

FORCE FEEDBACK CONTROL OF TOOL DEFLECTION IN MINIATURE BALL END MILLING

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1 BACKGROUND

Injection molding is an important manufacturing process for optical and mechanical components. The hard steel dies used in this process play a direct role in the quality of molded parts. Traditionally, fabricating these dies involved rough milling followed by heat treatment, grinding, and polishing to the desired shape. 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 μm , tool deflection can create significant errors in the shape of mold surfaces. Deflections associated with miniature ball end tools can exceed 30 μm , rendering finished dies out of tolerance.

To date, most of the research associated with milling tool deflection compensation has involved open-loop techniques that use non-dynamic models of the cutting process to modify the desired tool path prior to cutting [2,3,4,5,6]. Research conducted at NCSU's Precision Engineering Center (PEC) resulted in open-loop correction techniques for tool deflection of miniature ball end mills [1]. This effort used a non-dynamic tool force model developed for diamond turning and modified it for ball end milling. These modeled cutting forces were used to predict tool deflections for specified machining conditions, and to modify the tool path before cutting. The specified tool path, together with a CAD model of the workpiece surface, were used to determine the depth of cut, feed rate, and normal cutting force vector. This information was then used to predict the magnitude and direction of cutting forces and tool deflections, which were used to modify the tool path off-line (prior to cutting). Form errors were reduced from 50 μm to less than 10 μm with accurate knowledge of the cutting conditions and parameters.

Despite the promising results obtained from off-line tool deflection prediction and open-loop compensation, these methods rely on accurate models of the cutting process and cannot adapt to changes in model parameters, disturbances in the cutting process, or uncertainties associated with workpiece alignment. Thus, open-loop compensation results are only as accurate as the assumed model parameters and workpiece characteristics. Critical model parameters such as tool wearland, workpiece material properties, and instantaneous spindle speed are difficult to estimate, and may change dramatically during milling.

This paper demonstrates that force feedback can be used to predict tool deflection and compensate for deflection during the milling operation, reducing susceptibility to uncertainties in model parameters and workpiece alignment. A specific force feedback approach is presented: tool deflection prediction (based on a non-dynamic model of tool stiffness). Real-time control algorithms incorporating this method were implemented and evaluated on a high-speed air bearing spindle. A tool stiffness model was developed to predict tool deflections (axial and radial) based on measured forces. Experiments involving machined grooves in hard steel workpieces, including simple slotting cuts and three-dimensional finishing operations, were conducted at various tool tilt angles to evaluate the effectiveness of force feedback control. Results indicate that profile errors can be reduced up to 80% compared to non-compensated cases. These results confirm that real-time force feedback control can significantly improve the dimensional tolerance and accuracy of injection molds created using miniature ball end mills.

2 TOOL FORCES AND DEFLECTIONS

The tool force model developed by Clayton [7] can be used to calculate cutting and thrust forces during milling operations. Inputs to this model include material properties and friction at the rake and flank faces of the tool. Tool geometry and cutting conditions 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. 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 experimental measurements using the three-axis load cell.

The long shank, ball end milling tools used in this research have a 4.0 mm shank with a 0.8 mm ball diameter end. When used to fabricate free-form surfaces, the tool can be loaded in the axial direction, the radial direction, or both. The tool stiffness is significantly lower in the radial direction (see Table 1), therefore regions of a machined surface where the tool is loaded primarily in the radial direction will be subject to large tool deflections and form errors.

Table 1: Measured and computed stiffness values for long shank, ball end tools

Axial Stiffness (N/m)	1421000
Radial Stiffness (N/m)	98930
25 degree Tilt Stiffness - Calculated (N/m)	419565
25 degree Tilt Stiffness - Measured (N/m)	455120

For the experiments presented in this paper, the tool was tilted at a 25 degree angle with respect to the z-axis to emphasize the effects of tool deflection. For arbitrary cutting conditions, the tool stiffness in the direction orthogonal to the workpiece (normal tool stiffness k_n) can be determined by the experimentally validated expression:

$$\frac{F_n}{\delta_n} = k_n = \frac{1}{\left(\frac{\cos^2 \phi}{k_a} + \frac{\sin^2 \phi}{k_r} \right)}$$

where: δ_n = normal tool deflection k_r = radial tool stiffness
 F_n = normal tool force ϕ = tool tilt angle
 k_a = axial tool stiffness

3 CLOSED-LOOP COMPENSATION OF TOOL DEFLECTION

Real-time force feedback can be used to predict and compensate for tool deflection during milling operations, reducing susceptibility to uncertainties in tool force model parameters and workpiece alignment. Figure 1 illustrates the effect that tool deflection has on a groove profile. The tool tip is programmed to follow a desired path. However, due to deflection the tool tip, the tool actually creates a depth of cut less than desired (labeled "actual depth" in the figure). The shaded area in this figure represents material not removed due to tool deflection.

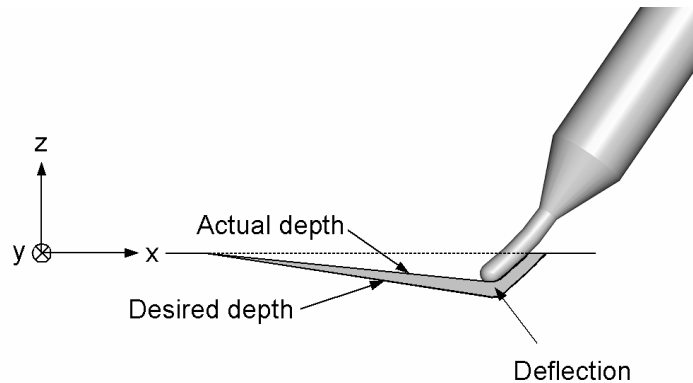


Figure 1: Tool deflection with desired and actual depth

A block diagram of the control algorithm used to predict and correct for tool deflection is shown in Figure 2. The concept behind this algorithm is straightforward: start with a desired tool path, measure real-time cutting force, use the tool stiffness model and measured force to predict tool deflection, calculate an error equal to desired position minus DTM encoder position plus predicted deflection. Once this error has been calculated, PID control either holds position, moves farther into the workpiece in the z-direction increasing the depth of cut, or moves out from the workpiece decreasing the depth of cut. With a validated stiffness model, deflection can accurately be predicted based on tool stiffness and a measured real time cutting force. In this way the system uses real-time force feedback to correct for errors associated with tool deflection and uses encoder feedback to maintain tool path stability. Error calculated by the PID control algorithm is:

$$\begin{aligned} \text{error} &= \text{desired tool position} - \text{encoder axis position} + \text{predicted tool deflection} \\ \varepsilon &= x_d - x + \delta_n \end{aligned} \quad (6)$$

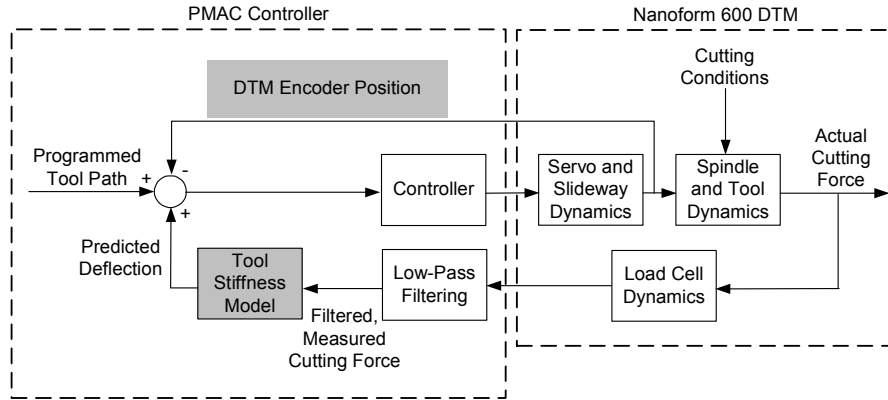


Figure 2: Diagram of predicted deflection algorithm

4 EXPERIMENTAL EVALUATIONS

To evaluate the effectiveness of the force feedback deflection compensation algorithms, extensive machining experiments were conducted on the Nanoform 600 DTM. Groove profiles were machined in S-7 tool steel samples (hardness > 55 R_c) mounted to a three-axis load cell. The workpiece was aligned with the axes of the Nanoform and cuts were made along the x-axis (left to right) with the tool tilted at 25 degrees from the z-axis to emphasize the effects of tool deflection (Figure 1).

Slotting cuts with linearly varying depth were made with and without compensation to evaluate the performance of real-time deflection compensation. Slots spanning 20 mm and 0-80 μm in depth were programmed, using a spindle speed of 10,000 rpm and a feed rate of 100 mm/min. This spindle speed was chosen because this was the minimum operational spindle speed to still have enough torque to make cuts in tool steel, and the feedrate was chosen to give a chip load of 5 μm/flute.

Typical results for closed-loop compensation using predicted cutting depth and a non-dynamic cutting force model are shown in Figure 3, with the upper plot representing the uncompensated cutting profile, the middle plot representing the compensated profile, and the lower plot representing the desired profile.

Profile errors were significantly and consistently improved throughout the cutting experiment. Maximum profile errors with predicted deflection compensation are approximately 4 μm, compared to 21 μm with the uncompensated cut. This equates to an 80% reduction in groove profile error. In contrast to the predicted depth

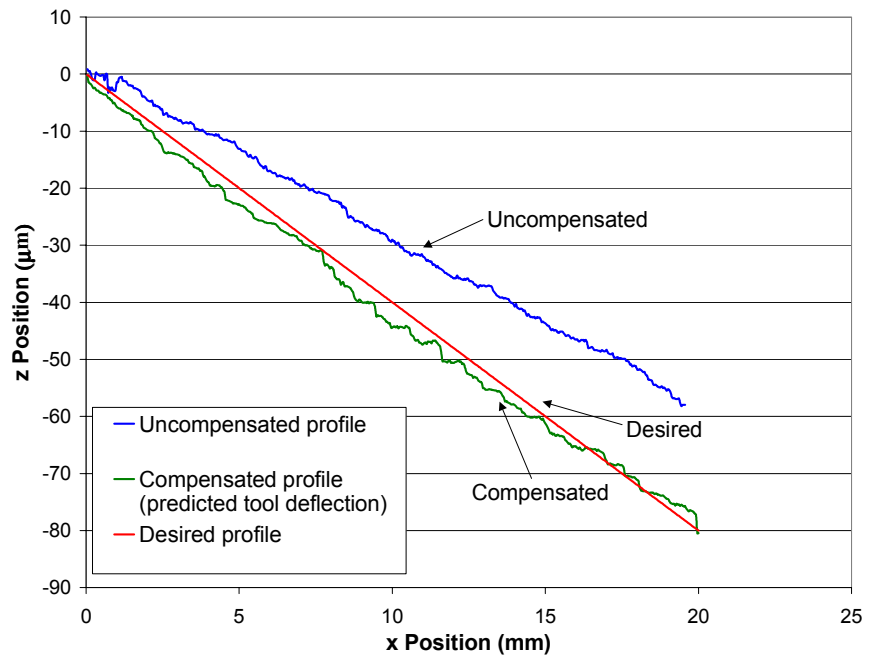


Figure 3: Experimental profile measurements: predicted deflection compensation, linear slotting cut

compensation, errors are initially small and remain small throughout the experiment (between +4 μm and 0 μm), resulting in depth error at the end of the groove of -2 μm .

5 CONCLUSION

The forces generated during milling with a miniature ball end 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 profile error because of low radial stiffness. Predicting tool deflection using real-time cutting force measurements can be used to compensate for errors arising from tool deflections and workpiece misalignment. Reduction in error in small groove profiles over non-compensated groove profiles can be as great as 80% depending on the profile.

Overall, force feedback control of miniature ball milling proved applicable in many situations for correcting errors in machined parts due to tool deflection. Significant reductions in profile error for large and small groove experiments were documented, though success depends heavily on the acquisition, processing, and filtering of cutting forces during machining.

6 REFERENCES

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