

Development of a compact ultra-precision six-axis hybrid micro-machine

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Abstract

High precision miniature and micro products which possess 3D complex structures or free-form surfaces are now widely used in industries. These micro products are usually fabricated by several machining processes in order to apply for various materials such as hard-to-machine steel and ceramic etc. The integration of these machining processes onto one machine becomes necessary since this will help reduce realignment errors and also increase the machining efficiency. In this research, an ultra-precision hybrid micro-machine which is capable of micro milling, micro grinding, micro turning, laser machining and laser assisted micro-machining has been designed and commissioned. Control software for on-machine metrology system (contact probe and dispersed reference interferometry (DRI)) and several plug-in modules including camera and handle system are integrated through a customised human-machine interface (HMI).

Keywords: Hybrid machine, precision machines design, micro milling, laser machining.

1. Introduction

The demands for high precision micro products and components have increased in a wide range of industries such as electrical, optics, biomedical, aviation and automotive [1]. The common characteristics of these micro components or products are (1) features size from few micrometres to hundred micrometres; (2) high precision tolerances; (3) good surface finish; (4) 3D or complicated structures; (5) advanced or hard-to-machine materials s.g. ceramics or hard steels [2].

Currently, these highly precision miniaturized 3D complex parts are manufactured via a variety of separate high precision machining processes such as micro milling, micro grinding, laser machining electron discharge machining (EDM), electro-chemical machining (ECM) and ultrasonic machining (USM) [3, 4]. Unfortunately, while workpiece is transferred from one stand-alone machine to another, the machining time and alignment errors will be increased.

In order to avoid re-positioning errors and reducing the machining time, some hybrid machines have been developed in recent years. A qualitative comparison between the hybrid machine and the traditional machine are shown in Fig. 1. Chavoshi and Luo classified hybrid micro machining process as combined and assisted hybrid machining [5]. It can be observed that hybrid machining process integrates traditional machining processes (milling, grinding etc.) and non-traditional machining process (EDM and ultrasonic etc.).

For the combined hybrid machining, Chung et al. integrated micro-milling, micro-EDM and ECM machining modules into a compact micro-machining system [6]. A hybrid μ EDM which combined micro milling, turning and micro EDM has been developed by Mikrottools Ltd in Singapore. For the assisted hybrid

machining, Suzuki et al. developed an ultrasonic vibration assisted polishing machine to finish micro aspherical molding dies [7]. Ultrasonic/ milling machines are developed by many companies such as DMG and OptiPro etc.

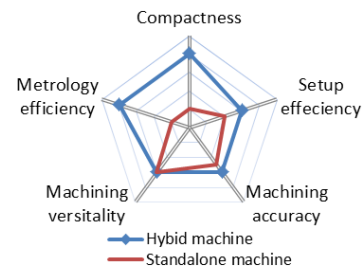


Fig. 1 Comparison of hybrid machine and standalone machine

Micro laser machining is not only a good non-traditional machining process to remove material but also an efficient process to heat workpiece so as to improve its machinability by reducing its strength. Chang used nanosecond pulsed laser to remove micro burrs which generated by milling process and the results show that burrs are completely removed and surface roughness are also improved [8, 9]. Chang also carried out laser-assisted micro grinding experiment for ceramic materials. The result shows that better surface roughness can be obtained and subsurface damage can be avoided [10].

The paper presents development of a hybrid machine which combines micro milling, micro grinding, micro turning with laser machining capacities for the fabrication of 3D micro products and components. The machine is equipped with a PC-based CNC controller which will through a customized human machine interface (HMI) to control machine motions, on-machine metrology system (contact probe and

dispersed reference interferometry (DRI)) and several plug-in modules including camera and work handle system.

2. Structural design of the hybrid machine

In order to achieve mass production of 3D complicated micro parts with high precision tolerances and good surface finish, a robust machine design has been carried out. The main considerations of designing such a hybrid machine include high dynamic stiffness, compact size and interchangeable machining modular. The maximum workpiece size is $\Phi 150 \text{ mm} \times 150 \text{ mm}$ in various materials such as plastic, silicon carbide and hard steel. The structural design of the machine involves layout design, frame structure and isolation, linear/rotary stages design and tool interfaces.

2.1. Machine design philosophy

The machining capability and stability of the high speed machining process will be significantly influenced by the machine static/dynamic stiffness and natural frequency. A novel machine configuration and robust machine base design are designed to achieve high static/dynamic stiffness and natural frequency for this machine. The machine base and closed loop gantry are made of synthetic granite which offers high damping ratio, excellent thermal stability and high control bandwidth. The dimension of this compact hybrid machine is 850 mm in width, 840 mm in depth and 1800 mm in height (including supports and machine guards).

The hybrid machine system has more than 6 DOFs and thus extra care should be taken when selecting the arrangement of the axes and designing base structure. Double column structure is chosen to support the high speed spindle and laser heads respectively. Fig. 2 shows the arrangement and internal connections between machine base and each moving axis. The machining force loop is composed by numbers of mass-spring blocks, representing each flexible chain.

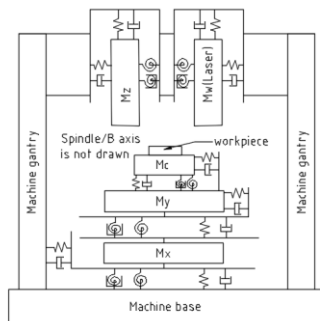


Fig. 2 Dynamic structure of the hybrid machine tool

Ideally, each axis is totally constrained by five degree of freedoms and the sixth one is the desired motion direction. In this case, the undesired motion freedoms are constrained by air bearing, which adopts a novel design concept to achieve high stiffness. Several tests have been conducted to measure the stiffness of the bearings. A certain load is exerted to the stage and precision capacitive probes with 0.2 nm resolution are used to measure the displacements at two locations and the position repeatability is $\pm 30 \text{ nm}$. Vertical stiffness of 200 N/ μm for the X axis and 104

N/ μm for the Y axis at 5 bar supply pressure is recorded. Roll stiffness of the X axis is 3.6 Nm/ μrad at 5 bars.

The feedback control loop is typical cascade architecture with current/velocity/ position loops. Fig. 3 shows the open/closed loop transfer function of the linear axis without extra load. The controller generates sweep frequency current signals for the linear motor as the input, which is proportional to actuating force. The output of the FRF test is from encoder feedback. The band width is around 110 Hz, which guarantees fast response to motion commands and cutting force disturbances.

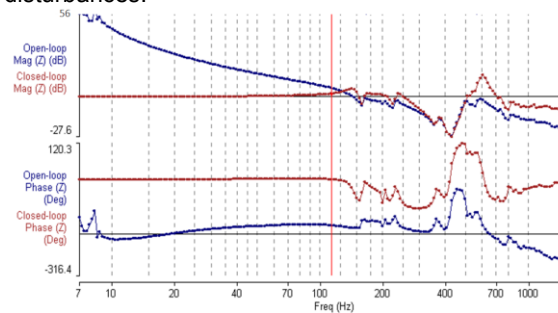


Fig. 3 Open/closed loop characteristics of linear axis

Finite element analysis (FEA) is conducted repeatedly during the design stage of the machine structure. From the analysis results, the structure of the designed frame has been optimized in order to reduce the loop length while providing enough space and stiffness. The result of first natural frequency of the machine is 189.7 Hz.

2.2. Motional stages

In this hybrid machine, there are six axes including four linear axes and two rotary axes. The main specifications of the each stages and spindle are summarised in Table 2. The 4 linear (X, Y, Z and W) axes and C axis rotary table attached on the X and Y stages are air bearing stages with linear/rotary motor drives. These linear air bearings are featured with micro recessions which provide extraordinary stiffness, developed by UPM Ltd. The materials of these four linear bearing stages are aluminium alloys coated with anti-abrasive materials. The working table (C axis rotary table) is made by using steel in order to avoid damage or corrosion. The advantages of these stages and drives are summarised as follows:

1. Light metal and low mass.
2. No friction, high precision.
3. No backlash, no lead-screw errors.
4. High velocity and acceleration.
5. Long bearing life.
6. Easy assemble and clean.

The B rotary axis (Aerotech AGR75 gear-drive rotary stage) attached on the Z axis is used to hold a high speed spindle. The B rotary axis uses gear drive stage which will hold and keep the high speed spindle at any programming position without power supply.

3. Control system

Control system will not only synchronise the motion of the multi axes but also serve as the bridge to integrate several additional plug-in modules. The Aerotech A3200 controller is chosen as the CNC controller. The open architecture control system

provides great flexibility for operation and future development. A schematic diagram of PC-based controller for the hybrid machine is shown in Fig. 4. A3200 offers a great capability to control built-in accessory module to recognize the workpiece and its position, and enable to adjust the position and signal to the cutter all within one system. This integration will not only reduce the setup cost but also increase reliability. A3200 provides interface to high resolution encoders and many various connections for plug-in modules. All position, velocity and acceleration information are feedback to a PC-based computer through Aerotech A3200. In the software system, a human-machine interface (HMI) shown in Fig. 5 has been developed by a customised operating environment. The controller system provides user right management. The standard user can utilize CNC module and Plug-in modules to manufacture components. And the administrator has access to the machining database and controller parameters.

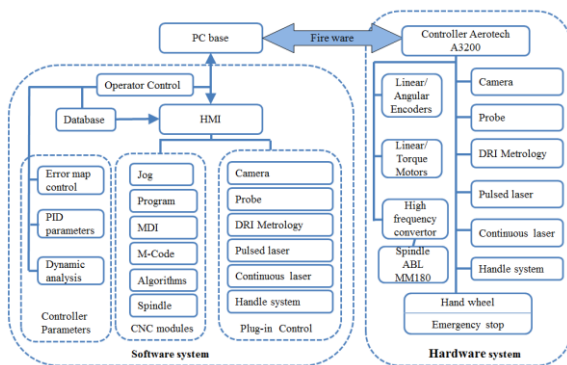


Fig. 4 The diagram of PC-based controller system architecture



Fig. 5 An example of customised human-machine interface

4. Laser, plugin modules, assembly of the hybrid machine and demonstration

In this hybrid machine, two lasers (pulsed laser and continuous laser), on-machine metrology system (contact probe and dispersed reference interferometry (DRI)) and several plug-in modules including camera and handle system are integrated to achieve multifunction for different machining requirements. These modules are based on the W axis and located by a changeable EROWA system and its repeatability is less than 2 μm . The functions of each module are introduced as follows:

Laser systems-

- Pulsed laser – is used to manufacture micro structures or remove micro burrs which are generated by micro milling process. The maximum laser power is 20W and the smallest spot size is about 15 μm .
- Continuous laser – is used to assist micro milling/grinding process. The maximum laser power is 200 W and the spot size is 4 mm diameter.

On-machine metrology systems-

- Touch probe – is used to identify the origin point of the workpieces (X, Y and Z co-ordinations). It also can be used for single point measurement of machined components and products. The repeatability of this probe is less than 0.25 μm .
- DRI metrology – is an on-line non-contact metrology system which is used to detect edges, scan profiles and measure surface roughness of workpiece. Its measurement repeatability is 1.25 nm.

Additional functions-

- Camera – is used to obtain the edges, surface quality and the alignment Z axis of the cutters and workpiece. The camera resolution is 2592 x 1944, and field of view is 1.44 mm x 1.07 mm, so the pixel resolution can achieve 0.55 μm , which is sufficient for tool alignment and rough workpiece inspection. The camera will use a LED ring light as the illumination, which is attached in front of the lens. The lens has a working distance of 75 mm and it guarantees a safe position for the camera.
- Material handling system – system is used to change workpieces. The robot can upload raw materials to the EROWA 50 RSA in the hybrid machine and it is also used to remove the fabricated components after machining. The maximum load of the raw material is 5 kilograms.

Fig. 6 shows the commissioned hybrid machine. The X, Y and C axes are attached to basement of the hybrid machine. The spindle, Z and B axes are attached to the left frame. The W axis, pulsed laser, continuous laser and plug-in modules are fixed to the right frame of the machine. This hybrid machine offers the capability of machining 3D miniature complicated components and products which require high manufacturability and productivity for all kinds of materials such as PMMA, tool steel, Titanium alloy, Cobalt-Chrome alloy, ceramics and sapphire. The auto-tool changing system will be integrated in the hybrid machine in the future.

Preliminary experimental trials have been carried on this machine. The machined micro-lens mount, fly-eye mould and carbon fibre papers are shown in Fig. 7. The resin micro-lens mount has smallest feature of only 0.2 mm. It is machined by micro-milling with spindle speed of 60K rpm by a CBN milling cutter. A single crystal diamond milling cutter is used to fabricate fly-eye array with fine reflective surface on copper material and repeatability and stiffness of the machine is essential. Micro holes are machined by nanosecond laser on this hybrid machine. The laser power 0.2W is used to fabricate carbon fibre paper and it requires small focus point and lower

thermal effect zone. In the future work, hybrid micro-machining trials will be carried on this machine.

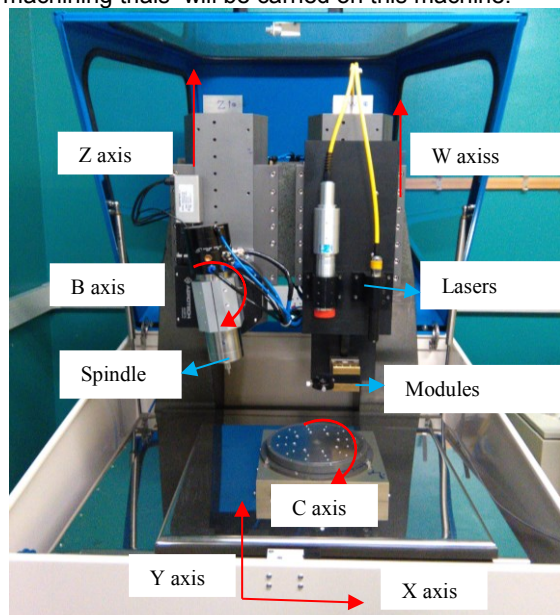


Fig. 6 The ultra-precision hybrid micro-machine

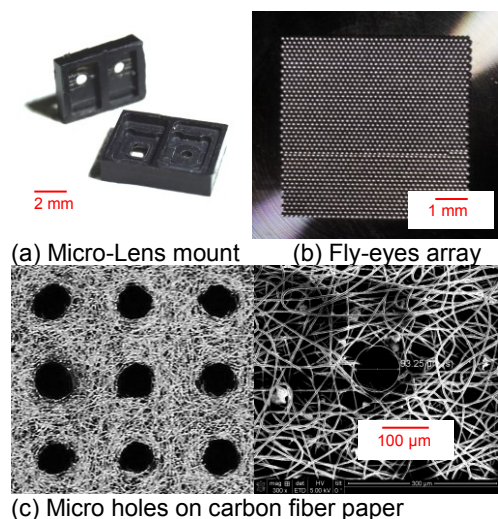


Fig. 7 Micro-product by micro milling and laser machining

5. Concluding remarks

In this research, a compact hybrid machine is developed for manufacturing precision 3D complicated products and hard-to-machine materials for a wide range of industries such as electro-optics, biomedical automotive and aerospace etc. This machine is

equipped with laser machining and laser-assisted milling which avoids the shortcoming of the conventional micro-milling operation. Laser is not only used to assist micro-milling/grinding hard-to-machine materials but also remove micro burrs which are generated by micro-milling process. Furthermore, it can reduce repositioning errors and decrease machining time because all machining processes are done in one compact hybrid machine. Alignment errors can be significantly minimized by using metrology touch probe and applying error compensation. On-line metrology system provides effective feedback for quality control. In the future, more machining experiments will be conducted to verify the accuracy of this hybrid machine.

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Table 1 Specification of the hybrid machine

	X, Y, Z ₁ and W axes	B axis	C axis	Spindle
Type	Air bearing slides	Ball bearing	Air bearing	Air Bearing
Stroke	X:400 mm Y:150 mm Z:150 mm	-10°~95°	360 °	N/A
Motion Accuracy	<0.1 μm	20 arcsec	<10 arcsec	< 5 μm
Resolution	1 nm	2.4 arcsec	1 arcsec	N/A
Drive System	Brushless linear motor	Gear motor	Brushless motor	Brushless motor
Maximum Speed	3000 mm/min	180°/s	3000 rpm	180k rpm