ABSTRACT

This paper addresses the development of meso-scale machine tool (mMT) systems, motivated by the need of achieving high accuracy and process efficiency. The rationale for machine tool miniaturization is described first followed by the description of the design of initial experimental testbeds that physically demonstrate the feasibility of the mMT concept. The testbeds utilize high-speed miniature spindles that are required to obtain appropriate cutting velocities for the efficient cutting of metals. The use of voice-coil actuated and piezoelectric feed drive technologies is also discussed. The mMTs are instrumented with load cells that collect force data for experimentation on micro-machining processes. Three-dimensional features are machined on one of the testbeds and cutting force data, surface finish data, and machined feature profiles are presented.

INTRODUCTION

Miniature components are needed for a wide range of applications from the aerospace to the biomedical industries. Many of these components contain three-dimensional features and are made from materials such as stainless steel, titanium, brass, and aluminum. Parts of the size of 500 μm with holes 125 μm in diameter and wall thickness of 25-50 μm are now commonplace. Such components are currently being manufactured on large, ultra-precision machine tools.

Recently, a number of investigations have been reported on the machining of micro-scale features and components and the associated issues of process mechanics at this level. Precision-machining processes have been studied on milling machines (Bao and Tansel, 2000; Schaller et al., 1999; Friedrich et al., 1998; Adams et al., 2001) and diamond turning machines (Lucca et al., 1994; Cheung and Lee, 2001). In general, this work has been conducted using conventionally-sized, specially-fitted ultra-precision machine tools.

Given the part size and the cutting forces present during micro-machining, using large machine tools results in a very inefficient utilization of resources in terms of floor space, energy requirements, and costs. These ultra-precision machines generally require expensive and specialized design features to achieve the desired level of accuracy.

Many sources of error present in machine tools scale favorably with miniaturization (Kussul et al., 1996), allowing the simplification of the design to meet the accuracy requirements, resulting in a less expensive machine tool. For instance, shorter Abbe offsets result in less amplification of angular errors. This allows for the use of components with less stringent geometric...
tolerances, and, therefore, result in less expensive components. Smaller moving masses mean less inertial effects and less energy required to move the machine components. Less input energy also results in smaller heat dissipation that results in smaller thermal distortions of the machine structure and less expensive machine designs to transport the thermal energy away from critical components.

Some research has been directed toward developing smaller machine tools. Kitahara et al. (1996) developed a micro-lathe measuring 32 mm in length. As reported by Lu and Yoneyama (1999), this micro-lathe suffered from poor accuracy and very limited shape generation capability. Accordingly, Lu and Yoneyama (1999) developed a miniaturized lathe almost an order of magnitude larger, 200 mm in length. This lathe was instrumented with a tool dynamometer and a study of the cutting forces was performed. However, the cutting speeds were exceptionally low, around 1 – 3 m/min for brass, due to the use of a 15,000-rpm dc motor for the spindle.

In this paper, the authors present the design and evaluation of miniature machine tools that are capable of achieving significantly higher cutting speeds, producing three-dimensional features in metals, and recording the cutting force signal during machining. Data is presented that evaluate the performance of these testbeds.

**RATIONALE AND OBJECTIVES FOR mMTs**

In defining the specific problem domain for the mMT development, it is important that size and precision requirements are considered as separate issues but yet in a joint way. Figure 1 schematically represents the size/precision problem domain. In the bottom to the right, the conventional ultra-precision problem domain is depicted, for which there has been considerable research, including the pioneering work led by Bryan (1979) at Lawrence Livermore Labs in the 1970’s. Similarly, the upper left part of the graph depicts the micro and nano-scale sized problems that the MEMS and material science fields continue to address. To the upper right those applications that deal with ultra-precision at the micro-scale level are represented. It is the goal of this research to consider mechanical manufacturing at the meso-scale through the use of meso-scale machine tool systems. An important characteristic capability of such systems will be the ability to machine 3-D features with no materials constraints, which further differentiates the mMT system from the typical MEMS and LIGA systems.

Two sets of metrics are driving the conceptualization and development of the mMT systems. The first is *relative accuracy*, defined as the ratio of the attainable tolerance-to-workpiece size, and the second is *volumetric utilization*, defined as the ratio of the machine and workpiece volumes. It is evident that the second metric is also closely related to the energy efficiency of the mechanism.

Figure 2 quantitatively identifies the region of the initial effort in terms of the relative accuracy. The objective is the development of meso-scale machining capabilities with relative accuracy between $10^{-2}$ and $10^{-4}$ when machining objects with dimensions between 50 and 5000 μm, considered “conventional meso-scale machining” (region D in Figure 2). It is believed that later developments can substantially increase this metric. It can also be seen that in absolute terms this development would yield tolerances corresponding to ultra-precision machining on conventional equipment.

Figure 3 highlights the relation of the envisioned meso-scale machine tool to conventional machines. It is evident that conventional machines exhibit a very low volumetric utilization. This is, in particular, the case when machining small parts on conventional machines where the volumetric utilization can exceed $10^{5}$. The development of mMTs attempts, on the meso scale, to improve this ratio by 10 to 100 times. The bold ellipse in Figure 3 shows the region of this effort.

In developing an mMT, the various functions of the machine tool system that need to be considered are those that are fundamental to conventional systems: a rotating or stationary cutting tool, a means to rotate the cutting tool or the workpiece at the necessary speeds, a device to facilitate relative motions between the workpiece and the cutting tool, including actuation of axes, part fixturing, a physical structure within which to integrate the aforementioned functional components, a motion...
controller, and a power source(s). Initially, machine tool systems in the (50 mm)$^3$ to (250 mm)$^3$ volume range will be developed, with the power source(s) and controller residing outside of this space. It is important from the outset that these entities are considered as machine tool “functions”, not to be confused with the elements and mechanisms that are traditionally used to achieve these functions in conventional machine tools.

In the meso-machine tool system, the range of motions, motion increments, and the forces required to facilitate motion are all orders of magnitude below those that are required of conventional machine tool systems. Since traditional macro-actuators with high rotor mass cannot be used because of the requirements of dynamics, accuracy, and “gentleness,” new feed-drive technologies need to be considered.

### mMT TESTBED DEVELOPMENT

The goals of developing the mMT testbeds are two-fold. The first goal is to develop testbeds in which various technologies could be studied for use in further machine tool miniaturization developments. The second is to use these testbeds to study the micro-milling/drilling processes. Several different types of mMT prototype testbeds have been developed to explore the feasibility of different feed-drive and spindle technologies and to explore the cutting performance in milling and in drilling operations. Evaluations are still in progress. The two principal feed-drive technologies that have been used are voice-coil motors and piezoelectric actuators. A brief description of the testbeds developed to study these two technologies follows.

#### VOICE-COIL-ACTUATED SYSTEMS

**Performance Specifications.**

Since one purpose of this testbed is to machine three-dimensional features in metals, sufficient cutting speeds need to be obtained for efficient material removal. To obtain a cutting velocity of 200 m/min with tools of diameter of 250 - 500 μm spindle speeds of 125,000 - 250,000 rpm are required. Obviously, smaller diameter tooling will require even higher spindle speeds. In order to effectively study the machining process at feed values of a few μm/tooth, a spindle with submicron runout is desired.

To obtain high quality components and have the ability to create complex features, closed-loop positioning feedback is required. Ideally, submicron resolution is required to make the features that are desired.

Cutting force measurement is required to allow for a closer inspection of the micro-milling process. Expected cutting forces are of the order of magnitude of 100 mN. This requires that a force sensor with a threshold limit well below 100 mN is used.

Since the tooling that will be used varies from 50 μm to 500 μm in diameter, it is desired to
have a camera to magnify the image to facilitate tool and workpiece setup and to monitor the condition of the tool.

The specification on the overall size of the initial testbed was set at 250 mm by 250 mm by 250 mm. Once additional information is gained about the cutting forces and stiffness requirements for the micro-milling process, a second-generation testbed will be developed of considerably smaller size.

**Testbed Design.**

In this section, the design of the miniature machine tool testbed shown in Figure 4 will be described. Descriptions of the components used in the machine as well as the process sensing equipment used will be presented. Finally, the controller capabilities will be briefly mentioned.

![Figure 4. VOICE-COIL ACTUATED MACHINE TOOL TESTBED.](image)

The testbed is composed of three subsystems: 1) a system to provide the rotation of the cutting tool, 2) a system to provide relative motion between the tool and workpiece, and 3) a system to monitor the cutting process.

**Spindle.** A promising technology for the spindles of a miniaturized machine tool is the high-speed spindles used in the dental industry. These air-turbine spindles are very small (< 20 mm in diameter and length) and are very inexpensive. However, these spindles will require improved runout capability. Therefore, while the accuracy improvement of these small air-turbines is being investigated, a larger, more accurate air-turbine spindle was chosen for the first testbed.

The spindle chosen is shown in Figure 5. This spindle has a maximum rotation speed of 150,000 rpm. It has a removable collet to allow for tooling with diameters ranging from 0.8 mm to 4.0 mm. Most available miniature tooling has a 3 mm shank, so the spindle is able to accept standard tooling available from many suppliers. The runout determined by evaluating the variation in the peak forces was estimated to be approximately 1 μm.

![Figure 5. AIR-TURBINE SPINDLE MOUNTED ON A LINEAR SLIDE.](image)

The spindle is mounted on a micrometer-driven linear slide to facilitate the changing of the tooling. The spindle can be retracted from the workpiece, the tooling changed, and then moved back into cutting position.

**Positioning system.** After surveying the available technologies for the positioning subsystem of the mMT's, two drive technologies were of immediate interest - piezoelectric friction drives and voice-coil drives.

Voice-coil positioning systems with linear encoders for position feedback and higher holding force were chosen for the first mMT testbed due to the availability of packaged positioning systems and the desire to further quantify the mMT cutting force system. This system utilizes direct-drive technology so that the motion is smooth and free from any backlash. The cutting velocity is easily adjusted and controlled.

Two voice-coil systems from SMAC are packaged together to achieve three-dimensional motion between the tool and the workpiece. In the current configuration, all three axes are stacked on the workpiece-side of the testbed, while the tool is held in a stationary location during cutting. As shown in Figure 6, a single-axis stage with 20 mm of travel is mounted onto a two-axis X-Y stage with 25 mm of travel for each axis.

Each axis of the voice-coil system is equipped with a 1 μm resolution encoder. A PID control loop is used to provide position feedback. The three axes have a maximum dynamic force capability of 80, 42.5, and 10 N, for the X, Y, and Z-axes, respectively. The vertical (Z) axis is equipped with a spring counterbalance to compensate for the weight of the load cell and workpiece.
Although current voice-coil systems are relatively large (125 mm by 125 mm footprint), a more compact, in-plane XY system is under development.

Sensing. A Kistler Model 9018 tri-axial load cell is mounted on the vertical stage to obtain the cutting forces. This load cell has a threshold load of 10 mN with a dynamic range of 1000 and 2000 N for the in-plane and the axial directions, respectively. The load cell is 16.5 mm in diameter and 7.5 mm in thickness and weighs 8.5 g. To accurately measure the in-plane forces, a preload of 13 kN is applied through the two steel block pieces on each side of the load cell.

Controller. A four-axis controller provided by SMAC is used to process the encoder signals, perform the positioning feedback, and deliver the necessary current to the voice-coil actuators. The controller also has programmable outputs allowing the collection of the following error, encoder position, and motor current.

MACHINE PERFORMANCE OF THE VOICE-COIL ACTUATED SYSTEM

In this section, the capabilities of the mMT testbed are addressed. First, the contouring capabilities of the controller are discussed. Then, the forces obtained with the load cell are presented. Finally, some measurements of the slot accuracy, the cross sectional profile and the trench bottom surface roughness are presented.

Contouring Capabilities

PC-based software has been developed on the MS Windows platform that emulates the functionality of a Machine Control Unit (MCU) of a three-axis milling machine. The core of the MCU is a software-based Digital Differential Analyzer (DDA) interpolator implementing linear, circular and helical interpolation. The input to the MCU is a standard part program in G-code that can be either manually programmed or generated by post-processing the Cutter Location (CL) data file using a CAD/CAM system.

Machining tests on 6061-T6 aluminum were performed to evaluate the performance of the machine. Initially, straight slots were milled. Once the ability to machine straight slots was verified, planar interpolation was implemented. Circles of 2 mm in diameter were machined at 125,000 rpm as shown in Figure 7 with a 250 μm diameter, two-fluted, carbide flat endmill using a feedrate of 0.4 mm/s. A slot was then machined with the same feedrate across each circle with an axial depth that varied from 60 μm to 140 μm with a wavelength of 1 mm.

Three-dimensional interpolation was also performed. Circles with diameters varying from 2.4 mm to 0.8 mm were machined using a feedrate of 0.5 mm/s with a varying depth of cut as shown in Figure 8 utilizing a 500 μm diameter, two-fluted carbide ball endmill. The depth of cut varies within every quadrant from 100 μm to 250 μm.

Force Data

The feed direction force for a slot machined at 90,000 rpm, with a depth of cut of 100 μm, and a feed of 4 μm/tooth is shown in Figure 9. After the initial entry into the slot, the peak forces for this case were observed to be around 1 N. A sample of the entire three-dimensional cutting...
forces showing the tooth-passing pattern is clearly shown in Figure 10.

The noise level of the load cell is shown in Figure 11. This level of noise, about +/- 20 mN, is representative of all the collected data.

**FIGURE 8. MACHINED CIRCLES WITH VARYING DEPTH OF CUT AND CAD DEPICTION OF PROFILE.**

**FIGURE 9. FEED DIRECTION FORCE FOR MILLED SLOT**

**Following Error**

The ability of the controller to follow the prescribed path was studied in order to verify that the voice-coil actuators are powerful enough for the application. The following error from the controller was collected during the machining of full slots under varying conditions – axial depths of cut from 50 – 100 μm, spindle speeds of 90,000 – 120,000 rpm, and feed velocities from 1.5 mm/s to 12 mm/s. The maximum following error observed under the condition of 90,000 rpm, 100-μm axial depth of cut, and 4 μm/tooth feedrate was 3 μm, or 3 encoder counts. Currently, a more compact in-plane voice-coil system is being developed with a 100 nm resolution encoder. This hardware improvement will significantly reduce the following error and improve the accuracy of the mMT.

**FIGURE 10. THREE DIMENSIONAL MACHINING FORCES FOR 7 REVOLUTIONS.**

**FIGURE 11. NOISE LEVEL IN THE LOAD CELL FORCES.**

**Surface Profile**

A Wyko NT1000 optical profiler was used to measure the surface of the machined slot. A cross section of the slot is shown in Figure 12 below. Evidence of burring can be seen in the left of the figure as the top surface bulges up near the slot. The sidewall surface sloped appearance is attributable to the inability of the optical system to measure vertical surfaces.

**FIGURE 12. CROSS SECTION OF A MACHINED SLOT.**

A measurement was also taken of the surface along the length of the varying depth slot
that was shown in Figure 7. The surface profile along the middle of the slot is shown in Figure 13. It can be seen that the surface profile exhibits the desired trajectory, a sine wave with a peak-to-valley of 80 μm and a period of 1 mm.

![Surface Profile](image1)

**FIGURE 13. PROFILE ALONG BOTTOM OF VARYING-DEPTH SLOT.**

**Surface Roughness**

A rectangular area at the bottom of the slot was also measured using the Wyko NT100 optical profiler, and the surface height values are shown in Figure 14. The measured surface roughness parameter, \( R_a \), computed from the Wyko measurement, for this slot was 0.27 μm.

![Surface Height](image2)

**FIGURE 14. SURFACE HEIGHT AT THE BOTTOM OF THE SLOT.**

**PIEZOELECTRIC-ACTUATED SYSTEMS**

To establish the feasibility of further miniaturization, to explore and assess different component technologies, and at the same time, achieve a significant reduction in the cost of the mMT a testbed that utilizes piezo-actuators and dental turbine based spindles is also being developed. Piezoelectric actuators are very attractive because of their low cost, small size and the possibility of generating unlimited travel distances.

**Performance Specification.**

Tests were conducted using a set of piezoelectric actuators that operate similar to the "inch-worm" principle connected to two cross-roller guided linear stages with 12 mm of travel as shown in Figure 15(a). The theoretically achievable speed is greater than 50 mm/s, the resolution is 0.1 μm, and the holding force is 10 N. The experimental testbed, developed for drilling and milling operations, has a 320,000-rpm air turbine spindle similar in configuration to dental handpieces and to hand-held engraving tools (see Figure 15(b)). The spindle cartridge used is made by NSK and uses miniature ball bearings and a 1.5 mm collet.

The testbed is also equipped with a three-component KISTLER 9251A force transducer. The transducer has a threshold load of 10 mN with a dynamic range of 2500 and 5000 N for the in-plane and the axial directions, respectively. The load cell is a 24 mm square of 10 mm thickness and weighs 32 g. To accurately measure the in-plane forces, a preload of 10 kN was applied through the transducer's mounting plates.

While piezoelectric actuators have several advantages such as low cost, small size and unlimited travel, their use in open-loop designs suffers from four problems affecting their ability to maintain a constant, programmable velocity: (1) the velocity of the actuators is very sensitive to preload, (2) the applied loads, in this case the cutting forces, cause significant velocity variations, (3) during one cycle of motion, the velocity of the stage is not very constant, and (4) since the actuators operate in an on/off mode, adjusting the velocity, while maintaining a smooth velocity, is very difficult. It was therefore necessary to implement closed-loop control to meet the accuracy targets. Feedback is provided by LVDTs with a 6 mm linear range that offer very high resolution. The selected system topology allows for drilling and slotting operations by micro-drills and mills.

The developed configuration indicates that this combination of technologies holds the promise of developing systems as small as 25 mm x 25 mm x 25 mm.

**SUMMARY AND CONCLUSIONS**

This paper presented the rationale for the development of the meso-scale machine tool (mMT) systems. In the paper, the development of two meso-scale machine tool testbeds was presented. One mMT testbed utilized voice-coil positioning systems and a larger, more accurate air-turbine spindle. Another testbed of
approximately 25% of the volume of the first utilized piezoelectric actuators and a less accurate, but much smaller and higher speed air-turbine spindle. Both testbeds have spindles capable of achieving appropriate cutting velocities for the cutting of metals. Machined surface profile and surface roughness were presented for features machined on one of the testbeds.

The testbeds were instrumented to perform experimentation of the micro-milling/drilling processes. Force data collected during machining was shown to possess a low-noise level and able to show the tooth passing nature of the cutting force.

FIGURE 15. (a) TWO AXIS PIEZO-ACTUATED TESTBED CONFIGURATION AND (b) 320,000 rpm AIR-TURBINE SPINDLE

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