

## CLOSED LOOP CONTROL OF MILLING TOOL DEFLECTION

D. Hood, S. Clayton, G. Buckner, T. A. Dow, K. Garrard,  
*Precision Engineering Center, North Carolina State University*

### BACKGROUND

Injection molding is an important manufacturing process for optical and mechanical components. The hard steel dies used in injection molding play a direct role in the quality of molded parts. Traditionally, fabricating the dies involved rough milling followed by heat treatment, grinding and polishing. Recently, high-speed machining of heat-treated steel (hardness  $> 55 R_c$ ) has become a viable approach for reducing fabrication times while retaining the necessary shape control. However, as feature sizes drop below 1 mm with dimensional tolerances on the order of 10  $\mu\text{m}$ , tool deflection can create significant errors in the shape of mold surfaces.

A previous research effort at NC State developed open-loop correction techniques for tool deflection of small ball end mills [1]. This effort involved predicting tool forces and the resulting tool deflections for specified machining conditions and compensating for these deflections by modifying the tool path. A CAD model of the surface along with the planned tool path was used to determine the depth of cut, feed rate, and normal vector to the surface. This information was used to calculate the magnitude and direction of cutting forces that cause tool deflection. Compensation for tool deflection has proven very successful and errors can be reduced from 50 to less than 10  $\mu\text{m}$  if the cutting conditions are known precisely. Unfortunately, this is not typically the case. For example, the tool or workpiece may have dimensions different than expected or be imprecisely positioned, resulting in cutting depths that are larger (or smaller) than expected. Open-loop compensation cannot correct for these types of errors.

This paper describes research to develop a real-time, force feedback control algorithm for milling operations that compensates for tool deflection. The workpiece is supported on a three-axis load cell and is machined using a small ball end tool driven by a high-speed (60,000 rpm) air bearing spindle. The output of the load cell provides feedback to control the depth of cut. As the tool deflects, the measured cutting forces drop in a predictable manner, and the controller changes the tool setpoint to correct for the error. Different depths of cut and loading angles change the magnitude and direction of the force and illustrate the accuracy and repeatability of this error correction scheme.

### EXPERIMENTAL APPARATUS

The experiments described in this paper were conducted using a Nanoform 600 diamond turning machine with 3 orthogonal linear axes and a high-speed milling spindle. Figure 1 is a photograph of the machine. The spindle is a Westwind air bearing, air turbine unit with a maximum speed of 60,000 rpm. The cutting tools are two flute, ball end TiC milling cutters with a diameter of 0.8 mm and lengths from 0.8 to 7 mm. A three-axis load cell supports the workpiece, and is used to measure the tool forces that are fed back to correct for tool deflection. In this experiment, only the force perpendicular to the workpiece surface (the z-direction component) is corrected. The Delta Tau PMAC control system collects force data from the load cell in real time and computes the corrected slide command.

### TOOL FORCES

**Predicted Forces** The tool force model developed in [1] provides formulas for calculating the cutting and thrust forces developed during milling. Inputs to this model are the material properties (Rockwell hardness, Young's

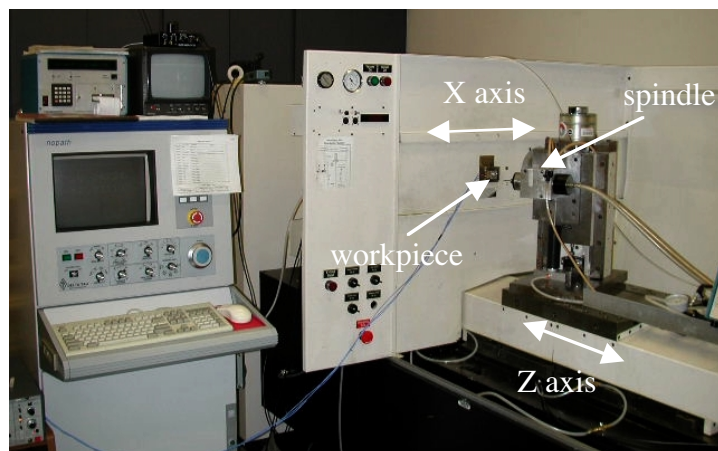


Figure 1. NanoForm 600 DTM with linear slideways and high-speed milling spindle.

modulus) and friction at the rake and flank faces of the tool. Tool geometry (ball end radius and number of flutes), spindle speed, upfeed and cross feed, depth of cut and tilt angle of tool are used to find the cross-sectional area of the chip and the area of contact between the flank face of the tool and the workpiece. The model can be written as:

$$F_c = \frac{HA_c}{3} \left( \frac{\cot \phi}{\sqrt{3}} + 1 \right) + \mu_f A_f \left( 0.62H \sqrt{\frac{43H}{E}} \right) \quad (1)$$

$$F_t = \mu \left[ \frac{HA_c}{3} \left( \frac{\cot \phi}{\sqrt{3}} + 1 \right) \right] + A_f \left( 0.62H \sqrt{\frac{43H}{E}} \right) \quad (2)$$

where

$A_c$  = cross sectional area of the chip

$A_f$  = area of the tool flank face

$\phi$  = shear angle in the workpiece

$\mu$  = friction coefficient on the rake face

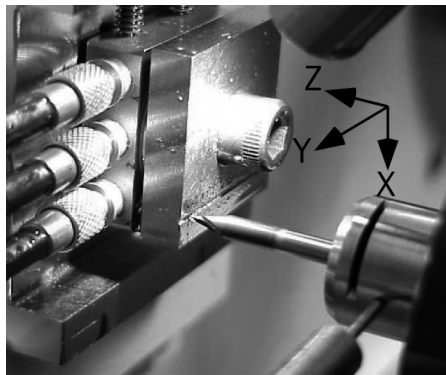
$\mu_f$  = friction coefficient on the flank face

$H$  = Rockwell hardness of the workpiece

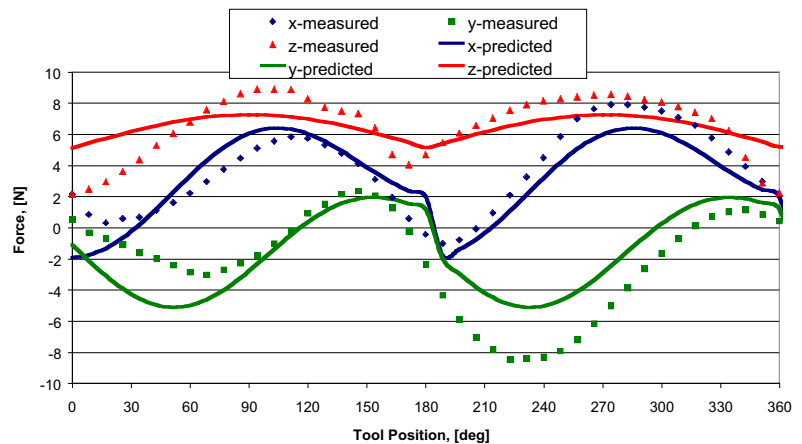
$E$  = Young's modulus of the workpiece

These forces rotate with the flank face of the milling tool, but can be readily converted to orthogonal forces (in the x, y, and z machine directions) for comparison to measured forces.

**Measured Forces** Preliminary cutting experiments were conducted to validate the tool force models (1) and (2). Cutting forces were measured using a 3-axis piezoelectric load cell, pictured in Figure 2a. This load cell was mounted below the workpiece on the x-axis of the diamond turning machine, while the high-speed spindle was mounted on the z-axis slideway (Figures 1 and 2a). Experimental results for an S-7 steel workpiece machined at a spindle speed of 10,000 rpm, a feed rate of 20  $\mu\text{m}/\text{rev}$ , and a cutting depth of 100  $\mu\text{m}$ , are presented in Figure 2b. This figure compares the predicted forces with average force measurements for three consecutive revolutions of the tool. The z-component of force in Figure 2b is dominated by the tool thrust force - Equation (2) - because the tool is normal to the workpiece. The x and y force components are influenced more by the cutting force - Equation (1), that rotates in the plane of the workpiece and changes from an x-direction force to a y-direction force every quarter rotation of the tool.



(a)



(b)

**Figure 2.** (a) Ball end milling tool and workpiece mounted on a 3-axis dynamometer

(b) Measured and modeled cutting forces for S7 steel workpiece: spindle speed = 10,000 rpm, feed rate = 20  $\mu\text{m}/\text{rev}$ , depth of cut = 100  $\mu\text{m}$ .

## TOOL STIFFNESS AND DEFLECTION

The TiC milling tools have a 3 mm shank which tapers down to the ball diameter (0.8 mm). These tools come in two lengths, the longer tool having a 4 mm extended section equal to the diameter of the ball end. Since a ball mill is used to fabricate free form surfaces, the tool can be loaded in the axial direction, the radial direction, or both. The stiffness of the tool is significantly less in the radial direction (see Table 1), therefore regions of a machined surface where the tool is loaded in the radial direction will create dimensional errors.

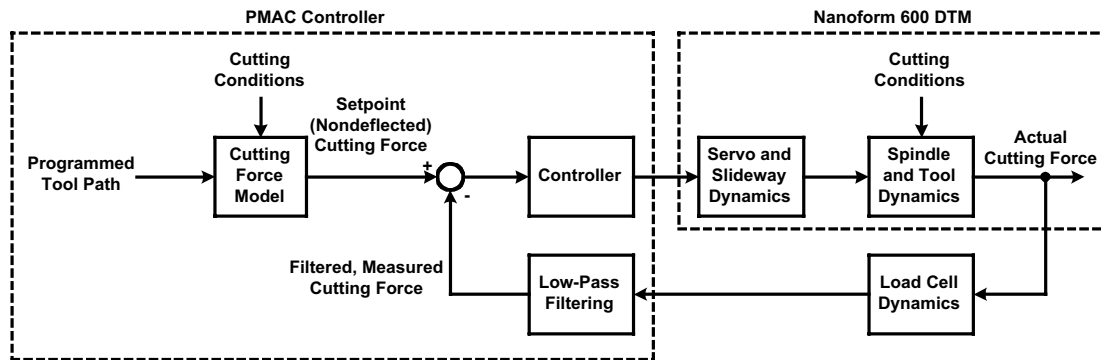
**Table 1.** Experimental stiffness measurements for ball end milling tools

| Tool Length (Stiffness direction) | Measured Stiffness, N/m |
|-----------------------------------|-------------------------|
| Short (Radial)                    | 406,203                 |
| Short (Axial)                     | 845,000                 |
| Long (Radial)                     | 198,533                 |
| Long (Axial)                      | 840,000                 |

### CONTROL SYSTEM DESIGN

With a validated cutting force model (Figure 2b) and tool stiffness measurements (Table 1), tool deflections during machining can be accurately predicted. Combining the model and stiffness measurements with real-time cutting force measurements enables the compensation of tool deflection errors. Compensation is done based on the average force per tool revolution in the direction of interest. Because the tool will be loaded in a variety of directions during a milling operation, the control algorithm must take into account both the magnitude and the direction of the forces.

A block diagram of the control algorithm is shown in Figure 3. The concept behind this algorithm is straightforward: calculate the expected z-axis force for a desired tool path, part position, and cutting conditions and compare it to measured z-axis force. If the measured force is equal to the predicted force, the z-axis setpoint is unchanged. If the measured force does not match the predicted force, the setpoint cutting depth is modified in accordance with the model. In this way, the system can correct for errors associated with tool deflection and workpiece positioning errors.



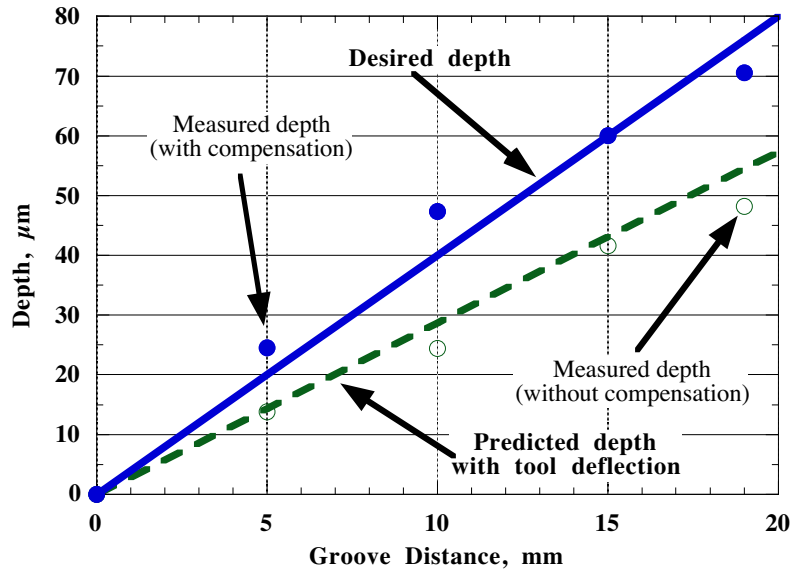
**Figure 3.** Block diagram of the tool deflection compensation algorithm

There are many practical considerations that make implementation of this algorithm difficult. First, the Nanoform 600 machine controller has safety limits on maximum axis velocity, acceleration, and following errors allowed during program execution. Using standard PMAC commands, it was determined that the machine could not move fast enough to compensate for tool deflection in the z-direction at the required x-direction feed rates (375 mm/min). To execute the correction scheme, a motion program was written that performs error measurement and PID closed loop control while the PMAC control loop operates in “open loop” mode. To facilitate this open loop controller/closed loop motion program, the proportional, integral, and derivative gains in the PMAC controller as well as the following error limits were set to zero. The axes were controlled through a motion program implementing PID control with output written directly to the DAC offset voltage register for each motor. Axes controller gains were tuned using Ziegler-Nichols techniques for the specific steps each axis would make during groove cuts. Additionally, low-pass filtering of the measured cutting force was necessary to achieve desirable performance. Finally, measuring “quasi-static” forces using a piezoelectric transducer is complicated by sensor drift and phase lag. This type of sensor would not be appropriate for extended cutting experiments.

### CUTTING EXPERIMENTS

To evaluate the tool deflection compensation algorithm, a series of experiments was conducted on the Nanoform DTM. Full immersion slots with linearly varying depths of cut were machined in S-7 tool steel samples with and

without real-time deflection compensation. One preliminary set of experimental results is shown in Figure 4. This figure shows the measured and predicted cutting depths for a tool tilted at  $25^\circ$  to the surface normal. Grooves spanning 20 mm and 0-80  $\mu\text{m}$  in depth were programmed, using a spindle speed of 10,000 rpm and a feed rate of 375 mm/min. The lower line represents the predicted uncompensated cutting depth, derived from the cutting force model, and the corresponding data points represent measurements made using a Form Talysurf at specific locations along the groove. The upper line represents the predicted compensated cutting depth, with actual measurements represented by data points. This data indicates that the cutting force model accurately predicts average tool deflections, as the experimental measurements are very close to the predicted curves. The data also shows that the deflection compensation algorithm significantly improves the accuracy of the machined groove, though the limited measurement spacing does not reveal higher-frequency variations.



**Figure 4.** Measured and predicted cutting depths for a variable depth groove: with and without compensation (groove depth = 0-80  $\mu\text{m}$ , groove distance = 20 mm, feed rate = 37.5  $\mu\text{m}/\text{rev}$ , spindle speed = 10,000 rpm)

## CONCLUSIONS

The forces generated during milling with a miniature tool are relatively small (less than 10N) because of the limited size and strength of the tool edge. However, tool deflections can be a significant source of surface errors because of the low stiffness of these ball end tools. The cutting force model accurately predicts these forces, and can be used to compensate errors arising from tool deflections and workpiece misalignment. The compensation algorithm presented here provides an avenue to reduce fabrication times and improve surface accuracies for hardened steel mold dies.

## ACKNOWLEDGEMENT

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## REFERENCES

1. T. Dow, E. Miller, A. Sohn and K. Garrard, Compensation of Tool Forces in Small Diameter End Mills, ASPE Proceedings, vol. 20, pp. 546-550 and to be published in Precision Engineering in 2003.