130 Development of a miniaturized machine tool for machining a micro/meso scale structure

J.H. Lee1, S.R. Park1 and S.H. Yang1
1 Department of Mechanical Engineering, Kyungpook National University,
Daegu, S.Korea email: syang@knu.ac.kr

Summary

Miniaturized machine tool can be used to produce 3D features based on CNC and PC-NC technology in the micro/meso scale. Wide applications of CNC technology are developed and there are lots of know-hows in the cutting process and their CNC application. It helps micro/meso scale structure to machine components which can be used directly for practical applications. In the present research, as the machine tool is miniaturized, the manufacturing machine tools costs less when compared to the equipment used in other micromachining technologies. Moreover, with advancement of micro tool technology, the cutting process can be used to produce micro/meso scale parts. In conclusion, the proposed system can reduce the cost by utilizing the current machining technology, and as a result, complex micro/meso parts can be produced efficiently with high productivity.

Keywords: miniaturized machine tool, micro tool, PC-NC, micro/meso scale structure, PZT actuator, miniaturized stage

1. Introduction

The demand for micro/meso scale mechanical parts is increasing as they are required by more and more smaller products. Their applications are growing from the automobile industry to the biomedical field. Recently, the structure of these parts has become more complex and precise. For manufacturing micro/meso scale parts, new manufacturing technologies are being developed. Silicon based Micro Electro Mechanical Systems (MEMS) process is a well-known method among present micro machining technologies. A removal process by ablation with high-density beam such as excimer laser has been introduced. The process with laser results in high accuracy of machined parts. However it is hard for MEMS technology to be applied to produce arbitrary 3D features and complex components. Materials used for their processes are limited, and cost much. Also, these technologies require excessive efforts for producing shapes in the size range between 10–10,000 microns, called micro/meso scale range1). The laser technology has many drawbacks for practical use due to various factors such as small pulse energy, unreliability, instability, and high photon cost2).

To overcome these limitations, many alternative techniques have been employed. Especially, with advancement of the micro tools, the cutting process can be adopted to produce micro/meso scale parts. Material removal by mechanical force costs less and has mass production ability and deals with any metallic material. Moreover, because of wide applications of the Computerized Numerical Control (CNC) technology and a lot of know-hows in the cutting process and their CNC application, macro scale propeller and impeller NC data can be used directly to make the same shapes in the micro/meso scale. However conventional machine tools need much power to cut metallic materials and the size of the system must be big enough to increase its stiffness. As parts are small and their dimension is micro scale rather than macro scale, studies of miniaturized machine tools are increasing to reduce resource, space, and energy consumption. Small parts can be efficiently produced by miniaturized machines. Hence, the possibility of miniaturizing the equipment itself has come to the front. The idea of "To produce small parts, use small machine equipment", is being considered. It appears that the miniaturized equipment can lead to achieving acceptable accuracy at low cost as compared with other technologies. It makes considerable savings in terms of energy consumption3).

This research shows that a miniaturized manufacturing system can be used to produce arbitrary 3D features. This system consists of a stage unit, a spindle unit, and a controller. Overall system dimensions are 300x150x150mm and the machine type is horizontal. To achieve a precise positioning system, the miniaturized stage with PZT actuator is controlled by IBM-PC with 250 nm resolution. A linear encoder is used as a feedback sensor and the digital Proportional Integral (PI) controller is applied. To avoid adhesion and scratching during cutting process, the speed of the air spindle is maintained at maximum speed of 40,000 rpm. Also, it has conventional CNC technology based on PC-NC such as interpolator and interpreter, etc. In the present work the performance of controller is demonstrated with 200 μm diameter end mill. The proposed system can reduce the cost of manufacturing and apply current machining skill. As a result, complex micro/meso parts can be produced efficiently with high productivity.
2. Hardware of miniaturized machine tools

A high accuracy stage is required for micro machining. PZT actuator can drive with nanometer resolution. The resolution of PZT actuator is good, however its stroke is only several tens of micrometers. To eliminate this disadvantage, inchworm mechanism was developed\(^4\). The structure of linear motor is shown in Fig. 1.

![Fig. 1 Structure of linear motor](image)

The details of present mechanism developed are as follows. PZT actuators operate in a resonant mode. When the actuator is electrically energized, friction force is generated on the contact point as the actuator expands. The friction force causes the stage to move.

<table>
<thead>
<tr>
<th>Table 1 Specifications for each axis</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Total travel</strong></td>
</tr>
<tr>
<td><strong>No-load speed</strong></td>
</tr>
<tr>
<td><strong>Step resolution</strong></td>
</tr>
<tr>
<td><strong>Stall force</strong></td>
</tr>
<tr>
<td><strong>Holding force</strong></td>
</tr>
<tr>
<td><strong>Overall dimensions</strong></td>
</tr>
<tr>
<td><strong>Weight</strong></td>
</tr>
</tbody>
</table>

The specifications of one axial PZT actuator are shown Table 1. Total travel stroke is 13mm. Holding force can work for self-locking. Step resolution is 0.1 micron (100nm). However the overall system resolution is 250nm because of misalignment between the stage and the spindle, cutting force etc. The overall dimension of PZT actuator is 48x48x14 mm.

![Fig. 2 Three-axis positioning system using miniaturized stages with tool holder](image)

To achieve a precise positioning system, a linear optical encoder is used as the feedback sensor. X and Z-axis encoder have 50nm resolution. Y-axis encoder has 10nm resolution. Fig. 2 shows the three-axis positioning system using miniaturized stages with tool holder. Size of this system is 300x150x150 mm and the machine is horizontal type. The micro tool is mounted on the air spindle. To avoid adhesion and scratching, the air spindle has max speed of 40,000 rpm. A 200 \( \mu \)m flat end mill is used. The feature of the end mill is shown in Fig. 3. This system is controlled by IBM-PC and Digital Signal Processor (DSP). The machined part is measured by a Coordinate Measuring Machine (CMM).
Fig. 3 Micro tool after cutting process

3. Software of miniaturized machine tools

![Block diagram of overall control system]

Fig. 4 block diagram of overall control system

Fig. 4 shows the block diagram of overall control system. The miniaturized stage with a PZT actuator is controlled by IBM-PC. Drive Circuit is a power amplifier for the PZT actuator, and the digital PI controller with Anti-windup is applied for precise positioning. To set gain values, we use the relay auto tuning method, one of the empirical methods. When there is no vibration using the Ziegler-Nichols’s tuning method, this method works very well(560). Table 2 shows the gain value for each axis.

<table>
<thead>
<tr>
<th></th>
<th>X axis</th>
<th>Y axis</th>
<th>Z axis</th>
</tr>
</thead>
<tbody>
<tr>
<td>$K_p$</td>
<td>2</td>
<td>3</td>
<td>1</td>
</tr>
<tr>
<td>$K_i$</td>
<td>88</td>
<td>215</td>
<td>100</td>
</tr>
<tr>
<td>$K_a$</td>
<td>2.5</td>
<td>1.6</td>
<td>5</td>
</tr>
</tbody>
</table>

Table 2 Gain value for each axis

The velocity is important in micromachining because of the small size of machine tools. Therefore the controller must have velocity limiter. In order to overcome the problem of windup, a controller with Anti-windup capability is used. Fig. 5 shows the PI controller with Anti-windup(7).

![Block diagram of PI Controller with Anti-windup]

Fig. 5 PI Controller with Anti-windup
The motion commands similar to the NC part program are used to produce a sequence of very small step movements along the machine axes. CNC interpolators generate the reference signals for driving of CNC machine tools. These technologies are inherited in the present system. The system use data generated by interpolator\(^5\). However the data generated by CNC interpolator is just for macro machine having micrometers resolution. Therefore we have to convert the data. As shown in Fig. 6, the part program is made by PC through mapping to each axis. DSP takes charge of the fine interpolator and position controller. The linear and circular interpolator is developed in software and implemented. This interpolator is sampled-data type. Fig. 7 shows the tool path using rough interpolator. The tool path is generated by Bezier curve. The tool path data is mapped to each axis. The sampling time of interpolator is longer than that of controller. Therefore desired input value is divided into the number of control sampling times within the interpolator’s sampling time.

Fig. 6 NCK (Numerical Control Kernel) Flowchart  
Fig. 7 Tool path using rough interpolator

CNC machine tools have been widely used in order to improve the machining accuracy and increase productivity. As the CNC machine tools play a central role in manufacturing processes, the replacement to the newest technology machines is needed. However, for most industries purchasing the new machines is not necessarily a solution because they are very expensive and quickly become obsolete. As an alternative plan for enhancing the capability of the existing machines, the reconfiguration of the available old ones is presented. In reconfiguration, a PC is often used as the Machine Control Unit (MCU). By using a PC, the new software modules for the advanced technology can be developed and added to the machine tools easily\(^9\).

Fig. 8 Schematic of PC-NC

The software interpolator generates the required tool path data. The data is stored in queue, in the PC. The PC checks the pending interrupt bit. If DSP takes the data on shared memory, the PC writes the new data on the shared memory. If the PC writes the new data on the shared memory, then DSP can take the data to the queue. The real time fine interpolator sends the input to the PZT actuator.

4. Performance of system

As shown in Fig. 9, the data is captured about 3 axes for a period of 100 seconds. In X-axis, the overshoot is occurred during continuous long distance movement. In Fig. 9 (b), the output signal is within the range of ±250 nm. These data shows that the resolution of this system is guaranteed 250 nm.
Fig. 9 Profile captured on cutting process – x-axis is time (ms) and y-axis position (μm)

Fig. 10 Machined part by miniaturized machine tool.

The dimension of machined part is 3x2.5x0.27mm as shown in Fig. 10. The micro tool passes 40 times in X direction, slowly moving in Z direction. The micro machining using the miniaturized machine tool is successfully completed. It is possible to use this method in the industrial field, if smaller micro tools and more precise and accurate stage are developed. New methods can also be employed for improving the surface finish.
5. Conclusions
The arbitrary 3D feature is successfully machined in micro/meso scale. The study shows that the micro/meso products can be manufactured by a miniaturized machine tool using CNC and PC-NC technology. The G-code can be obtained from the well-known CAD/CAM software. G-code is interpreted by interpreter. The initial tool path data is generated by rough interpolator and this data is interpolated again by a fine interpolator. Then the interpolated data at sampling time instructs PZT actuator to move. All of these processes are based on CNC technology. Moreover by miniaturizing the machine tool, the energy consumption is reduced. It demonstrates the controller performance when machined with 200 μm diameter end mill. The proposed system can reduce the cost of manufacturing using the conventional machining skill. Complex micro/meso parts can be produced efficiently with high productivity using this method.

6. Acknowledgements
This project was sponsored by grants from the Strategic National R&D Program (M10214000237-02B1500-03810), Ministry of Science & Technology.

References