USING PROCESS MODELS TO OPTIMIZE MODULATED TOOL-PATH
CHIP BREAKING OPERATIONS

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INTRODUCTION
This paper discusses recent results from a collaborative research project involving the Y-12 National Security Complex (Y-12) and the University of North Carolina at Charlotte (UNC Charlotte) that was first introduced at the October 2009 American Society for Precision Engineering Annual Meeting in Monterrey, California. The previous presentation, titled “Machine Performance Requirements Associated with Modulated Tool-Path Chip Breaking” described the basic process for using unique, oscillatory part programs to continuously create user-selectable chip lengths and the machine performance requirements associated with this process.

The modulated tool-path (MTP) chip breaking technique uses a part program generated oscillatory motion of the machine’s axes, parallel to the machining tool path, to intermittently engage and disengage the cutting tool from the workpiece cut face, as shown in figures 1 & 2. (Figure 1 demonstrates the basic concept; figure 2 shows a more accurate representation of the chip face.)

This approach successfully creates segmented chips by producing irregular waves in the cut face; however, it can also introduce complex finish characteristics on the workpiece surface due to the varying feedrate and “recutting action” associated with the oscillatory motion. While this somewhat irregular surface finish pattern is not a concern during the roughing or semi-finish pass, it must be addressed for finishing operations, which leads to the challenge of attempting to optimize the sometimes conflicting goals of creating the desired chip length and surface texture while maintaining process throughput.

Y-12 and UNC Charlotte have developed models that predict the chip length and surface finish for various MTP process parameters and machine testing protocols have been developed that determine the ability of a particular machine to accurately execute the MTP commands. In general, shorter chip lengths are produced when using higher oscillation frequencies; however, the ability to produce the higher speed slide motion is limited by the capabilities of a particular machine tool. Reducing the spindle speed reduces the oscillation frequency needed to produce a particular chip length but this process change also impacts the machining time...
and can make it difficult to achieve the desired surface feet per minute cutting conditions. Understanding the impacts of these process parameter changes on surface finish is also non-intuitive due to the changing feedrates and the “wiping motion” created by the MTP process.

This paper discusses a technique for finding the process parameter “sweet spot” that uses process models to integrate workpiece characteristics and tolerances, desired chip lengths and process “feeds and speeds,” and machine performance capabilities and presents experimental results from the machining tests used to validate the process optimization predictions.

EXPERIMENTAL MODELS

Figure 3 shows the relationship between the MTP Amplitude Ratio (oscillation amplitude divided by the global feedrate) and the phase shift in the oscillation motion, between sequential spindle rotations, needed to produce broken chips.

![Figure 3. MTP parameter values that produce segmented chips. (The amplitude ratio is the MTP oscillation amplitude divided by the global feed per spindle revolution. The phase shift is the relationship between the oscillations that occur on sequential spindle revolutions.)](image)

As might be expected, small amounts of oscillation amplitude in relation to the global feedrate (inches per spindle revolution - ipr) will not produce broken chips because there isn’t enough “retract motion” to disengage the cutter from the workface. Similarly, small amounts of phase shift will produce a “wavy cut face” but the chips will be unbroken. (This region of unbroken chips is depicted as a “white area” in subsequent chip length charts in order to more easily clarify the model predictions.)

Figures 4 & 5 show two views of the results from modeling the relationship between the MTP oscillation amplitude, the number of MTP oscillations per spindle revolution (OPR), and the ratio of chip length to workpiece diameter for an axes feed of 0.003 inches per revolution (ipr). (The information is presented in terms of OPR and chip length/workpiece diameter as a means of normalizing data.)

![FIGURE 4. Model prediction of chip length/workpiece diameter in relation to the MTP oscillation amplitude and oscillations per spindle revolution (with a 0.003 ipr axes feed).](image)

Two important predictions shown in these figures are that the chip length is relatively insensitive to OPR for OPR values above about 2.8 and to the oscillation amplitude. (As long as the oscillation amplitude is large enough to break the chips.) This means that if OPR values in the range of 2.2 to 2.8 can be achieved, then the chip length/diameter parameter will not change much over the oscillation amplitude range from 0.005” to 0.015”. Shifting to the higher frequency range associated with OPR’s around 3.5 provides little reduction in chip length and requires either a significant increase in the dynamic performance of the machine tool or an accompanying decrease in the spindle speed. The actual uncut chip length will depend on the part diameter (distance of the tool from the spindle centerline) and the degree of chip compaction and chip curling that is present. If a cylindrical part is being machined, the MTP process parameters can be selected based on the diameter of the workpiece and the desired chip size and axis feed. For a facing cut, the MTP parameter selection process is more complicated when a constant surface feet per minute (sfm) mode is desired because the spindle speed is constantly changing as the tool moves toward the spindle centerline.

The surface profile that is produced by the MTP process is also an important process characteristic and figure 6 [1] shows the model prediction of the workpiece surface finish that
will be produced when using a 0.031" radius cutter, a 0.003" feed, and a speed of 300 sfm. (The dark blue regions surrounding the “oval islands” are the areas in which the chips will not break.)

An additional characteristic of the MTP surface profile is that it varies around the circumference of the workpiece as well as along the tool path, as shown in the computer simulation results depicted in figure 8. In most cases, the MTP process parameters should be selected to minimize the variations in the surface profile.

EXPERIMENTAL RESULTS
Machining tests were conducted using aluminum workpieces and a diamond turning machine to...
avoid machineability complications when comparing the predicted and actual surface profiles on cylindrical, facing and tapered machining operations. (The machining parameters used were 300 rpm, 0.025 ipr, and a 0.02" radius diamond tool.) Two different sets of MTP oscillation parameters were chosen to validate the model predictions. One set of parameters was chosen to produce distinctly structured surface finishes, while the other set was selected to validate the low surface texture predictions (blue regions). The surface profile was characterized using a stylus profilometer.

Figure 9 shows a summary of the results from the machining tests. The D1 – D8 data was collected from cylindrical parts, the F1 & F2 tests involved facing cuts, and the T1 – T4 experiments were performed on tapered workpieces. (The predicted surface texture value is plotted on the left for each set of test conditions.) There is generally good agreement between the predicted and measured surface profiles and the mean variation between the data sets, over the 14 test runs, is approximately 4 microinches. In addition, figure 10 shows a comparison of the predicted and actual surface profiles for the D2 test conditions.

**FUTURE WORK**

The experimental tests conducted to date have demonstrated good agreement between the surface profile model predictions and the results obtained with constant rpm diamond turning operations. Future activities will extend these tests to the constant sfm machining of faces and tapers.

**REFERENCES**


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