An Ultra-high Speed Spindle for Micro-milling

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1.0 Introduction

Milling is the fabrication technology of choice for a wide range of complex three-dimensional components, in a wide variety of materials. It is most commonly used to produce features ranging in size from a few millimeters up to thousands of millimeters. Small diameter milling cutters (~0.10 mm dia.) are widely and inexpensively available, and are mostly used to create small features in graphite EDM electrodes used to manufacture injection molding dies. There exists a wide variety of important applications for micro- and meso-scale mechanical systems which require high-strength materials and complex geometries that cannot be produced using current MEMS fabrication technologies. Micro-milling [9] is one fabrication technology with potential to fill this void by adding the capability of free form machining of complex 3D shapes from a wide variety and combination of engineering alloys, and other materials.

2.0 Difficulties and Challenges of Micro-Milling Technology

Micro-milling technology has many challenges associated with the scaling of the milling process, resulting in inefficiencies in the process. These include:

1. *Tool failure*. Micro milling tools often fail by fracture at the tool root, as opposed to edge wear. Because of the small diameter of the tools, the cutting forces must be kept very small so as not to exceed the bending stress fatigue limit of the tool.
2. *Chip Load*: In order to keep the cutting forces sufficiently small, the chip thickness must be very small, often less than 1 micrometer.
3. *Cutting Edge Radius*: Commercially available micro-end mills typically have cutting edge radii on the order of 2 to 3 micrometers, substantially higher than the desired chip thickness. This means that the effective rake angle of the cutting edge is highly negative, leading to cutting force coefficients much higher than in conventional milling..
4. *Spindle Runout*: Commercially available micro-milling spindles typically have radial runout at the tool tip on the order of 1 to 2 micrometers or more, larger than the desired chip thickness; leading to overloading of the tool and premature failure.
5. *Cutting Speed*: As the tool diameter decreases, the spindle speed must increase to achieve the same (optimum) peripheral cutting speed. For very small tools, spindle speeds over 500,000 rpm are required.

Inefficiencies in milling small features result directly from the relationships between a cutting tool's breaking strength, the cutting force, and the material removal rate (MRR). End mills act much like long, thin, end-loaded cylindrical cantilever beams, where the maximum bending stress (σ_x) is:

$$\sigma_x = \frac{32 F_c L}{\pi D^3} \tag{1}$$

where L is the tool length, D is the tool diameter, and F_c is the transverse cutting force. For a given L/D aspect ratio of the tool, the bending stress increases with the square of reductions in tool diameter. Therefore, in order to prevent tool breakage, the cutting force must be reduced. The maximum tangential cutting force is approximately:

$$F_c(\mathrm{N}) = K_s(\mathrm{N/mm}^2)\left[b(\mathrm{mm}) \underbrace{\left(\frac{f_r(\mathrm{mm/min})}{n(\mathrm{rev/min})\, m(\mathrm{teeth/rev})} \right)}_{ChipLoad} \right] \tag{2}$$

where K_s is the cutting force coefficient of the workpiece material, b is the axial depth of cut, and f_r is the feedrate, n is the spindle speed, and m is the number of teeth on the cutter. To reduce the cutting force, it is necessary to reduce the chip load, or maximum chip thickness. This can be accomplished either by decreasing the feed rate, or increasing the spindle speed. For a cut with radial depth, a, the MRR is:

$$MRR\ (\mathrm{mm}^3/\mathrm{min}) = f_r\,(\mathrm{mm}/\mathrm{min})\,b(\mathrm{mm})\,a(\mathrm{mm}) \qquad \textbf{(3)}$$

From Equations 1-3, we can see that as we reduce component size by a scaling factor, $\boldsymbol{k<1}$**,** the MRR decreases at the rate of $\boldsymbol{k}^3$. If spindle speed is held constant, the cutting force must reduce by a factor of $\boldsymbol{k}^2$**,** necessitating a reduction in the feed rate by a factor $\boldsymbol{k}$. This relationship does not take into account the large tool edge radius and spindle/tool runout relative to the chip thickness in micro-milling, which causes higher cutting force coefficients and tends to increase cutting forces for a given chip area, necessitating even further reductions in feed rate to prevent tool breakage. One solution to this problem is to increase spindle speed to maintain the desired peripheral cutting speed, while also minimizing runout. However, for very small diameter end mills, the required spindle speeds can be 500,000 rpm or higher.

3.0 Ultra-high Speed Micro-milling Spindle Design Concept

The previous analysis of micro milling demonstrates the need to develop a spindle capable of extremely high rotational speeds, while maintaining sub-micron radial error motions. Commercially available micro-milling cutters typically have a 0.125-inch diameter shank, approximately 1.25 inches long, with the actual cutting flutes ground on the end of the shank. The proposed spindle system supports the tool shank in a porous carbon air bearing, custom designed for this application. The tool shank itself is driven by a friction wheel which is driven by a commercial high speed spindle. The drive ratio of the friction drive system is approximately 8:1, making it possible to achieve tool speeds over 500 krpm using commercially available high speed motorized spindles. The friction wheel is coated with a compliant polymer coating which reduces the contact stiffness, and helps to insure that error motions of the drive spindle will not be transmitted to the tool shank. The drive spindle is mounted on the base frame with a set of spherical washers and 4 adjusting screws. This arrangement allows the motor axis to be tilted in two perpendicular directions to control the normal force between the friction wheel and tool shank. The drive spindle axis is slightly tilted relative to the tool shank axis, so that the friction force has a small vertical component, forcing the tool shank against the thrust air-bearing stop. This also allows easy tool change by stopping the motor and rotating the tool shank by hand in the opposite direction to force the tool out of the air bearing. The entire air bearing assembly is supported on a 3-axis force sensor to allow for continuous measurement of cutting forces. The conceptual design of the ultra-high speed micro milling spindle is shown in Figure 1.

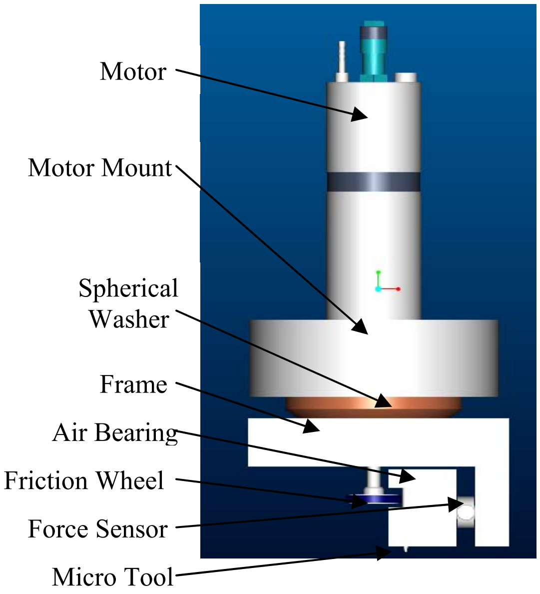

Figure 1. Spindle conceptual design

3.1 Model Development & Analysis

The drive spindle is selected based on torque and power calculations using Tansel's [1] cutting force model for micro-milling, and the projected tool and material combinations. A finite element analysis of the selected motor and friction wheel assembly predicted a lowest critical speed of 85k rpm with aluminum as the friction wheel material.

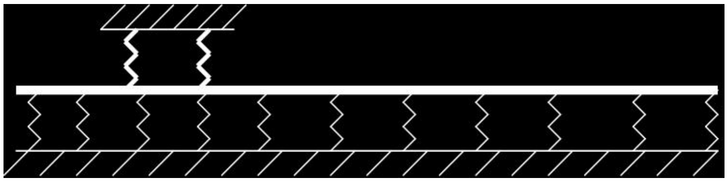

Figure 2: FE Model of the tool air-bearing and friction wheel

A finite element analysis of the micro-tool/air-bearing/friction drive assembly was also performed. Figure 2 shows the FE model. The tool inside the air-bearing is modeled as a continuous beam supported on springs with composite stiffness equivalent to the air bearing stiffness. The stiffness of the custom air-bearing was predicted to be approximately 4.3e4 N/m by extrapolating from published stiffness values of other air bearings produced by the vendor. The beam is also contacted by another spring with stiffness equivalent to the Hertzian contact stiffness between the tool and the friction wheel, which was estimated to be 1.68e6 N/m. The analysis predicts the lowest natural frequency of the system to be 4291 Hz. This corresponds to a rotational speed of approximately 257,000 rpm, and points to the need to increase the air bearing stiffness in future versions.

4.0 Experimental Set-up & Testing

The prototype micro-spindle was assembled and tested at the University of Florida Machine Tool Research Center. The nominal speed ratio between the drive spindle and the tool is 7.9:1 if no slip occurs. The micro-spindle system was interfaced with a National Instruments data acquisition card using LabView to allow measurement and control of the drive spindle speed, as well as 3-axis cutting force measurements, and run-out measurements. The air bearing is supplied with very clean air at 100 psi. For initial cutting tests, the micro-spindle was mounted on a large high speed milling machine which has hydrostatic guide-ways to insure low vibration levels in the machine. Figure 3 shows a photograph of the set-up.

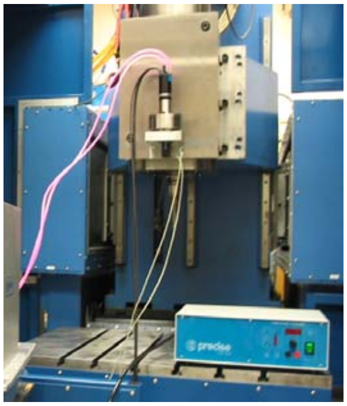

Figure 3: Experimental Set-up

4.1 Run-Out Measurements

Radial run-out measurements were carried out using Lion Precision capacitance probes. Initially, the radial runout of a point on the drive spindle arbor was measured at various spindle speeds both with and without the friction wheel mounted. The results are shown in Figure 4. There is a clear parabolic increase in radial runout when the friction wheel is mounted, which is attributed to centrifugal forces arising from wheel unbalance.

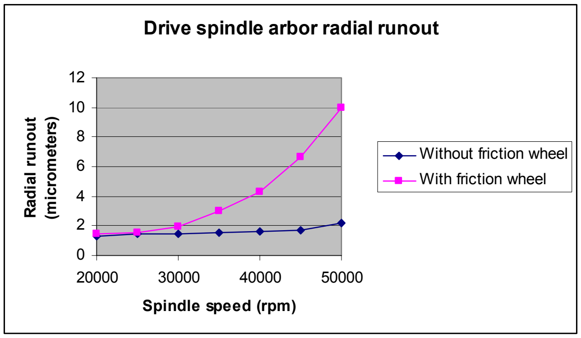

Figure 4. Run-out of drive spindle arbor

Next, the radial runout of the friction wheel surface was measured using a capacitance probe reading against the wheel surface through the polymer coating. The runout on the wheel surface measured approximately 60 micrometers, al though this value is somewhat unreliable since it contains effects both due to the non-circularity of the metal portion of the friction wheel, and thickness variations of the polymer coating.

Finally, a gage pin was inserted in the air bearing and driven by the friction wheel. The radial runout of the gage pin was measured at a point approximately 6mm from the end of the air bearing. The measured runout here was on the same order of magnitude as the friction wheel surface. These results show that the friction wheel surface is far too irregular for this application, and the imperfections in its surface are transmitted into the tool shank and amplified at the tool tip. Further analysis of the air bearing and friction wheel, and improved manufacturing methods for the friction wheel are needed to rectify this problem.

4.2 Cutting Force Measurements

Although the tool tip run-out was exceedingly high, preliminary cutting tests were performed to evaluate the cutting performance of the micro spindle. The initial cutting tests were performed at a drive spindle speed of 10,000 rpm which yielded a nominal tool speed of approximately 79,000 rpm. Slotting cuts were performed using tool diameters ranging from 0.03(762μm) inches to 0.005(127μm) inches. Slot depths of one-sixth of the tool diameter, and one third of the tool diameter were used. Figure 6 shows the feed direction force record for 127μm cutter with a 42.33μm slot depth and the largest achievable feed rate without tool breakage of 0.045 mm/min (0.376 μm/tooth). The

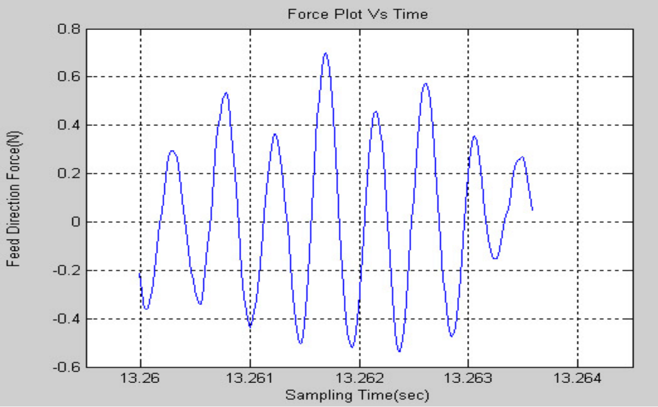

Figure 6: Feed direction force plot

passage of individual teeth is clearly evident in the force record. Significant variation in the peak cutting force is evident, and may be due to asynchronous error motions of the tool. Typical cutting test results are shown in Table 1. Both Tlusty's[2] and Tansel's [1] cutting force models were used to calculate the cutting force coefficient, K_S, using the average maximum feed direction force. For milling with macro tools, K_S for this material will be on the order of 800 N/mm^2. These results illustrate the increased specific cutting force coefficient as the chip thickness gets smaller than the edge radius of the tool. However, the large tool point runout in the current spindle makes the chip thickness vary for each tooth, and creates a large uncertainty in the computed cutting force coefficient.

Tool Diam. (µm)	**Width of cut** (µm)	**Depth of cut** (µm)	**Feed /tooth** (µm)	**Avg Max Force** (N)	**K_S (Tlusty)** (N/mm^2)	**K_S (Tansel)** (N/mm^2)
762	762	127	1.18	0.5072	5780	3340
762	762	127	1.66	1.6709	13500	7810
508	508	169.33	2.24	0.8575	3870	4470
508	508	169.33	2.63	1.195	4590	5300
254	254	84.66	0.479	0.2106	9690	11200
254	254	84.66	0.479	0.2101	7320	8470
127	127	42.33	0.187	0.1919	41400	47800
127	127	42.33	0.376	0.2421	26000	30100

Table 1: Cutting test results – Aluminum 6061

5. Discussion and Conclusions

The design, assembly and initial testing of a prototype ultra-high-speed micro-milling spindle have been completed. The results are encouraging but significant challenges remain. The friction wheel shows excessive runout, which will necessitate proper balancing and improved methods for applying the friction coating. At drive spindle speeds greater than 20k rpm it appears that the tool shank begins to contact the inner surface of the air bearing. This is believed to be related to the problems with friction wheel runout and unbalance. Solution to this problem will require a more compliant coating on the friction wheel and improvements in the air bearing to increase its stiffness. Nonetheless, the spindle is capable of operating at speeds in excess of 500,000 rpm for short periods. Recorded cutting forces are comparable to those reported by other researchers.

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