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Challenges in machine design for large mirror manufacturing

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Abstract

This paper will present the challenges in designing an ultra-precision machining system for the manufacturing of large optical components of up to 1500 mm in diameter. The focus will be on the axis design setup and on the thermal management of the machining system to cope with the long processing times. Next to the long-term stability, the machine should not only allow for the manufacturing of symmetric surfaces in high accuracy, but also enable freeform manufacturing dynamics. A system design which solves these challenges will be presented in detail and discussed in this publication.

Ultra precision machines, machine design, large optics, diamond turning, freeform manufacturing

1. Introduction

The trend in miniaturization has pushed machines and production processes to their limits throughout the past decades. Opposite to that trend, the demand for extraordinarily large optical components, such as metal or glass/ceramic mirrors has increased recently [4]. Applications such as ground to space optical communication terminals, semiconductor EUV machines, astronomical instruments, high energy systems for fusion energy or defense systems require increasingly larger optics. Machines and metrology systems are not sufficiently available to satisfy these demands. A machine system solution for performing the optical shaping process in sub micrometer accuracy on such large optics is presented in this publication.

2. Manufacturing of large high precision mirrors

The manufacturing process that is selected for the production of an optical component will mainly be determined by the material of the optic and the required accuracy of the optical surface. For mirrors two different material groups are mainly considered:

- light metals, mostly aluminum, and
- ceramics.

Both material groups present their own challenges in processing. While aluminum is usually machined to optical quality by applying ultra precision diamond turning (cutting), ceramic is ground and polished.

The final accuracy of the optical surface is specified by applying the same specifications and parameters, independent of the material. Similar accuracy levels are required by any of the processes applied to machining the optic, hence, a machine platform that allows both, ultra precision diamond turning or grinding seems obvious.

The presented solution will allow both processes, offering a flexible platform for both optical mirror solutions, either metal or glass/ceramic.

3. Large machine design concept

In addition to the challenges that a conventional ultra precision machining system has to solve, two further aspect will have a large impact on the quality, when the size of the optic exceed 1000 mm:

- the high weight of the optical workpiece and
- the very long processing times for the optical surface.

How these challenges are tackled with the proposed solution will be discussed in the following.

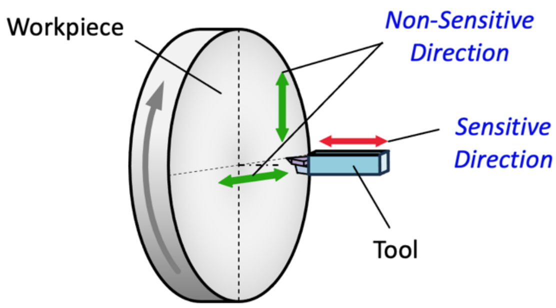

Figure 1. Directional sensitivity in a horizontal spindle setup

Two general machine concepts are applicable for machining centers, the vertical spindle setup, often called "portal frame" and the horizontal spindle setup, which is common in diamond turning machines [2]. In the presented solution, a horizontal spindle setup is chosen, as shown in Figure 1, even though the heavy workpiece handling would suggest a vertical setup in the first place. After considering the following points it will be clear that the horizontal spindle offers more benefits than the alternative.

The main reason for the choice of the horizontal setup is the angular displacement of the spindle, which is an air bearing and by nature will have compliance, when a heavy optic is mounted. That displacement will be perpendicular to the "sensitive direction" (see Figure 1) in a horizontal setup.

For a workpiece with a weight of 145 kg the spindle angular displacement was calculated, and the form error was derived depending on the size of the optic (Figure 2) [1]. The form error will only be influenced by a fraction of a nanometer, even at +1000 mm diameter, when a horizontal spindle setup is chosen.

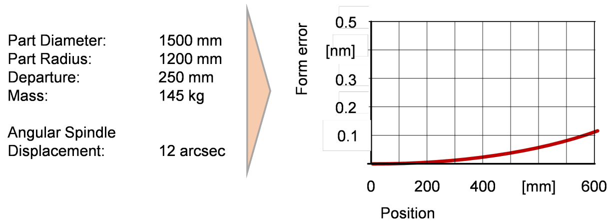

Figure 2. Form error on optical surface due to angular spindle movement

Other factors, like workpiece deformation by gravity have less impact on the form accuracy when the spindle is setup horizontally. Furthermore, a slow-tool servo or fast-tool servo operation will be much more efficient in this setup, causing less induced vibrations, which allows freeform surfaces to be machined.

3.1. Linear axis setup

Due to the weight of the optic, the horizontal spindle is mounted directly on the granite frame of the machine. Therefore, the selected machine design has a stacked linear axis (X & Z) concept. A stacked Z axis on top of the X axis minimizes the overall moving mass of the main spindle including the 200 kg workpiece, and reduces the utility support drag, such as spindle power cables and hydraulic lines. Additionally, considering the space required for tool metrology and the dressing spindle, the overall X-axis travel range needed to be larger. Figure 3 shows the machine axis setup.

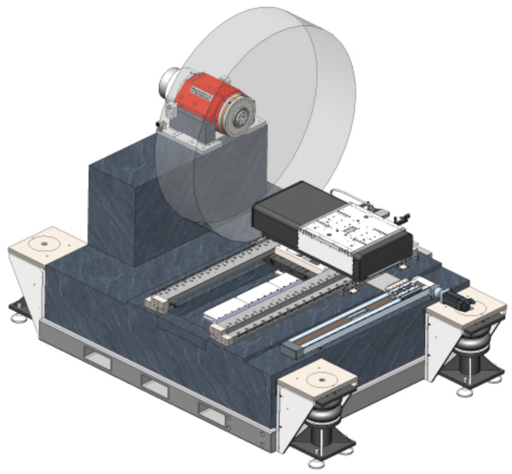

Figure 3. Stacked axis setup of 1500 mm ultra precision machine

Additionally, a horizontal machine configuration with stacked linear axes allows for the integration of a rotational B-Axis. This setup enables multi-tool configuration while also supporting tool normalcy operation, enhancing flexibility and precision in machining.

3.2. Thermal management of large machine

With a maximum machining size of 1500 mm in diameter, the processing time can extend to several days in some cases. Therefore, the thermal stabilization becomes critical, especially when a heavy mass component is in motion, it is essential to control energy losses caused such as by fluidic shear friction and motor heat to ensure process stability and precision [3].

A multi-level thermal control system is employed for thermal stabilization. The Temperature Management Systems (TMS) will stabilize the hydrostatic oil temperature for the linear axis, the pressurized air for the main spindle, and the air flow that is blown into the machining chamber (Figure 4). For each thermal loop, a series of thermal probes are positioned to monitor the temperature change over time and will have an active impact through PID regulation on the thermal properties. This way the machine will be in a thermally stable condition after a very short time, in contrast to thermal management systems that are conventionally used on ultra precision machines.

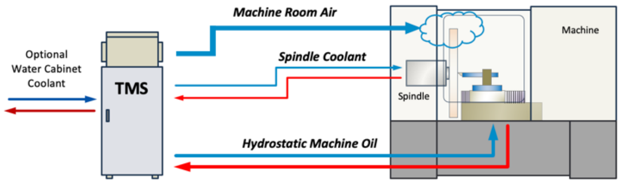

Figure 4. Thermal management of large ultra precision machine

4. Large frame ultra precision machine

As a result of the developments described above, the 1500 UPL ultra precision machine has been built (Figure 5). This machine offers the possibility to perform diamond turning or grinding with an additional grinding spindle.

Figure 5. 1500 UPL, the largest ultra precision machine [5]

5. Summary

Creating a concept for an ultra-precision machine that allows the manufacturing of optics up to 1500 mm in diameter involves a variety of challenges. The heavy weight handling on the machine was tackled by a horizontal spindle setup, that minimizes the induced surface form error by angular spindle displacement. A thorough thermal management and regulation system ensures thermal stability over the extremely long processing time. Further results on the achieved optical quality will be available very soon to underline the presented work.

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