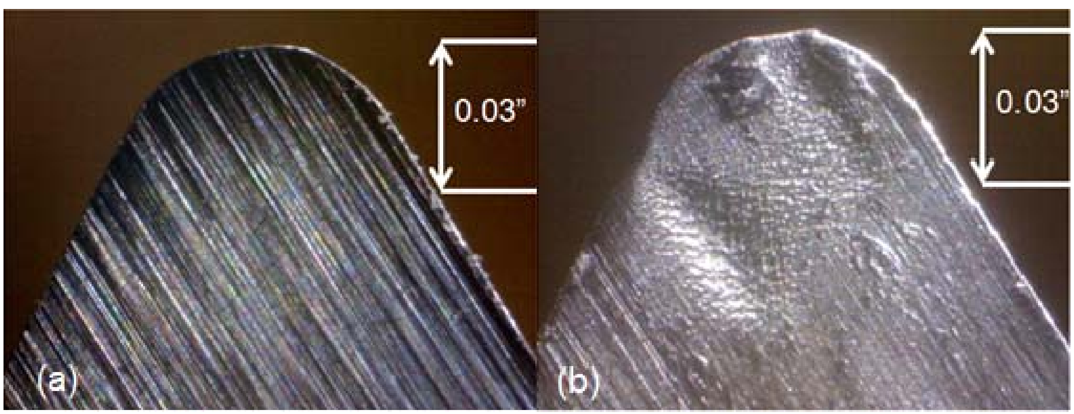

Figure 15: Chip Breaking Cut, 1.23 R_{af} (a) Original Insert (b) Worn Insert

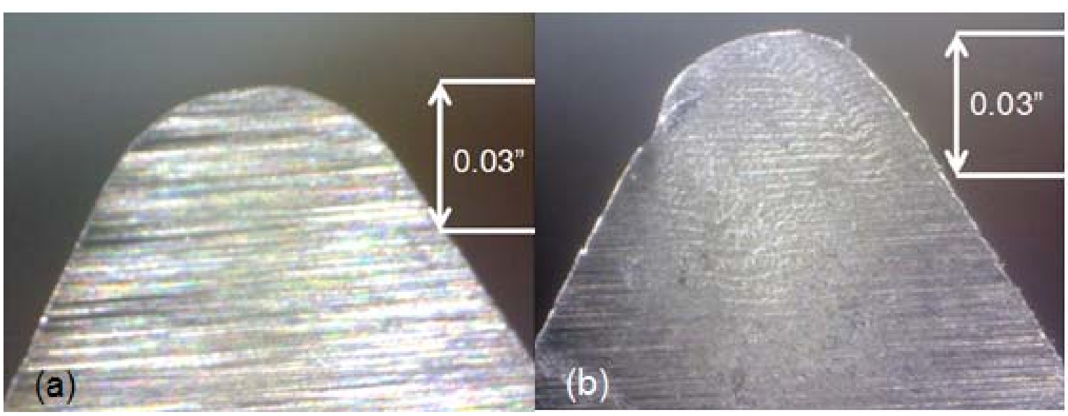

Figure 16: Chip Breaking Cut, 2.5 R_{af} (a) Original Insert (b) Worn Insert

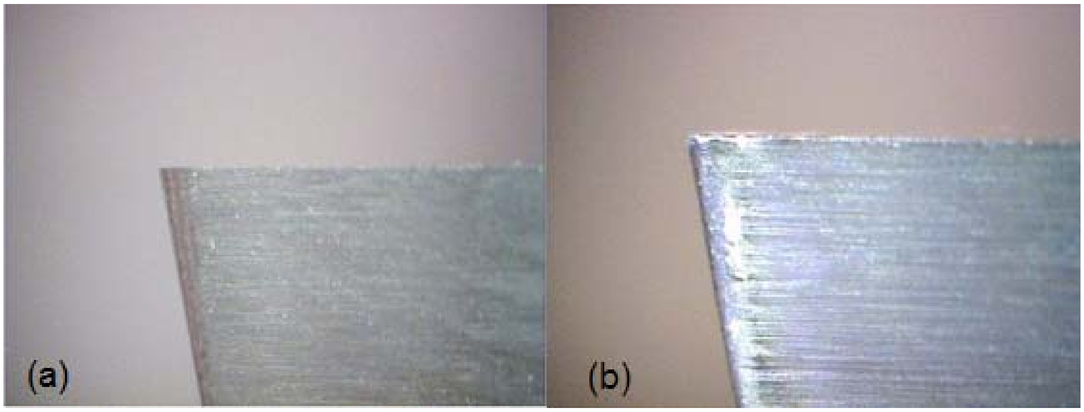

Figure 17: Conventional Cut (a) Original insert (b) Worn Insert

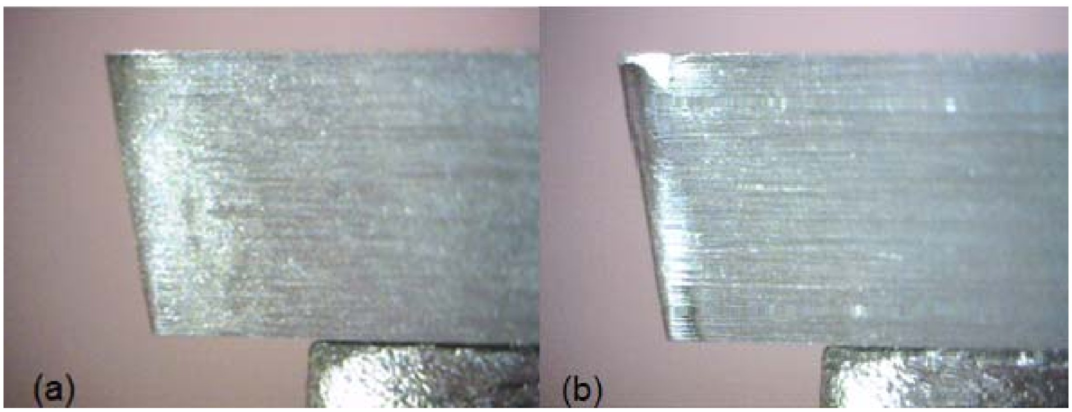

Figure 18: Chip Breaking Cut, 1.23 R_{af} (a) Original Insert (b) Worn Insert

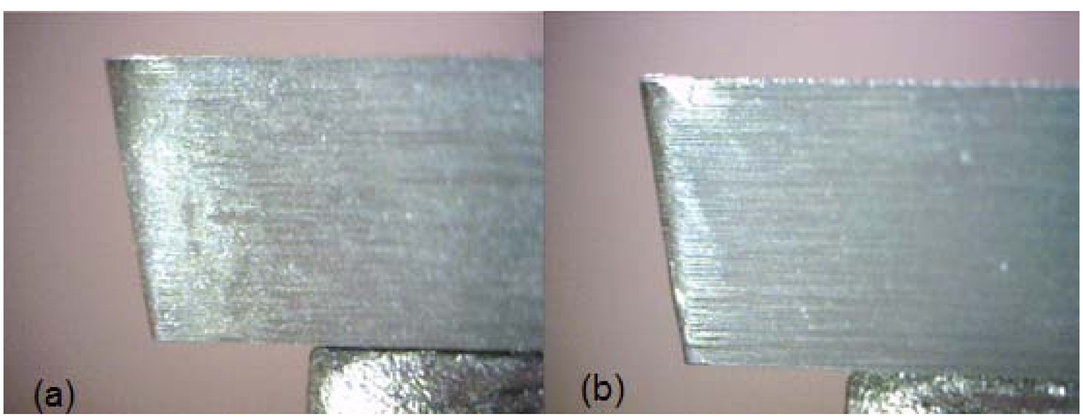

Figure 19: Chip Breaking Cut, 2.5 R_{af} (a) Original Insert (b) Worn Insert

As seen in Figure 14, the conventional cut has significantly greater amount of wear along the profile and much deeper craters than that of the inserts from the chip breaking tool-paths. The insert in Figure 16, with a 2.5 R_{af}, has the least amount of wear along these areas. This indicates that the amount of time the insert is engaged in the cut has a greater influence over the tool wear than the instantaneous feed rate. There does not appear to be as noticeable of a difference between the various cuts when viewing the flank of the insert compared to the face. However, the flank wear on the chip breaking inserts appears to be greater than that of the insert from conventional turning. This could be due to the higher instantaneous feed rate along the chip breaking tool-paths. Further tests need to be performed to evaluate the effects of tool wear on various metals, including more difficult to turn alloys and other insert grades and coatings.

Conclusion

Modulated tool-path chip breaking in CNC lathes has consistently shown to be an effective method to reliably induce broken chips. Using the simulations described in this paper, this method ensures an ability to choose oscillation parameters that will simultaneously result in desirable chip lengths and surface finishes. The experimental data from the diamond turning tests confirm that by minimizing machinability issues and machine errors it is possible to create distinctly structured or other desirable surface finishes that agree with simulation models. The experimental data and the graphs in Figure 6 and Figure 7 also show that high frequency oscillations such as with (Moriwaki 1991) are unnecessary. Results from the tool wear testing indicate that it may be possible to achieve lower tool wear rates in specific areas of the tool, although further testing needs to be conducted in order to confirm this. Additional work remains to include the affects of machine errors, such as with the grid plate testing, as well as affects associated with machinability issues often seen in more common operating conditions.

Acknowledgements

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References

1. Danley, J. D., 2000, Reducing the Machining Times in The Production of Titanium Parts, MS thesis, The University of North Carolina at Charlotte.
2. Miller, M.R., and Mulholland, G., and Anderson, A., 2003, Experimental Cutting Tool Temperature Distributions, Journal of Manufacturing Science and Engineering, 125, pp. 667-673.
3. Moriwaki, T., Shamoto, E., 1991, Ultraprecision Diamond Turning of Stainless Steel by Applying Ultrasonic Vibration, Annals of the CIRP, 40/1:559-562.
4. Palmai, Z., 1987, Cutting Temperatures in Intermittent Cutting, Int. J. Mach. Tools Manuf., 27: 261-274.
5. Smith, S., Woody, B., Barkman, W., and Tursky, D., 2009, Temperature Control and Machine Dynamics in Chip Breaking using CNC Toolpaths, Annals of the CIRP, 58/1:97-100.
6. Stephenson, D.A., Ali, A., 1992, Tool Temperatures in Interrupted Metal Cutting, ASME J. Eng. Ind., 114:127-136.
7. Tlusty, G., 2000, Manufacturing Processes and Equipment, Prentice Hall, Upper Saddle River, pp. 481-486, Chap. 8.