The dynamic design of an ultra-precision machine tool used for larger KDP crystal machining

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Abstract

This paper presents the design and dynamic optimization method of an ultra-precision diamond flycutting machine tool for flat surface machining of Potassium Dihydrogen Phosphate (KDP) crystal in half-meter scale. An accurate multi-degree-of-freedom dynamic model for this machine tool is built up to describe its static and dynamic characteristics. The effects of the tool tip response under the cutting force in the whole cutting path on surface topography and the dynamic structure loop of the machine tool are analyzed. The weak line of the structure loop is optimized to improve the dynamic performance of the machine tool. Preliminary machining trials are carried out, which shows this machine tool can successfully manufacture 430 mm × 430 mm surfaces on crystalline optics, with 1.3 μm flatness and 2.4 nm Ra roughness.

1 Introduction

KDP crystal is a kind of crystal material with good nonlinear optical and electro-optical properties. This crystal is largely applied in the laser fusion system of Inertial Confinement Fusion (ICF) program as harmonic frequency converters [1]. The KDP crystal has extremely harsh requirements of the topography in the ICF program. It requires the flatness less than 3 μm in the whole size of 430×430 mm^2, and the roughness values less than 3 nm Ra [3]. However, this material is so soft, fragile, gyroscopic, and thermally sensitive that traditional grinding and polishing methods are not suitable for processing this material, so it's final surface only can be achieved by cutting. Therefore, an ultra-precision flycutting machine tool urgently is required to be designed.

2 Static and dynamic characteristics analysis

The configuration of the flycutting machine tool is designed as shown in Fig.1. A bridge supports a vertical-axis aerostatic spindle and flycutter over a horizontal-axis hydrostatic slide. Mounted to the horizontal slide is a vacuum chuck that fixes the workpiece by vacuum power. The surface to be machined lays in a horizontal plane. This configuration can not only improve the rigidity of the machine tool but also reduce thermal deformation. In order to improve the stiffness of the spindle in the axial, a large support surface is adopted.

In order to describe its static and dynamic characteristics, an accurate multi-degree-of-freedom dynamic model for this machine tool is built up as shown in Fig.1. The tool-workpiece structural loop and the spindle shaft of the machine tool are also given.

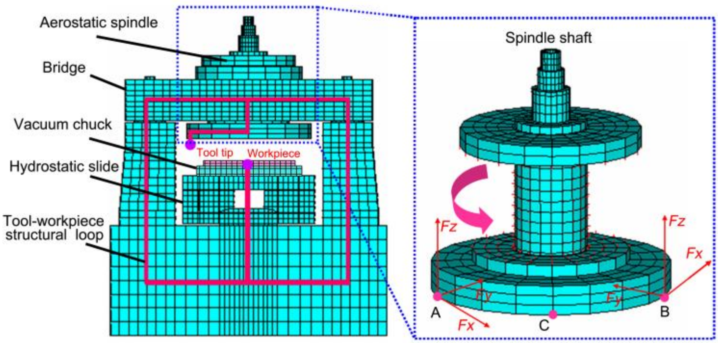

Figure 1: The FE model of the machine tool.

2.1 Static analysis

As the cutting proceeding, the cutter moves from point A to point B as shown in Fig.1. This cutting process is simulated by the Finite Element (FE) method. The results show that the tool tip has different displacement in *z* direction, with the cutting force is 1 N, 10 N and 10 N in *x*, *y*, and *z* direction, respectively. The displacement of the tool tip in *z* direction is shown in Fig.2, the maximum value up to 1 μm at point C, which will result in a convex surface. This phenomenon is because that the spatial position and direction of the cutting force change constantly along the whole cutting path. It indicates that to obtain a flat surface, the spindle axis should be located slightly forward to the slide, rather than vertical completely, when installing the spindle.

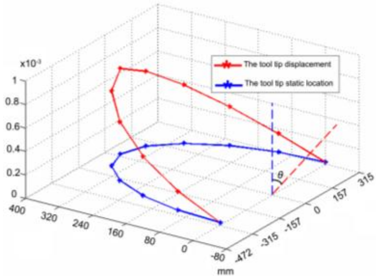

Figure 2: The displacement of the tool tip during the cutting proceeding.

2.2 Dynamics analysis

In order to improve the dynamic performance of the machine tool, analysis of the gantry structure machine tool in detail is given as follows. The contribution of the crucial machine components to the dynamic performance of the tool-workpiece structural loop is given in Fig.3. The response points are laid on the tool tip and workpiece, respectively. It shows that the first order mode of vibration of the tool-workpiece structural loop has the same mode shape with the machine structure, but the value is less than the machine structure's. The first order frequency of the spindle and slide occurs at 324 Hz and 425 Hz, respectively. It demonstrates that the spindle and the slide have a good dynamic performance; The weak link within the tool-workpiece structural loop is the machine structure, which has the most significant effect on the dynamic performance of the machine tool. That's because the machine structure provides the support and accommodation for the spindle component, the additional weight of the spindle makes the dynamic performance of the machine structure decrease sharply, the first order frequency decreases from 164 Hz to 105 Hz. Therefore, in order to improve the dynamic performance of the machine tool, the machine structure is optimized as follows.

The workspace provided by the machine structure is designed as 770×518 mm, thus it can meet the requirement of both machining the 430×430×10 mm workpiece and giving enough space for the spindle, slide and the vacuum chuck. The objective function is simply defined as the maximum value of the first order frequency of the machine structure. The limitation is the workspace provided by the machine structure, and the design variables are the structural parameters of the machine structure. After optimization, the first order frequency of the machine structure increases from 222 Hz to 325 Hz. The dynamic performance of the tool-workpiece structural loop rises from 116 Hz to 145 Hz.

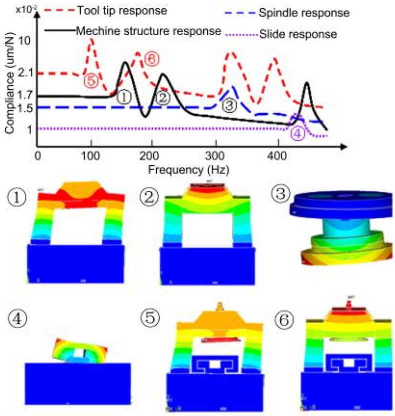

Figure 3: The influence of the components of the machine tool on the tool-workpiece structural loop. ①The first mode of the machine structure; ②The second mode of the machine structure; ③The first mode of the spindle; ④The first mode of the slide; ⑤ The first mode of the tool-workpiece structural loop; ⑥The second mode of the tool-workpiece structural loop.

3 Preliminary machining trials on the machine tool

The machine tool has been utilized to machine the KDP crystal with size of 430×430 mm. The preliminary machining results had a roughness of 2.4 nm Ra and a flatness of 1.3 µm as shown in Fig.4.

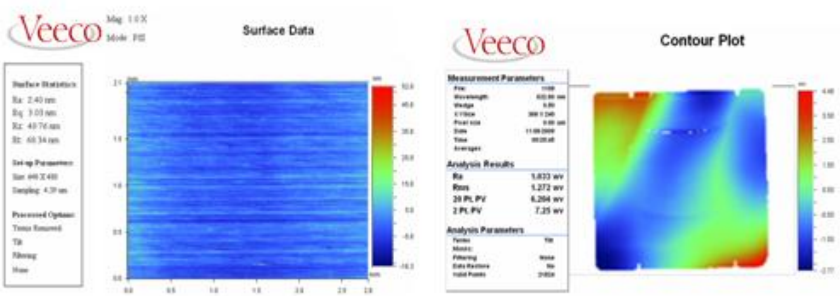

Figure 4: The test results.

References:

[1] Painsner JA, Boyes JD and Kuopen SA. National ignition facility. Laser Focus World 1994; 30: 75.
[2] Lahaye P, Chomont C and Dumont P. Using a design of experiment method to improve KDP crystal machining process. Proc SPIE 1998; 3492: 814–820.