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MODULATED TOOL-PATH CHIP BREAKING FOR DEPLETED URANIUM MACHINING OPERATIONS

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ABSTRACT

Turning operations involving depleted uranium frequently generate long, stringy chips that present a hazard to both the machinist and the machine tool. While a variety of chip-breaking techniques are available, they generally depend on a mechanism that increases the bending of the chip or the introduction of a one dimensional vibration that produces an interrupted cutting pattern. Unfortunately, neither of these approaches is particularly effective when making a "light depth-of-cut" on a contoured workpiece. The historical solution to this problem has been for the machinist to use long-handled tweezers to "pull the chip" and try to keep it submerged in the chip pan; however, this approach is not practical for all machining operations. This paper discusses a research project involving the Y-12 National Security Complex and the University of North Carolina at Charlotte in which unique, oscillatory part programs are used to continuously create an interrupted cut that generates pre-defined, user-selectable chip lengths.

INTRODUCTION

The Nuclear Security Enterprise (NSE) conducts turning operations involving ductile materials, such as stainless steel and depleted uranium, which can generate long, stringy chips that present a hazard to both the machinist and the machine tool. The NSE has tried a variety of chip-breaking approaches in the past that have ranged from the use of cutting tools with molded chip breaking features to a system for directing a high pressure fluid at the tool. The common attribute of the tested systems was the attempt to increase the bending of the chip so that the material would fracture. Unfortunately, none of the evaluated systems was acceptable when making a “light depth-of-cut” (0.005” – 0.01”) on a contoured workpiece. This paper discusses a research project involving the Y-12 National Security Complex (Y-12) and the University of North Carolina at Charlotte in which unique, oscillatory part programs are used to continuously create an interrupted cut that generates pre-defined, user-selectable chip lengths with any depth of cut, material or workpiece profile, [1, 2, 3].

EXPERIMENTAL WORK

The modulated tool-path (MTP) chip breaking technique combines an oscillatory motion with a conventional machining tool path to periodically engage and disengage the cutting tool from the cut face, as shown in the simplified perspective of figure 1. (The actual cut-face profile is more complex, as discussed later.) This approach uses the machine axes drives to modulate the tool position, along the part program tool-path, in a manner that is similar to the technique used in trochoidal milling. (While the MTP creates an interrupted cut on the cut face, the tool remains in continuous contact with the workpiece profile. A trochoidal tool path creates a circular motion that completely disengages the tool from the part. However, the axes servo system performance requirements are comparable for both methods.) The actual cut face profile is more complex than what is shown in figure 1 due to the multiple cutter engagements and disengagements that occur as the tool moves ahead with a particular global feedrate. (The instantaneous feedrate can also be significantly higher than the global feedrate as the tool moves back and forth along the tool path.)

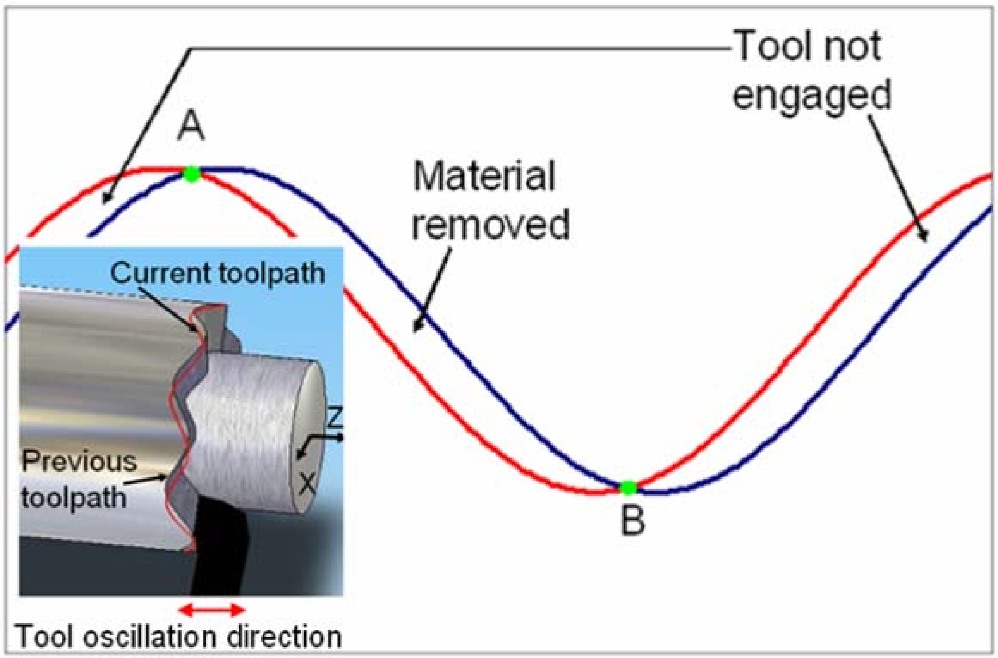

Figure 1. Exaggerated view of a cylindrical workpiece showing a wavy cut face surface created by an oscillating tool-path.

Figure 2 shows the simulation results from a model that relates the MTP process parameters (oscillations per spindle revolution and oscillation amplitude) to chip length (expressed as a function of workpiece diameter) for a global feedrate of 0.003”/spindle revolution. As might be expected, higher oscillation rates produce shorter chips; however, there is little to be gained by using OPR values greater than 4. Similarly, oscillation amplitudes above 3-4 times the global feed per revolution do not have a large impact on the chip length. In addition, an oscillation motion that is phase with the spindle rotation (OPR = 1, 2, 3 …), or too small, creates continuous chips even though the cut face profile is sinusoidal. (As indicated by the white areas “between and behind” the colored regions on the plot.)

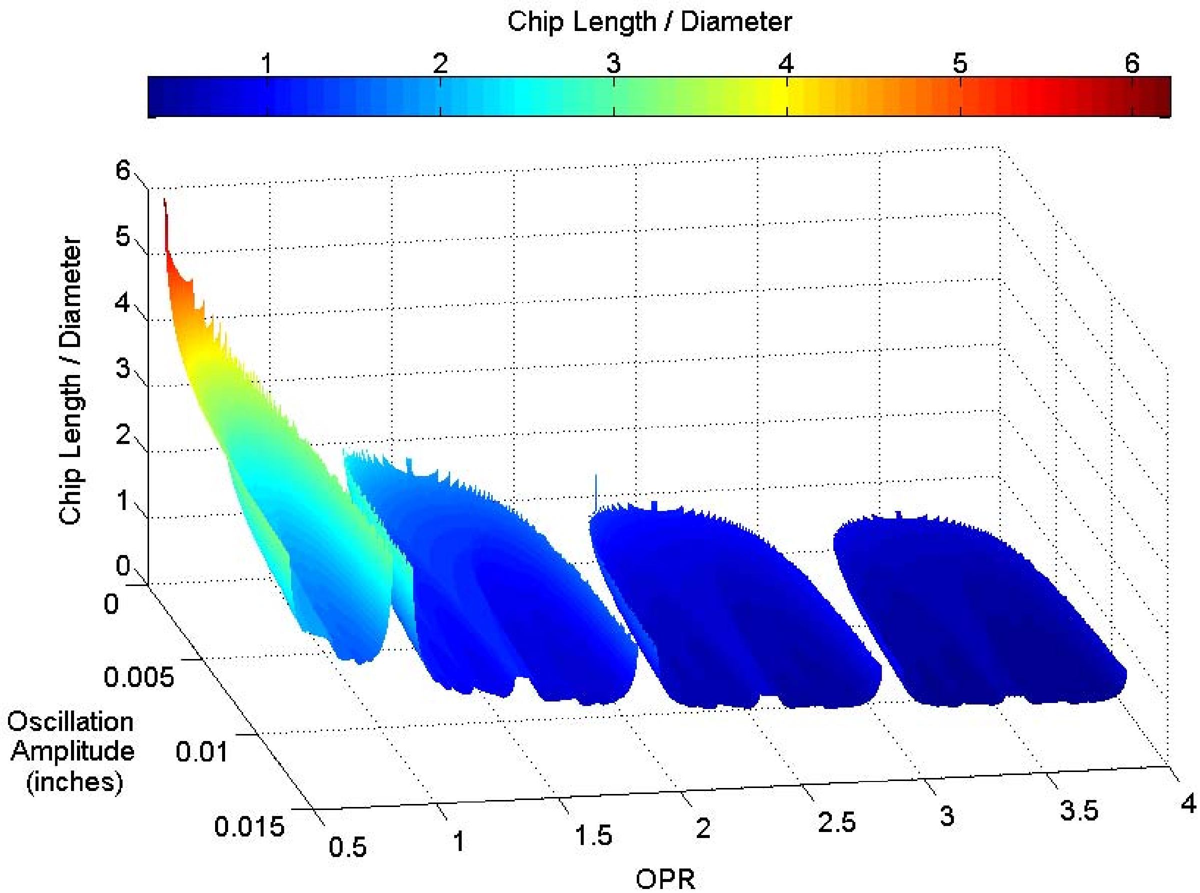

Figure 2. Relationship between chip length/part diameter, the oscillation amplitude, and the number of oscillations that occur for each spindle revolution (OPR) at a global feedrate of 0.003"/spindle revolution.

Figure 3 provides more detail concerning how the theoretical interaction between the tool and the cut face results in a particular chip length. Interrupted cutting conditions will occur as long as spindle rotation is sufficiently out of phase with the tool oscillation and the oscillation amplitude is sufficient to overcome the effect of the axes global feed per spindle revolution. (It is also likely that the chip will break just prior to the point at which the tool exits the cut, and the curves in figure 3 intersect, due to the inability of a very thin chip to maintain its integrity.) Given the sensitivity of the chip length to the MTP process parameters, it is important to understand how well a particular machine tool is able to execute the MTP commands.

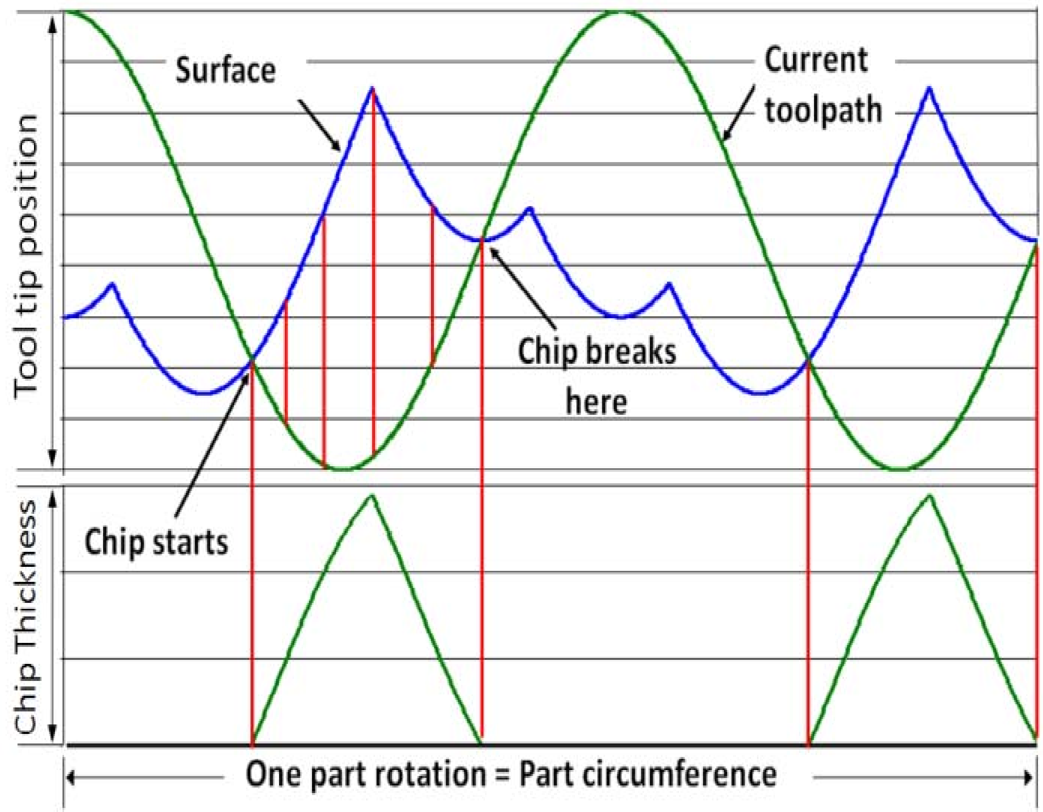

Figure 3. Relationship between the cut face profile and MTP that determines chip length.

Figure 4 shows a machine characterization set up in which a sensor nest and reference block are used to evaluate the ability of a machine to follow various MTP commands.

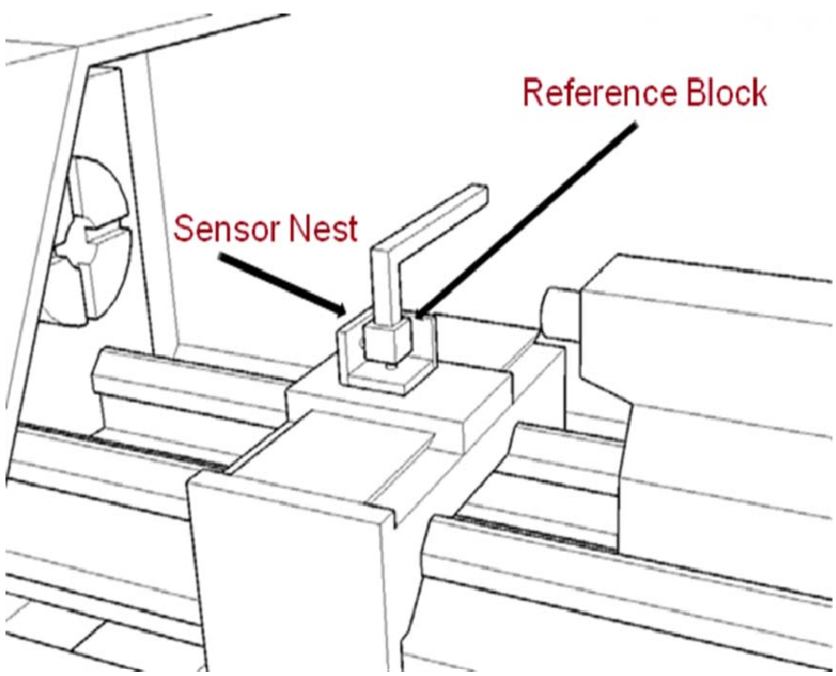

Figure 4. Machine characterization set up.

Figures 5 and 6 show test results obtained when different machine tools were commanded to execute a variety of oscillation commands. Figure 5 shows that some machine tools follow changes in increasing oscillation frequency relatively well while degrading the oscillation

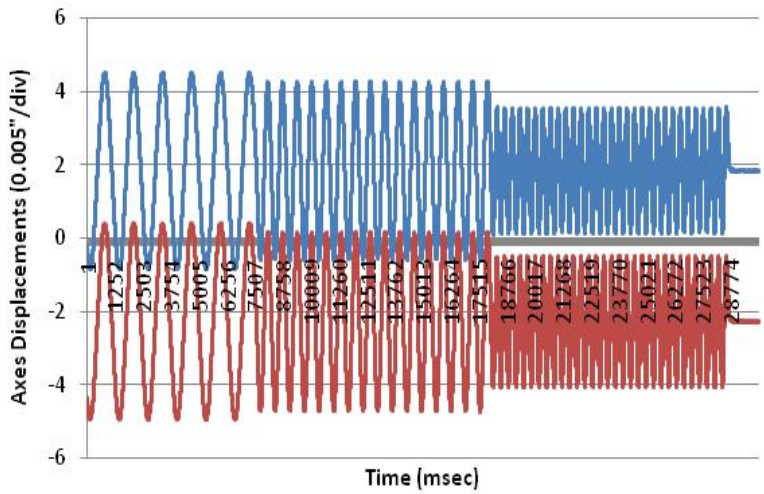

Figure 5. Machine response to different amplitude oscillation commands.

amplitude. Figure 6 shows that other machines maintain the desired oscillation amplitude in response to higher frequency oscillation commands by introducing motion delays. The net effect is that each machine has an oscillation amplitude and frequency range over which it is able to reliably execute the MTP commands. (Operation outside that range may be possible with appropriate adjustments to the MTP commands, i.e. increasing the amplitude command to obtain the desired machine response.)

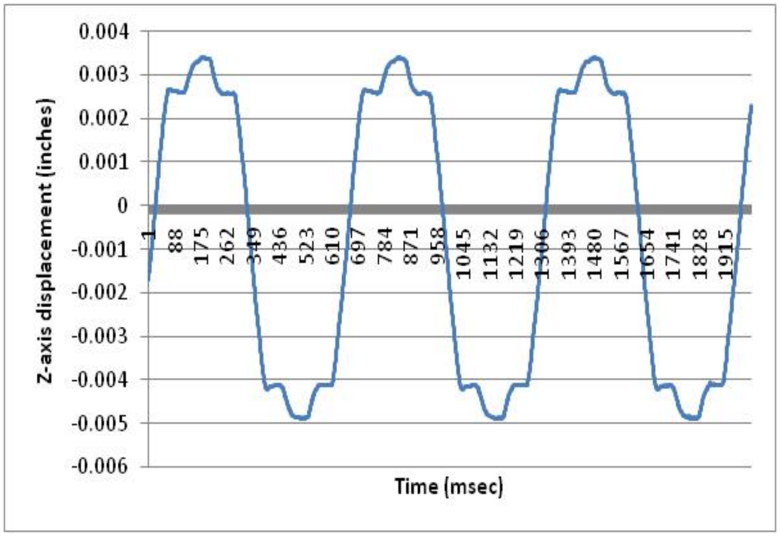

Figure 6. Machine that accurately executes oscillation amplitude commands by introducing motion delays.

A machine tool's ability to follow the dynamic MTP commands can also influence the workpiece surface finish quality and profile accuracy. Two dynamic performance characteristics that are important when determining the ranges of MTP process parameters that are appropriate for performing MTP chip breaking operations are cross-axis coupling and axes synchronization. These features can be evaluated using the approach shown previously in figure 4. The cross-axis coupling can be evaluated by oscillating one axis while measuring deviations from the desired null response on another axis as shown in figures 7 and 8.

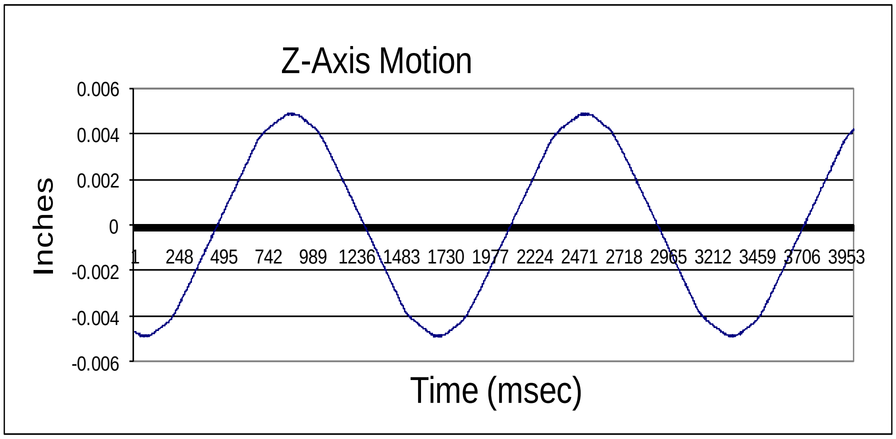

Figure 7. Z-axis response to dynamic Z-axis motion commands.

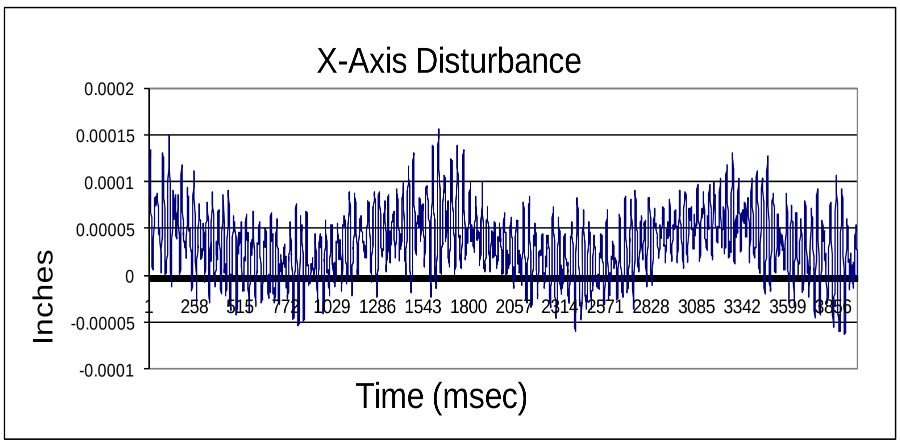

Figure 8. X-axis response to Z-axis motions.

The axes synchronization errors can be determined by simultaneously providing oscillating motion commands to both axes and then plotting the axes motion responses against each other. If both axes are given identical oscillation commands, then the X-Z motion plot should be a straight line with a 45 degree slope. Synchronization errors caused by a machine's inability to execute the commanded dynamic motions will be detected as deviations from the 45-degree line, as shown in figure 9. (More error is likely to be acceptable in a roughing stage than in a finishing cycle.)

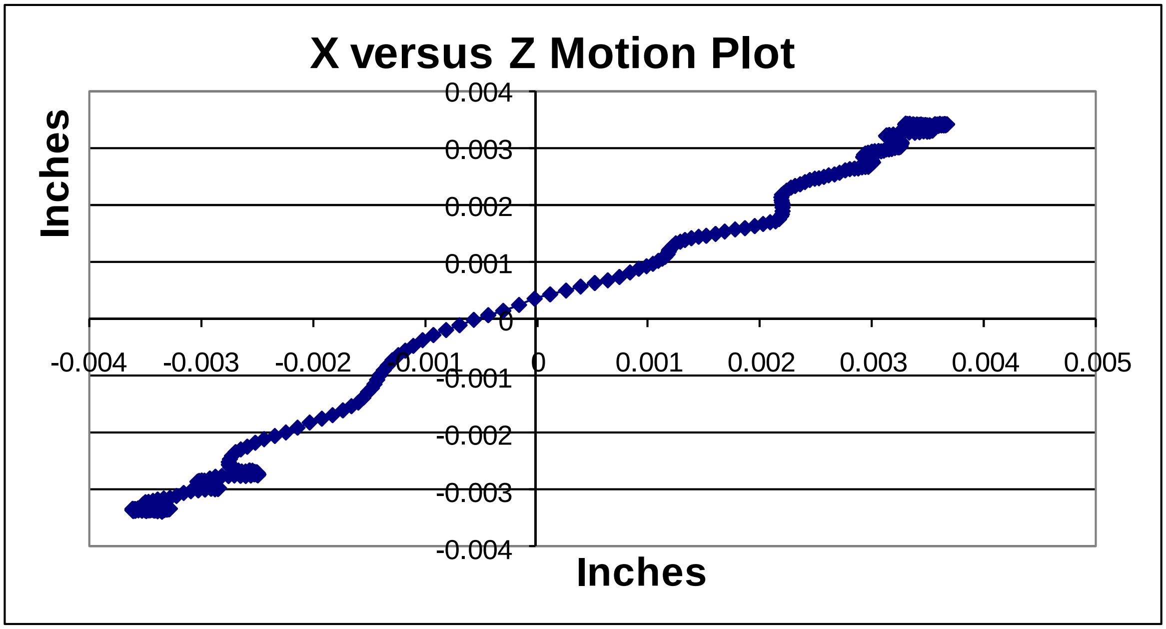

Figure 9. Axes synchronization errors detected with sensor-nest test.

The surface finish created by a conventional turning operation exhibits “barber-pole” surface-texture scallops along the length of the workpiece. However, MTP chip breaking creates surface features that are altered, in a complex fashion, by the modulated tool-path motion. Instead of exhibiting a “uniform thread” characteristic, the surface finish is determined by the composite impact of multiple machining passes, that occur in opposite directions, with a periodically changing feedrate, and is a function of the cutting tool size, the global and instantaneous feedrates, the oscillation amplitude, and the number of oscillations per spindle revolution. Figure 10 shows a model of the workpiece surface finish that would be created when using a 0.031” tool radius, a global feedrate of 0.003” per minute and various MTP parameters. It can be seen that the surface finish plot exhibits a repeating pattern that is symmetric around multiples of 0.5 tool path oscillations per spindle revolution, somewhat like the chip length plot shown earlier in figure 2. Another important characteristic is that the “deeper blue” regions of lower surface finish values tend to be less sensitive to changes in the amplitude of the oscillation while relatively minor changes in the oscillation frequency can produce large swings in the finish. This indicates that a machine tool’s ability to execute the oscillation frequency associated with the MTP part program commands is more important than its ability to achieve the intended amplitude. (See figures 5 & 6.) In addition, some amplitude adjustments can be achieved through tool path compensation techniques, while corrections for a degraded “frequency performance” are more difficult to achieve.

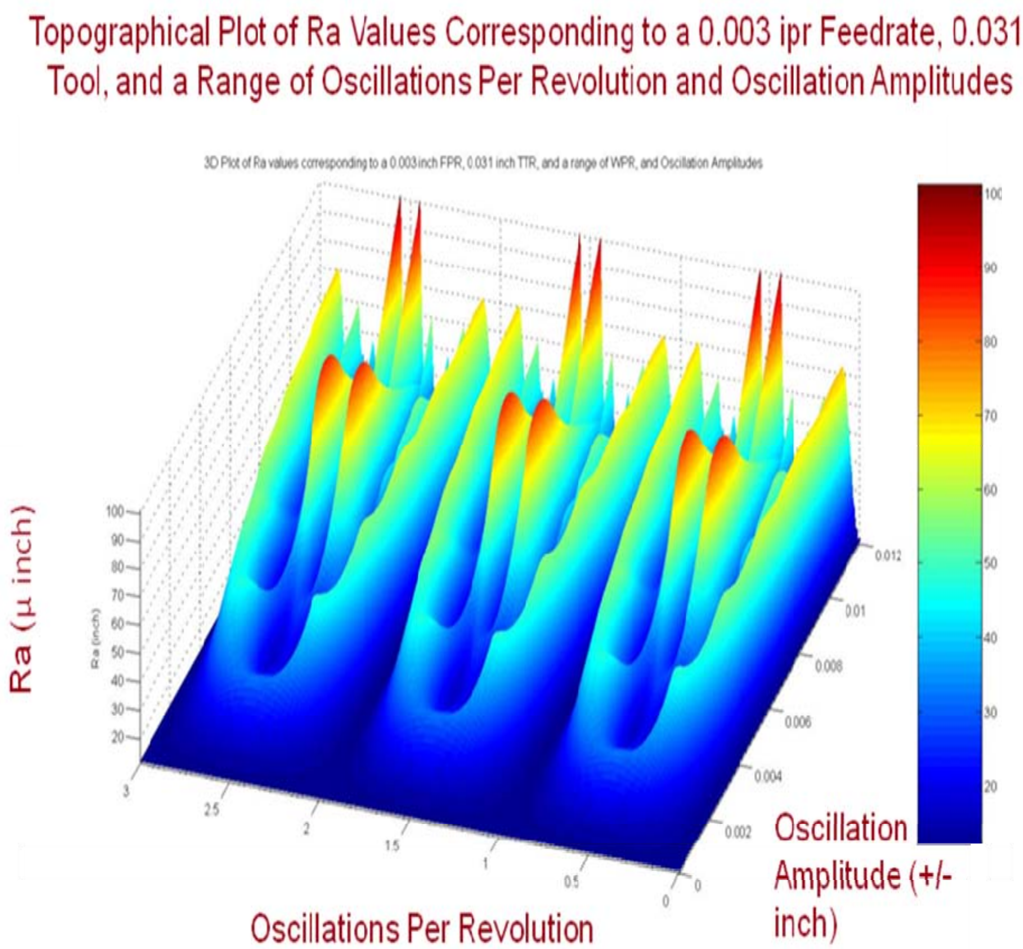

Figure 10. Model showing impact of MTP parameters on workpiece surface finish.

CONCLUSIONS

The test results described above indicate that it is necessary to tailor the MTP process parameters to a specific machine's performance characteristics and that the impact of these parameters on chip length and surface finish must also be considered. In general, higher oscillation frequencies produce shorter chips while creating more challenging operating conditions for the machine tool servo system. The surface finish models predict that there are multiple sets of parameters that can deliver a desired quality level and a reasonable match can be made with the parameters needed to produce a desired chip length. Some complications can arise when considering the desired axes feedrates and spindle speeds. Lower spindle speeds can lead to lower oscillation rates and axes feeds but may conflict with throughput and surface feet per minute goals. In addition, if an attempt is made to maintain constant surface feet per minute and oscillation amplitude values while machining the face of a part (the spindle speed increases as the cutter moves closer to the spindle centerline), the phase angle between the tool path modulation and the spindle rotation will vary and can result in regions in which continuous chips may be produced unless appropriate modifications are made in the MTP process parameters.

The current MTP chip breaking system provides methods for characterizing a machine tool's ability to execute the oscillatory motions involved in the MTP process and allows the user to select the operational "sweet spot" that combines the often conflicting goals of chip length, workpiece quality, and throughput with the dynamic motion capabilities of a specific machine tool by using computer models [4]. The MTP chip breaking program is generated using an algorithm that automatically monitors the phase between the spindle rotation and the tool modulation and makes the necessary adjustments in the MTP process parameters to assure the creation of segmented chips. It should also be noted that it can be desirable to use different MTP parameters on roughing and finishing cuts in order to improve the overall process throughput. In addition, other factors such as tool temperature and tool wear may be important factors in some applications and may need to be incorporated into the modeling process.

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