In order to obtain high reflectivity up to 80~keV, the next-generation hard X-ray telescope (HXT) require aspherical thin mirrors of 100 nm shape accuracy and less than 0.3 nm rms surface roughness with different sets of periodic length and number of layer pairs. A large ultra-precision single-point diamond turning and measuring machine has been designed and developed for making replicated aspherical mirrors from molding dies. As the primary results, the large molding dies with mirror length 400 mm and normal diameter 300 mm were machined based on the above-mentioned measurement system. The shape accuracies of cylindrical and aspherical aluminum alloy samples were obtained at ±54 nm p-v and ±92 nm p-v respectively by single-point diamond turning.

1. INTRODUCTION

There are three soft X-ray telescope satellites who work well in space presently to collect X-ray from the galaxy, Chandra from U.S. (1999) [1] with the highest imaging capability, XMM-Newton from EU (1999) [2] with the largest gathering light area and Suzaku from Japan (2005) [3] with the best light splitting performance respectively. They were all constructed by nested multiple grazing incidence reflecting mirrors consisted by a paraboloid and a hyperboloid in revolution. The surface roughness of coated film was about 0.5 nm rms. The next generation hard X-ray telescope, region above 10 keV, will be used to clarify the mastery of the extremely hot astrophysical or non-thermal high energy phenomena in universe. The proposed NeXT will to develop a next generation hard X-ray telescope with replicated Pt/C multilayer aspheric mirrors. The shape accuracy of aspheric mirrors is less than 100 nm and surface roughness is also less than 0.3 nm rms. The mirror is 600 mm in maximum diameter and 400 mm in length and the thickness of mirror substrate is 0.2 mm around. The next-generation hard X-ray telescope consists of the hundreds of nested mirrors with Pt/C multilayer. Since the limitation of the satellite weight and requirement of large mirror surface fir collecting power, the replication technology has to be adopted to manufacture the light-weight telescope.

Aluminum alloy covered with electroless nickel plating was used as a molding die material. The electroless nickel is diamond-turned into aspheric shapes in high precision and polished into less than 0.3 nm rms of surface roughness. Then, Pt/C multilayers are deposited on the electroless nickel molding die and glued a mirror substrate over the die with epoxy polymer [4]. The last process is separation of the mirror substrate from the molding die.

This paper will focus on the development of a large ultra-precision machine tool to make various ultra-precision molding dies up to 600 mm in diameter and 400 mm in mirror length, and straightness compensation and some experimental machining results.

2. LARGE ULTRA-PRECISION SINGLE-POINT DIAMOND TURNING MACHINE

2.1 Development of single-point diamond turning, polishing and measuring machine

Figure 1 shows the large ultra-precision single-point diamond turning, polishing and
measuring machine which was developed to make aspheric molding dies of 600 mm in diameter for next generation hard X-ray telescope [5].

Figure 1 Large ultra-precision single-point diamond turning and measuring machine.

The machine was supported by three air stages on a vibration proof foundation in a temperature controlled clean room. The machine tool has a large rotary table (C stage) supported by a precise air bearing with 0.001 degree resolution, and horizontal (Z axis) and vertical (Y axis) axes are driven by linear motors in range of 420 mm ultra-precision V-V roll slide with 1 nm resolution. Because two high precision linear laser scale with 0.14 nm resolution were adopted in Y and Z axis. The temperature of cooling oil and clean air are controlled 296.2 K ± 0.1 K for keep on the stability and repeatability of the large ultra-precision machine. The machine is controlled by CNC system.

With the support of double shaft linkage function, not only cylinder but also aspheric surface workpiece in revolution can be turned with special designed diamond tool. Ultra-precision polishing can be carried on by adding a polishing head on the same machine, because a water-proof of machine has been considered.

An ultra-precision measurement system in situ was also developed for shape accuracy measurement of a machined molding die with nanometer resolution. The measurement system can transmit the generated measuring NC program into machine tool’s command stack in the DNC mode to control measuring process through the high speed serial bus (HSSB). And the measurement system can obtain and store the measurement data of micro-displacement sensor and moving position signals (coordinate data) into memory and hard disk of industrial computer in real time.

2.2 Machining environment

For obtaining the good machining environment, the machine was put into an enclosure to keep on the stable temperature in a clean room, shown in Figure 2. The temperature fluctuation in the enclosure is about ±0.1 K, and less than ±0.07 K in machining area, though the temperature fluctuation in the clean room is higher than 1 K, shown in Figure 3.
3. COMPENSATION OF AXIS MOTION

3.1 Certification of a straightness gauge

It is necessary to compensate the axis motion error [6-8] by a straightness gauge. An optical straightness gauge with 450 mm in length was made especially to measure the straightness of machine tool. The straightness of the zero expansion glass-ceramic gauge is less than ±7 nm/400mm, shown in Figure 4, which measured by a laser interferometer. The profile curve in 400mm length was represented with the discrete 200 numerical points, which can be magnified to 8000 points by using the linear interpolation method in order to make it proportional to NC program with the step 50 μm.
3.2 Compensation of y- and z-axis motion

For obtaining the nice molding dies satisfied the strict requirements of hard X-ray telescope mirrors, the axis motion error of the ultra-precision machine tool must be compensated in nanometer scale accuracy. Therefore, the y- and z-axis motion errors should be measured accurately and rightly. A non-contact micro-displacement sensor with nanometer resolution has commonly been used to measure high precision motion measurement owing to its advantages of high resolution, good stability and scatheless to measured surface.

The y- and z-axis motion errors were measured using above built measurement system in situ and the straightness gauge with a straight line code NC program, shown in Figure 5 (Y axis movement). An original data can be obtained from the sensor. But the data includes two parts mainly: axis motion error and the gauge profile.

During the data process, the surface profile of the straightness gauge is subtracted from the original data in corresponding points. And the real straightness can be drawn out. Then, a new NC program was made based on the above measured and separated y-axis motion error. The new NC program code isn’t the single straight line command, which is consisted of many straight line commands with the step 50 µm along the moving direction. The point value in NC program is the opposite value of the point on the y-axis motion error data. It will compensate the motion error of machine tool axis. When the machine was moved along the y-axis with the modified NC program, the sensor was used to collect the new data.

Figure 6 shows the motion error of y-axis in two direction, +y forward and -y backward using above stated method. The motion error is ±98 nm and ±102 nm in the range of 400 mm along +y and -y direction respectively. After compensation, the straightness of y-axis is ±30 nm/400 mm. These data are the average of several measured data.
The same method was used in the measurement and compensation of z-axis motion. Figure 7 shows the motion error of z-axis in two direction, +z forward and -z backward. The motion error is ±170 nm and ±158 nm in the range of 400 mm along +z forward and -z backward direction respectively. After compensation, the straightness of z-axis is ±24 nm/300 mm. These data are also the average of several measured data.

The compensation results show that the method using modified NC program to reduce the motion error is effectual and practical. It can be used in machining for obtaining the high accuracy shape.

![Figure 7 Straightness of z axis movement before and after compensation.](image)

4. SINGLE-POINT DIAMOND TURNING OF LARGE WORKPIECE IN HIGH PRECISION
4.1 Single-point diamond turning of aluminum alloy cylinder

As an initial validating experiment, an aluminum alloy cylinder with mirror length 400 mm and diameter 300 mm was machined and measured. Figure 8 is the photo of single-point diamond turning with a special design diamond tool.

![Figure 8 Single-point diamond turning.](image)

After the original machine with a single straight line code NC program, the shape of the aluminum alloy cylinder was measured by the built measurement system with a high precision sensor. The NC program of measurement is modified by subtracting the motion error of y-axis. Then, the data of original machining error were used to make a new compensation machining NC program with the opposite value at an appropriate percentage. The aluminum alloy cylinder was re-machined with the compensation machining NC program. After that, the shape of the aluminum alloy cylinder was measured again for obtaining the machining error after compensation.
Figure 9 shows the shape accuracy of aluminum alloy cylinder. The original machining error is ±355 nm in 400 mm mirror length. And after several times compensation machining, the machining error was reduced to ±54 nm.

4.2 Single-point diamond turning of aspherical surface of aluminum alloy

The next generation hard X-ray telescope mirrors are consisted by multiple incidence reflecting mirrors with hyperboloid and paraboloid. It is necessary to machine an aspherical surface of aluminum alloy with mirror length 400 mm and diameter 300 mm to prepare for making the mirrors. How to measure such a large ultra-precision aspheric surface with nanometer accuracy is the essential task of fabricating the replicated mirrors and a challenge in measurement field with nanometer accuracy. The intersection point of two aspheric surfaces was selected as a measurement reference point for matching the measurement points with design data to calculate the shape error correctly. In this method, a short range nearby the intersection area was scanned by a sensor along the straight line. The intersection point can be detected according the calculation based on the data of the sensor as measurement reference point in y axis measurement direction. The position repeatability error of reference point had been controlled within 2 µm maximum, which can obtain the measurement shape error of aspheric surface within 10 nm in theory.

The same compensation machining method was used in single-point diamond turning of aspherical surface of aluminum alloy. Figure 10 shows the machining results, the original machining error is ±392 nm in 400 mm mirror length. After compensation machining, the machining error was reduced to ±92 nm. Figure 11 is the photo of Single-point diamond-turned aspherical surface of aluminum alloy.
5. SUMMARY

From the above-mentioned fundamental and experimental investigation and data process on the straightness error compensation and shape measurement of large mandrel on machine, the following conclusions are drawn:

1. A large ultra-precision machine tool has been developed with a precision measurement system on machine for making the molding dies for next generation hard X-ray telescope.

2. Proposed a new straightness compensation method based on an ultra-flat straightness gauge. After compensation, the straightness errors of Y and Z axis of machine tool are ±30 nm/400 mm and ±24 nm/300 mm respectively.

3. An aluminum cylinder and an asphere with mirror length 400 mm and normal diameter 300 mm were measured and re-machined on the developed ultra-precision machine tool. The shape errors were ±54 nm and ±92 nm in range of 400 mm respectively.

The machining and measurement in situ of large molding dies with nano-scale accuracy for the mirrors fabrication of the next-generation hard X-ray telescopes will be expected to perform leading edge of ultra-precision machining science with cutting edge technology.

6. REFERENCES