Research on Developing a Prototype NC EEM Machine for Machining High-power Laser Mirrors

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Elastic Emission Machining (EEM), invented by Professor Mori of Osaka University, has been proven to be able to make perfectly flat surfaces at the atom-size level.

In this paper, we will introduce a newly developed EEM machine in which all numerically controlled stages have been set in a tank filled with ultrapure water containing machining powder, and all driving and guiding components have been constructed with a hydrostatic system using ultrapure water.

1. Introduction

Elastic Emission Machining, or EEM, is the most advanced method of ultraprecise machining and was invented by Professor Yuzo Mori of Osaka University. The method yields a perfectly flat surface at the atom-size level and holds promise as a base technology that will support next-generation science.

Koyo has been working to develop EEM machines under the guidance of Professor Mori over the past twenty years, having been entrusted with this project by the Japan Science and Technology Corporation. As a result, we have developed a prototype for a new type of NC EEM machine, which is covered in this report.

2. Basic Principles of EEM

EEM is a method of ultraprecise machining based on reaction between solid surfaces using the reactivity of small powder particle surfaces. The method uses the flow of water to transport powder particles and is used for surface machining without providing excessive kinetic energy (Fig. 1).

With powder particles that react with workpiece surfaces, there is a chemical bond among the atoms of both surfaces, which changes the state of electron valence in that vicinity, and in some cases the bonding energy of the back bond of atoms of the work surface diminishes. By transporting powder particles via the flow of water, machining phenomenon occurs at the atom level (Fig. 2). Thus, EEM can be thought of as "chemical polishing that takes advantage of the reactivity of powder particle surfaces."

3. EEM Features

With EEM, only the site where powder particle surface atoms and atoms of the workpiece surface affect each other is machined. Since microscopic cavities on the workpiece surface are not machined, a flat surface can automatically be obtained by atom size order (Fig. 3).

With ultraprecise NC machining systems using EEM, small powder particles can be made to interact in only a specific area of the workpiece by controlled water flow, thus enabling the creation of an arbitrary spherical surface (min. profile accuracy 0.01 μm) with a flat surface on the atom level by machining each point on the workpiece surface in the exact amount required (Fig. 4).

4. Description of Prototype Research

Our research involved development of an NC machine for machining mirrors for high-output lasers using EEM. To be more specific, we studied application to the X-ray mirrors used in the synchrotron orbital radiation facility Spring-8, which began operating in 1996. In order to use the world's highest output X-rays effectively, it is necessary to finish an intricately shaped mirror called "Troysdale" on the atom level without unevenness.
Our research comprised an attempt to construct an unprecedented machining system and holds promise to open the door to ultracest accuracy machining.

Important items for development were:

1. Development of an ultrapure-water hydrostatic bearing system which does not contaminate a clean environment in order to achieve EEM in a favorable environment and stabilize the machining phenomenon.
2. Development of a machine body that could be operated while being completely immersed in ultrapure-water machining fluid.
3. Development of a refining system for cleaner machining fluid.
4. Development of position controlling technology and stage configuration that enable machining of Troydal mirrors and axially symmetrical mirrors.

This report in particular contains a general description of the machine itself and the ultrapure-water hydrostatic system and control system.

5. Material Selection

In the manufacture of the equipment, it was absolutely imperative to use materials that were stable in ultrapure-water and had minimal elution.

We therefore performed the elution test for several possible materials and selected SUS316, SUS304, alumite, a certain ceramic, etc (Fig. 5).

With EEM, which utilizes chemical reactions, it became evident that controlling the machining atmosphere was extremely important for reliably maintaining the machining phenomenon at a high level. With the machine we developed, in order to prevent impurities from the machining environment from contaminating the machining fluid, we set up the entire NC stage in a sealed machining tank filled with machining fluid. We also constructed all drive and guiding components using an ultrapure-water hydrostatic system in order to prevent the machining fluid from being contaminated by the stage itself.

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6. Total System

Fig. 6 shows the configuration of the NC EEM machining system. In addition to the machine itself and its control equipment, the system also consists of a fluid level controlling tank, a machining fluid storage tank, a liquid phase separating unit, and ultrapure-water refining equipment.

Ultrapure water from the refining equipment is supplied to the hydrostatic equipment in the machine. This causes an equivalent amount of machining fluid to spill over from the machining tank. The spilled over machining fluid is routed to the fluid level controlling tank, where it raises the level of the tank.

The position is detected by an ultrasonic sensor mounted on the top of the tank, and by controlling the circulating pump to the liquid phase separating unit, the same amount of liquid phase as the spilled over machining fluid amount is filtered out, and a certain water level inside the machining tank can be maintained.

Because liquid phase machining fluid is sequentially replaced by new ultrapure water, a stable machining environment is constantly maintained.

The specifications of the machine itself and its control equipment are as follows:

1) Machine
   - Outer dimensions: 2 880 (W) × 1 780 (D) × 1 760 (H) mm
   - Axes: X, Y, θ axes, spindle
   - Bearings: Ultrapure-water hydrostatic slide bearing, spindle
   - Feeding mechanism: Ultrapure-water hydrostatic screw
   - Stroke: X 600 mm Y 200 mm
   - Resolution: 1 μm

2) Control equipment
   - Control method: CNC control by high-speed data link with PC
   - Input data: Speed data for each 1 mm × 1 mm box in the mesh determined from measurement data of previous machining
   - Axes controlled: X axis, Y axis, θ axis, spindle
   - Machining speed: 0.1 mm/min to 600 mm/min
   - Control range: EEM machine, machining fluid refining system

7. Machine

A photograph of the machine is given in Fig. 7, and a three-dimensional drawing in Fig. 8. The X table, Y table and θ axis are stacked on the machine base, and the spindle unit including a rotating sphere and its pressurization mechanism are mounted on a column separately installed on the base.

In order to prevent outside contamination of the machining fluid, all the equipment is mounted in a sealed machining tank filled with the ultrapure machining fluid. To prevent contamination of the machining fluid by the machine itself, all drive and guiding components have been constructed by an ultrapure-water hydrostatic system with no contact sliding surfaces.

The machining tank consists of a base, side walls and cover and can be divided and disassembled if necessary; for instance, when mounting a workpiece inside. Although not covered herein, in order to lift the huge machining tank, we have also developed a special lifter that can be used in ultraclean rooms (Osaka University, class 1 level).
The equipment was assembled in an ultraclean room, and the task was further complicated by the need for special assembly techniques because of the perfectly washed parts.

Fig. 7 Appearance of the machine

Fig. 8 Drawing of the machine

Fig. 9 Inner structure of the spindle unit

8. Spindle Unit

The inner structure of the spindle unit is shown in Fig. 9. We also developed a pressurization mechanism that provides pressure to the work by advance force from the linear actuator conveyed to the machining sphere via pressure spring and load cell. By stopping advancement of the linear actuator when the signal from the load cell reaches a certain setting value, stable machining pressure by pressure spring can subsequently be obtained.

Fig. 10 shows the image of machining the Troydal work and axially symmetrical work.

Fig. 10 Image of machining

9. Hydrostatic System

Fig. 11 shows the basic principle of the hydrostatic system. By spraying high-pressure fluid into the microscopic bearing clearance, a sliding pad is floated and load can be carried with no contact. By using ultrapure water as a lubricating fluid, the equipment can be placed in machining fluid. However, there was a demand for achieving the desired performance with a minimal amount of flow, because the supply of ultrapure water is limited. In other words, optimal design to minimize bearing clearance, high-precision machining, assemble and adjustment technology were required.

When designing, we fabricated test samples and verified the validity of the theoretical formula. As a result, by making some corrections, we confirmed that the theoretical formula for hydrostatic oil bearings could be applied to hydrostatic water bearings.

We measured water flow of the final parts designed based on the compensation formula, and confirmed that it corresponded with calculations (Fig. 12, Fig. 13).
Figs. 14 to 16 show the appearance of the main parts we developed. We devised various measures for dealing with the peculiarities of the lubricating fluid, such as a special recess profile and arrangement for providing the angular stiffness.
10. Control Equipment

A control block diagram is given in Fig. 17. A machining program is automatically created based on speed data converted from measurement data of previous machining, and a move command is sent to CNC, and at that time we also added control by PC in order to prevent the machine from stopping due to an interruption in data.

Apart from the machine itself, machining tank internal pressure and hydrostatic system pressure can also be controlled simultaneously.

11. Conclusion

By combining the various elements we developed, we have succeeded in creating a prototype of a first-of-its-kind machining system whereby the entire NC stage is placed in a sealed machining tank filled with ultrapure machining fluid. This is the result of combining various technologies fostered by Koyo in the areas of machining technology and research and development involving hydrostatic and hydrodynamic pressure bearings. The equipment is currently operating in an ultraclean room at Osaka University and has achieved such goals as an organic molecular concentration of 20 ppb or less in the tank. We are still awaiting results of actual machining to be conducted at the university in the future.

Finally we would like to thank many professors at Osaka University and the Kyoto Institute of Technology and all of those at the Japan Science and Technology Corporation for their cooperation and guidance.

References