TWO-AXIS FORCE-FEEDBACK DELFECTION COMPENSATION OF MINIATURE BALL END MILLS

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INTRODUCTION

The fabrication of injection molding dies is an application of interest for this research. These dies are machined from hard steels (Heat treated to ~ 60 Rockwell C) to provide durable, wear resistant dies. Manufacture of these dies containing small features or precision surfaces require the use of tools with small radii. The tools required for such machining (Diameters < 1.0 mm) termed miniature tools are the focus of this research. These tools are available in several different shank lengths to accommodate various applications and die geometries. Figure 1 contains a photograph of the 0.8 mm diameter miniature ball end mills used. The tools are made of tungsten carbide with a titanium aluminum carbide coating. Although the tool material is very strong, the thin geometry of these tools results in low tool stiffness (0.2 N/μm and less) which becomes a significant factor machining heat treated steels. Deflections of these tools under low (10N) cutting forces can produce part errors of 50 μm with a 4.0 mm long shank. The goal of this research is to reduce tool deflection errors through the use of force-feedback machining. In previous research at the PEC, Hood [1] used the machine axes to compensate deflection of the tool normal to the part. In this compensation technique, the inertia of the machine axes becomes a limiting factor to the response speed of the system. To achieve higher bandwidth, Clayton [2] designed a single-axis tool actuator on the spindle with a force transducer for measuring cutting forces. The present work continues this focus by describing the performance of a two-axis force feedback spindle that measures and compensates for tool deflections in two orthogonal directions.

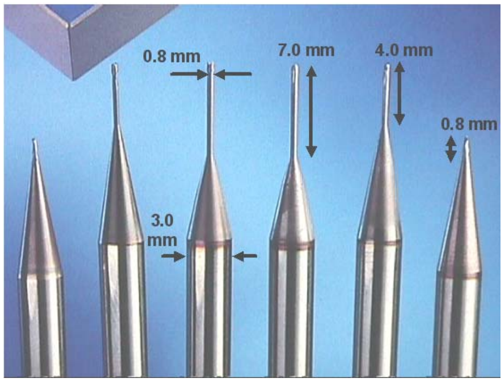

Figure 1. Miniature Ball End Mills

DESCRIPTION OF APPARATUS

The two-axis force feedback actuator uses piezo electric actuators to produce the tool displacement, flexures to guide the displacements, and capacitance gages to provide closed loop position feedback. The spindle actuator assembly contains two 3-axis piezoelectric load cell (Kistler Model 9251) mounted beneath an air-bearing machining spindle and above the actuation platform (See Figure 2). The load cell location was moved from the previous single transducers designs to better measure the real time cutting forces. The load cell was located such that the actuation forces could affect its reading reading. Separation of this force loop in the new design allows more accurate measurement of the cutting forces with minimal interference from the actuation forces.

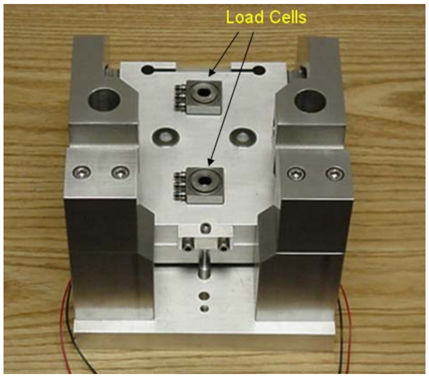

Figure 2. Force Measurement Platform

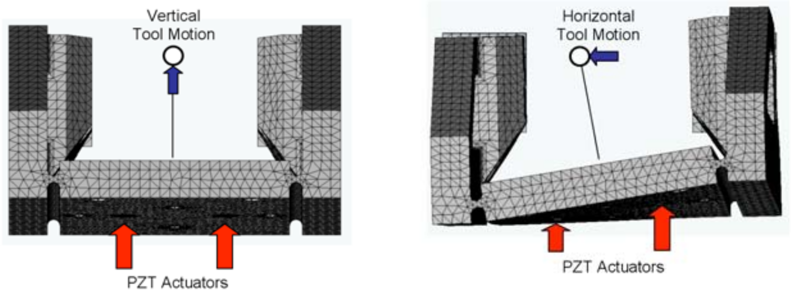

Figure 3. Horizontal and Vertical Tool Actuation

The two load cells are spaced evenly about the spindle's center of gravity to reduce the effects of in-phase or out-of-phase spindle vibration in processing of the force signal. Beneath the force measurement platform are two piezoelectric actuators used to produce the horizontal and vertical tool motion. The two actuators are driven differentially to produce horizontal motion and driven in parallel to produce vertical motion (See Figure 3). The structure contains two different flexure axes for the horizontal and vertical actuation to eliminate undesired tool displacement in the axial direction of the tool. The vertical axis is located in line with the tool center to prevent axial displacement while the horizontal axis is offset from the tool centerline to allow the horizontal actuation (See Figure 4). A photograph of the actuator assembly is shown in Figure 5.

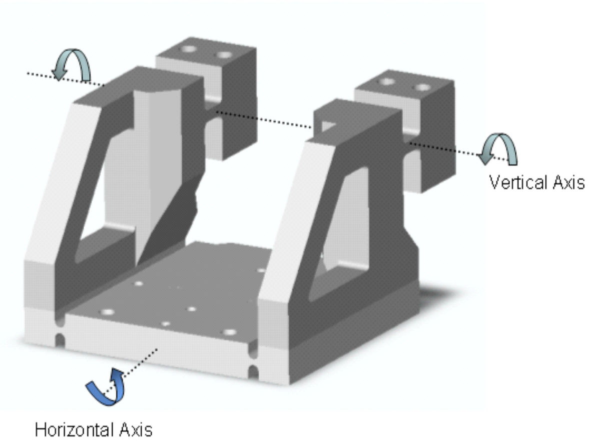

Figure 4. Horizontal and Vertical Flexure Axes

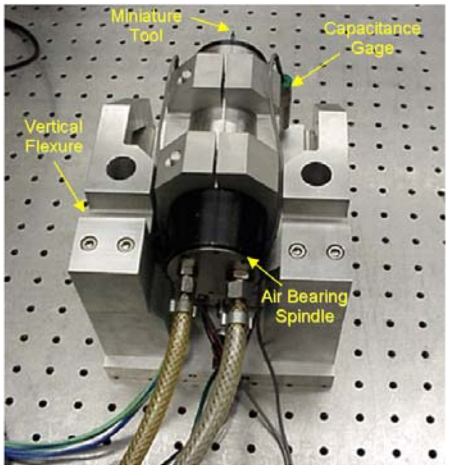

Figure 5. Spindle Actuator Assembly

The acutation system is a two-input two-output system where the displacement at each piezo stack affects both the horizontal and vertical tool position. Control of the actuator is achieved through decoupling of the horizontal and vertical dynamics. Proportional Integral (PI) control is used to control the horizontal and vertical systems separately and then recombined to solve for the individual voltage to each actuator. The horizontal controller produces the differential voltage between the two piezoelectric stacks while the vertical controller produces a sum. The command following of the two-axis actuator was evaluated with an 8 μm square profile. The square motion profile in Figure 6 was carried out in a total time of 500 ms. The entire force feedback control algorithm is shown below in Figure 7 where the horizontal and vertical tool forces are first measured to produce a desired horizontal and vertical tool position. The two axis controller then positions the tool to the desired position using capacitance gage closed loop feedback.

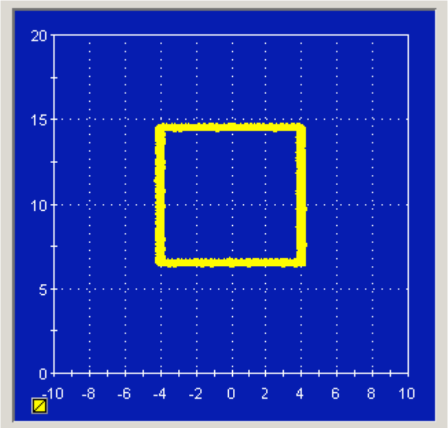

Figure 6. Command Following 8μm Square, 500ms

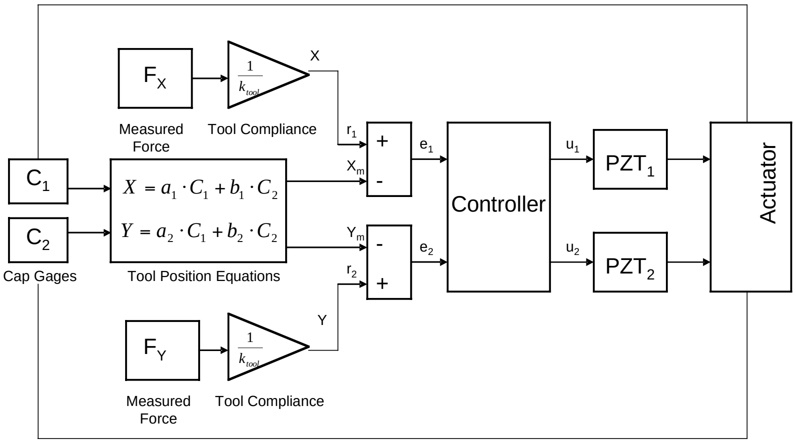

Figure 7. Force Feedback Control Algorithm

EXPERIMENTAL VERIFICATION

To exercise the two-axis force feedback actuator, two 3-dimensional surfaces were raster cut using the force feedback spindle actuator and a fixed spindle for comparison. The two axis spindle actuator was mounted on the Y (Vertical) axis of a Nanoform 600 DTM (Figure 8). The parts were raster cut feeding left to right along the X-axis and using the Y-Axis to provide the cross feed. A 5 mm diameter hemisphere was cut using both the force feedback spindle and a fixed spindle for comparison. A photograph of the raster cut hemisphere is shown in Figure 9. Probe interference when using the Talysurf profilometer near the walls of the hemisphere made it difficulty to obtain accurate measurements of this shape. A four-sided frustum was selected to improve measurement capability. The dimensions of four sided frustum are a 5mm square with a 1mm square located 1.5mm deep (Figure 10). The finished feature was measured by scanning across it with the profilometer. The machining forces for this geometry result in deflection of the tool in both of the active directions of the system as shown in Figure 11. A comparison of the surfaces produced by the force feedback spindle and the fixed spindle are shown in Figure 12.

Figure 9. 5mm Hemisphere

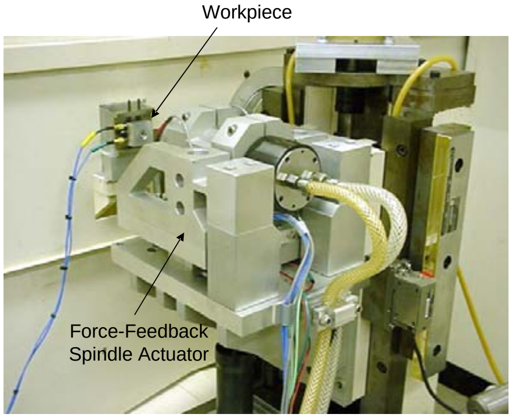

Figure 8. Experimental Apparatus

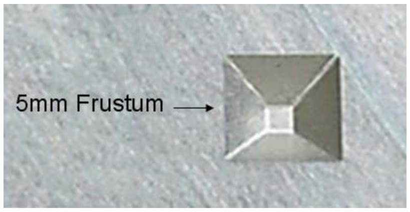

Figure 10. 5mm 4-Sided Frustum

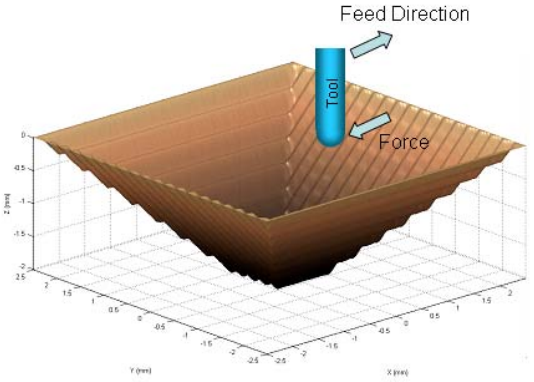

Figure 11. Feed Direction and Tool Force Direction

Here the error for tool deflection is corrected by moving the tool into the part by approximately 15µm over the uncompensated profiles.

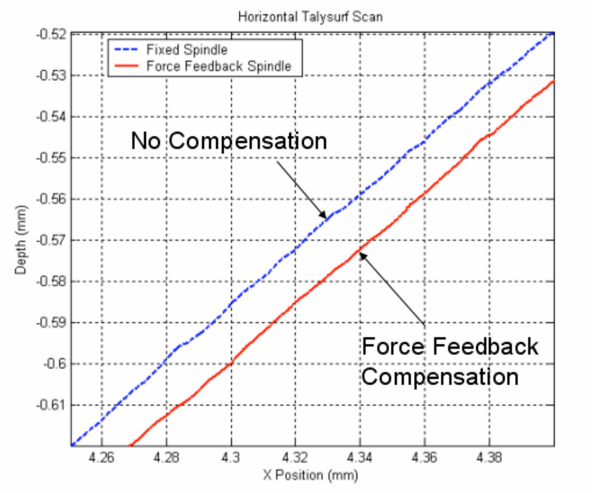

Figure 12. Part Measurement Comparison

The machining parameters of the four-sided frustum were first a rough cut using a cross feed (ΔY) of 250µm and increasing depth (ΔZ) of 200µm until the rough cut depth of 1.2mm was achieved. A federate of 50mm/min was used for both the rough cut and final pass. The final pass was a 300µm depth of cut with 100µm cross feed (ΔY) to obtain the final part geometry.

CONCLUSIONS

The mechanical design of the 2-axis system allows the machining force in each direction to be independently measured and the tool end positioned to compensate for the resulting deflection. Two 3-axis load cells are used to measure the force and the correction is made with two piezoelectric actuators that use capacitance gages for position feedback. Techniques for capturing the peak force, using that force along with the tool compliance to create a positioning error, comparing that error with the cap gage readings and sending the filtered commands to the actuators have been developed and demonstrated. Two machined features are described: a 5 mm radius hemisphere and a 5 mm wide 4-sided frustrum. Each surface was machined using a raster scan technique and the magnitude and direction of the machining forces were measured and tool deflection compensated. Error in final part geometry due to tool deflection was reduced by 15µm through the implementation of force feedback compensation.

REFERENCES

1. Hood, D., Clayton, S., Buckner, G., Dow, T., Garrard, K., "Closed Loop Control of Milling Tool Deflection", ASPE Proceedings, Vol. 27, pg 623.
2. Clayton, S. Freitag, K , Dow, T.A., "Closed Loop Control of Tool Deflection", ASPE Proceedings, Vol. 30, 2003, pg 459.