# COMPENSATION OF TOOL FORCES IN SMALL DIAMETER END MILLS

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## ABSTRACT

Miniature solid carbide end mills are being used to produce small features in hard metal surfaces. These tools, in either straight or ball end configuration, can produce intricate shapes in very hard steel (H>55Rc), quickly and without grinding. However to reach into small features, the length of the tool becomes large enough (length/diameter ratio >5/1) to influence the dimensional tolerances of the machined part due to deflection of the tool. This deflection is a response of the tool to the machining forces that are in turn a function of the tool geometry, cutting condition, tool wear, lubrication, etc. This paper describes the magnitude of the cutting and thrust forces, the influence of tool wear, the stiffness of the tool and the errors in machined features as a result of the tool deflection.

## INTRODUCTION

In past research programs, the Precision Engineering Center (PEC) has developed a model for predicting the forces on milling cutters in both the cutting and the radial direction. This model grew out more than a decade of involvement by the PEC with diamond turning and the need to predict tool force changes that accompany minor changes in the tool geometry due to wear. This model has been applied to the milling geometry and predicts cutting and thrust forces as well as changes in those forces associated with wear on the tool edge. For a small tool, the forces associated with cutting can produce a significant deflection of the tool and result in errors in the shape of the machined part. This is a particular problem for a ball end mill because cutting can take place at different points around the radius of the tool and therefore along directions with different stiffness. As a result, the shape of the part will be influenced. By developing compensation techniques for these errors, improved accuracy for machined parts are possible.

## TOOL FORCES

### PREDICTED FORCES

The tool force model provides a formula for calculating the cutting and thrust force developed during milling. The inputs to the model are the material properties (hardness, modulus), friction at the rake and flank faces of the tool, tool geometry (ball end radius), spindle speed, upfeed and cross feed, depth of cut and tilt angle of tool. The model can be written as:

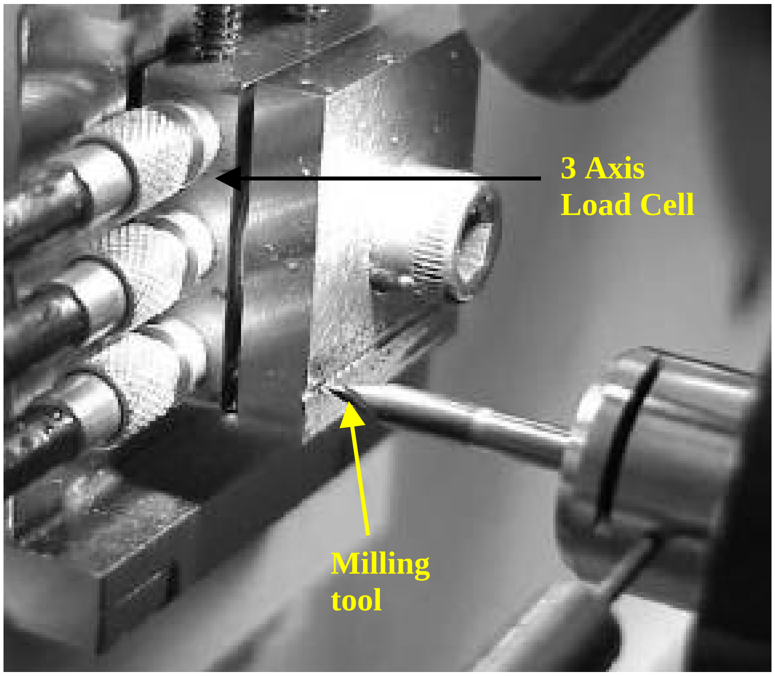
$$F_c = \frac{HA_c}{3}\left(\frac{\cot\phi}{\sqrt{3}} + 1\right) + \mu_f A_f\left(0.62H\sqrt{\frac{43H}{E}}\right) \tag{1}$$

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

where

$A_c$ = cross section of the chip,
$A_f$ = area of the tool flank face,
$\phi$ = shear angle in the workpiece,
$\mu$ = friction coefficient on rake face,
$\mu_f$ = friction coefficient on flank face,
$H$ = hardness of the workpiece, and
$E$ = modulus of the workpiece.

For the milling geometry, these forces rotate with the flank face of the tool. The predicted values can be converted to forces in the x,y, and z directions and then compared to measurements made with a stationary load cell.




## Measured Forces

The forces have been measured with a 3 axis piezoelectric load cell pictured at right. This load cell is mounted on the x axis of a diamond turning machine while a high speed spindle driving the milling tool is mounted on the z axis. The milling tool can be rotated at speeds up to 60,000 rpm and the axes can move at speeds up to 500 mm/min. The tool can be mounted such that it is normal to the workpiece or at an angle up to approximately 60˚.

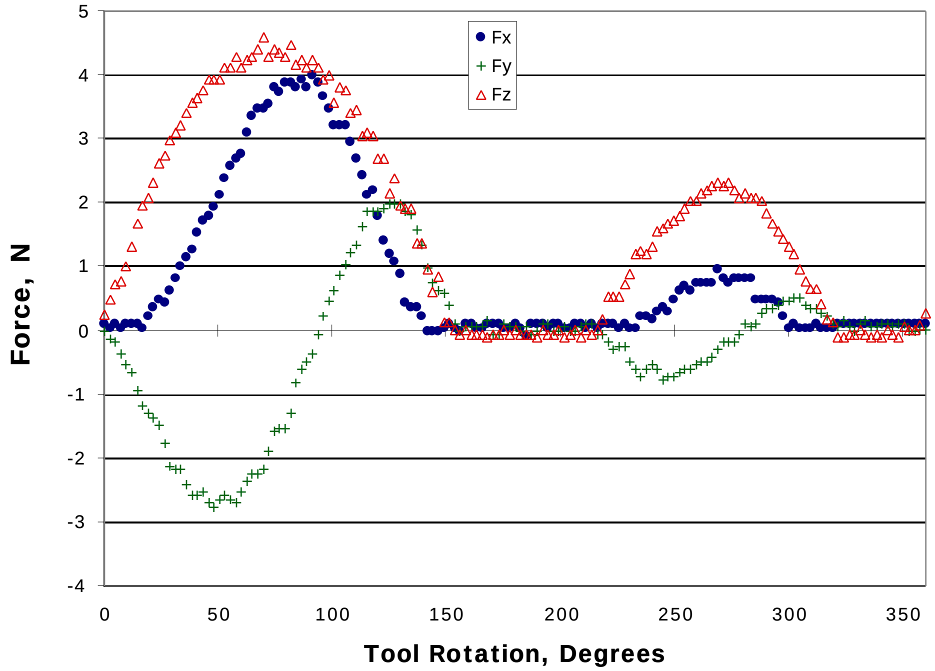



**Figure 1.** Measured tool forces cutting hard steel at 25 µm depth of cut, 19 µm/flute feed rate using an 0.8 mm diameter ball end mill at 20,000 rpm tilted 10˚ with respect to surface normal.

A sample of the output of the load cell is shown in Figure 1. This plot shows the average forces in the x, y and z directions for 3 consecutive rotations of the tool. Note that the forces for the first flute are significantly higher than for the second (approximately twice as large) as is the period of contact between the flute and the workpiece. The reason for this inequality in forces is likely the effect of tool runout; the magnitude of which is 10 µm for the high-speed spindle used. The z-component of the force in Figure 1 is dominated by the tool thrust force, Equation (2), because the tool is almost normal to the workpiece (10˚ of tilt). The x and y forces are influenced more by the cutting force, Equation (1), which rotates in the plane of the workpiece and changes from a force in the x direction to a force in the y direction for each 90˚ rotation of the tool.

## TOOL STIFFNESS

The miniature milling tools are fabricated from tungsten carbide with a titanium aluminum nitride coating. The tools have a 3 mm shank which tapers down to the ball diameter (see the photograph above). The ball end can be at the end of the tapered section for the short tool or at the end of an extended section with a diameter equal to the ball. The long tool discussed later has an extended section of 5 mm. Typically a ball mill is used to fabricate free form surfaces and as a result the tool can be loaded axially, radially or both. The stiffness of the tool is quite a bit less in the radial direction than in the axial direction. Therefore, regions of the machined part that load the tool in the radial direction will cause significant tool deflection and the part dimensions will be different than expected.

The tool was modeled as a cantilever beam mounted in a spindle with finite axial and radial stiffness. Because it is made up of straight and tapered sections, the model is straightforward and a simple analytical calculation was made. However, the stiffness of the spindle is an unknown that must be measured. The measured and predicted stiffness are shown in the Table below. The predicted stiffness of the long tool is quite close to the measurements but the short tool stiffness is overpredicted because of unmodeled changes in the shape of the reduced section as a result of grinding the ball end mill geometry.

| Tool Length (Stiffness direction) | Measured Stiffness, N/m | Calculated Stiffness Including Spindle Stiffness, N/m | Calculated Stiffness Neglecting Spindle Stiffness, N/m |
|---|---|---|---|
| Short (Radial) | 406,203 | 557,000 | 971,000 |
| Short (Axial) | | 845,000 | $300 \times 10^6$ |
| Long (Radial) | 198,533 | 208,000 | 250,000 |
| Long (Axial) | | 840,000 | $60 \times 10^6$ |

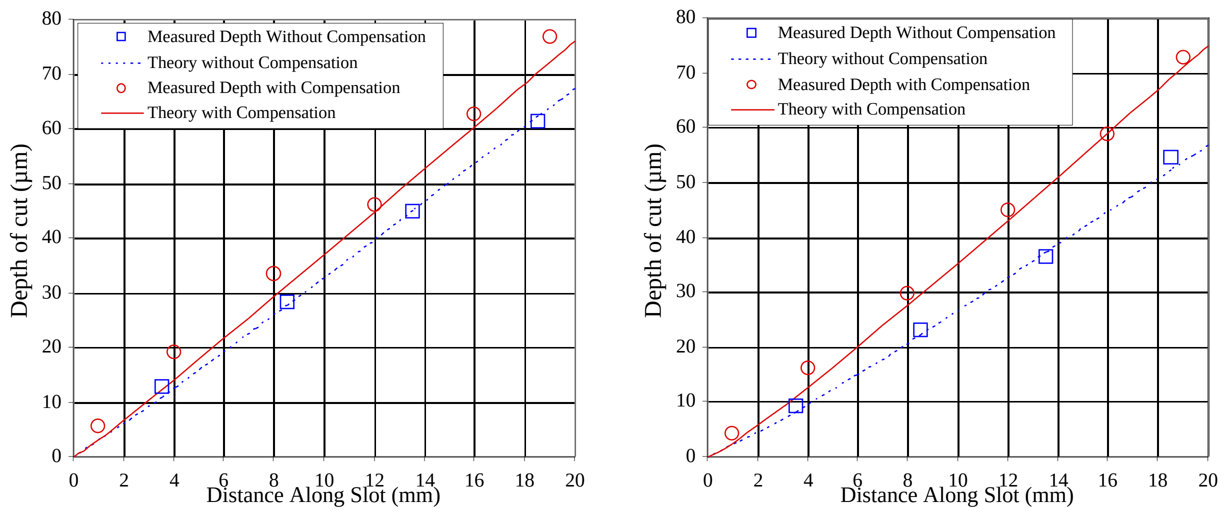
## TOOL DEFLECTION

### DEFLECTION PREDICTION

With a force model and the stiffness of the tool measured, the deflection of the tool during machining can be predicted. Because the tool will be loaded in a variety of directions during a milling operation, the model of tool deflection must take into account the direction of the cutting forces as well as their magnitude. Such a model has been created and used to predict deflections in several different experiments.

## DEFLECTION MEASUREMENT

**Variable Depth Groove** One experiment used to corroborate the model is to mill a slot with a varing depth of cut using tools tilted at different angles with respect to the workpiece. In this way the influence of depth of cut and tool orientation can be evaluated quickly. The results on one set of experiments is shown in Figure 2. Figure 2(a) shows the measured and predicted deflections for a tool tilted at 25˚ to the surface normal and following a commanded slope beginning at 0 depth of cut and continuing to 75 µm after 20 mm of motion. The lower line is the predicted tool deflections for the feed and speeds of the experiment and the points represent the depth of cut measured on the part using a Form Talysurf at several locations along the line. The upper line is the desired path of the tool (0-75 µm slope) and the points are the result of the experiment where the theoretical compensation is applied to the cutter path. The data shows that the model does an excellent job of predicting the deflection as well as providing guidelines to produce the desired shape.




a) 25 degree tilt angle  b) 50 degree tilt angle

**Figure 2.** Uncompensated and compensated tool deflections in hard tool steel machining a variable depth groove from 0-75 µm (feed rate = 10 µm/flute, speed = 20,000 rpm)

Figure 2(b) shows the results of similar experiments but with the tool tilted at 50˚ from the normal. In this case the forces are directed more in the radial direction (the direction of lower stiffness on the tool) and the uncompensated deflection is larger than the 25˚ case. The model provides an excellent fit both for the uncompensated deflections as well as target points to produce the desired slope.

## DEFLECTION COMPENSATION

The process typically used to produce highly accurate parts is to machine the desired shape, measure the resulting shape and compensate the tool path to produce the desired shape. This is commonly applied to diamond turned optical parts but these geometries are much simpler than the prismatic parts produced on a multi axis machining center. The proposed compensation technique is based on the shape of the part and the setup of the machine that influences the contact direction of the tool and workpiece at each point on the surface. Based on the model for force and tool deflection, the tool path can be modified to compensate for the deflection of the tool and produce a more accurate machined component on the first try.

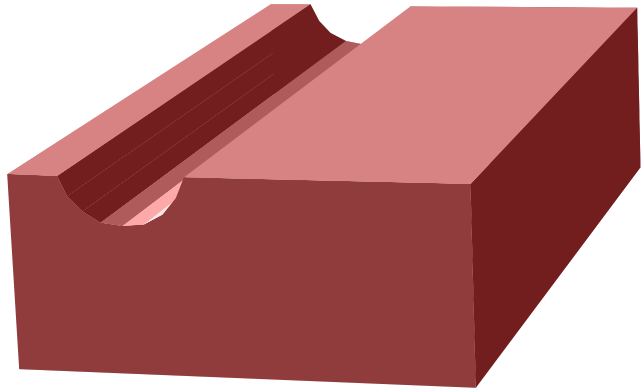


**Figure 3.** Geometry used for the compensation experiments

The geometry selected for the compensation experiments is shown in Figure 3. The particular feature of interest is the shape of a torus (with a radius of 8.4 mm, a width of 12 mm and a depth of 3 mm). The part was placed in the spindle of a DTM and rotated at low speed (<30 rpm). The specimen was first machined using a much stiffer poly-crystalline CBN tool that produces a reference shape within 1 µm of the desired radius. The part is then machined using the miniature end mill with a different up-feed and cross-feed rates and different depths of cut. The shape of the groove after the milling experiments was compared to the reference shape and the deflection of the tool was determined.

Other experiments were performed using a modified part program based on the stiffness of the tool and the angle of contact between the tool and the workpiece. This procedure is the same as described in Figure 2.. The compensation technique resulted in parts with significantly less shape error - the error was reduced by an order of magnitude to ±2 µm.

## CONCLUSIONS

The forces generated during milling with a miniature tool are relatively small because of the limited size and strength of the tool edge. However, the tool deflection can be significant because of the low stiffness and long length of these tools. The model for tool force does an excellent job predicting the forces associated with cutting as well as the contribution from tool wear. The compensated tool path based on the forces and orientation of the tool with respect to the workpiece provides an avenue to produce the first part right.

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