Submicron cutting depth achievement for ultra-precision flycutting machine tool based on supplied pressure controlling

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Abstract

In this paper, a novel and convenient method to achieve submicron cutting depth setting is presented for the flycutting machine tool. Based on the phenomenon that aerostatic bearings are slight deformed under the air pressure, fluid-solid interaction simulations are performed to obtain exact deformations of bearings under different pressures. Furthermore, static measurements show good agreements with the simulations. The flycutting experiments indicate that the displacement of the tool is about 100nm when supplied pressure increases from 0.49MPa to 0.52MPa, which means the submicron cutting depth is achieved by changing the pressure in a small amplitude. This method is significant for machining optical crystals.

Keywords: Ultra-precesion flycutting; Aerostatic spindle; Submicro cutting depth; Fluid-solid interaction; Supplied pressure

1 Introduction

Ultra-precision flycutting technology is a vital processing technology in the field of ultra-precision machining, especially in processing some special materials, such as potassium dihydrogen phosphate (KDP) crystals which are particularly brittle, easy to deliquescence and can’t be processed by traditional grinding and polishing [1-3]. The surface topography of the workpiece is copied from the tool-tip on flycutting, so that the machining accuracy depends on the absolute accuracy of the flycutting machine tool. The manual spiral feed unit of the flycutting machine tool could hardly achieve cutting depth in submicron level [4-5]. However, for many kinds of optical materials, such as KDP crystals, their brittle-ductile transition thickness is less than 200nm [6], thus it is significant to present a stable and convenient method to achieve submicron cutting depth setting. There are kinds of solutions which could achieve submicron cutting depth, K. Cheng and D. Huo made a thorough comparison and discussion of these solutions [7]. For a kind of machine tool which has no CNC feed function along the cutting depth direction, a novel method to feed in axial direction is carried out in this study which could achieve submicron cutting depth by controlling supplied pressure.

In this study, a special ultra-precision flycutting machine tool for KDP crystals is employed. The machine tool is assembled with an aerostatic spindle system, as shown in Figure 1. The cutter is mounted on the outer cylinder of the cutter head which rotates with the shaft. The aerostatic spindle with the cutter is supported by the aerostatic bearings which consist of two thrust plates and one radial bearing. Bearings would be slight deformed when the supplied air pressure is changed in small amplitude, then the distance between the tool and the workpiece would be changed [8], which means the cutting depth changes.

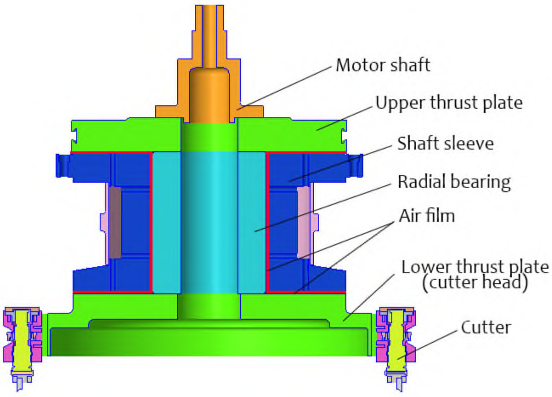
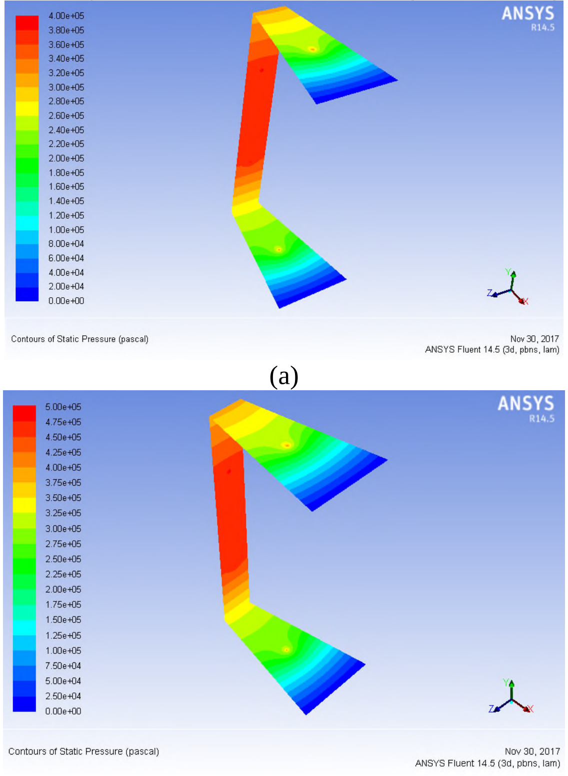


Figure 1: The aerostatic spindle system

2 Fluid-solid interaction simulation

For the analyses, the ICEM-CFD software is used for grid division firstly and the Workbench software is used for coupling [9-10]. The FLUENT module is used for fluid analyses, the Static Structural module is used for solid analyses and the solution would be obtained by coupling the fluid and solid in the Workbench.

Due to the eighteen orifices of the air film distributed evenly in the circle, a 1/18 model is established for simplifying the calculations and the arc edges are replaced by regular polygons. Since the air film has a pretty large aspect ratio, it is suitable to use structural grids, which have characteristics such as simplified the boundary condition setting, simplified calculation and much efficient compared with unstructured grids. In the FLUENT, the air is set as laminar, the inlet pressure is 0.4MPa (gauge pressure) and the outlet pressure is 0MPa (gauge pressure). Then the solution of fluid analysis is imported to the Static Structural module for the coupling simulation. Finally, the pressure distribution of air film and deformations of the structure could be read from the results. Similarly, another two simulations whose input pressures are 0.5MPa and 0.6MPa are carried out respectively. The results are shown as Figure 2 and Figure 3.



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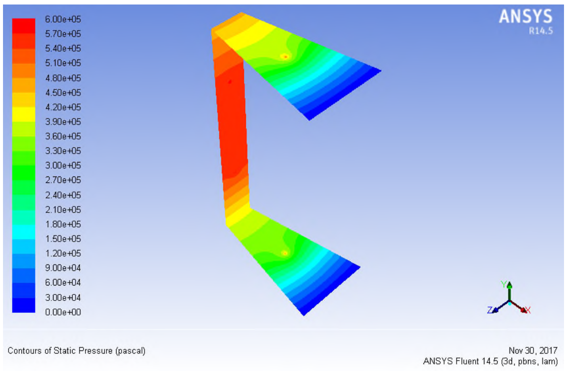

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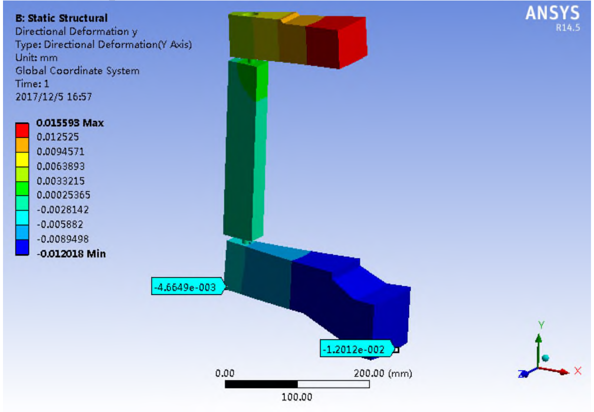
Figure 2: Contours of pressure distributions; (a)0.4MPa; (b)0.5MPa; (c)0.6MPa



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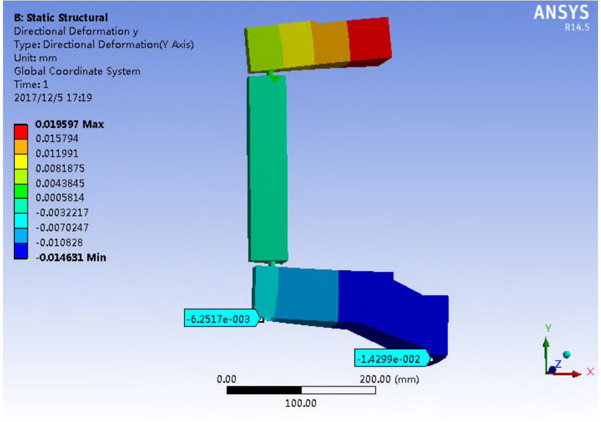

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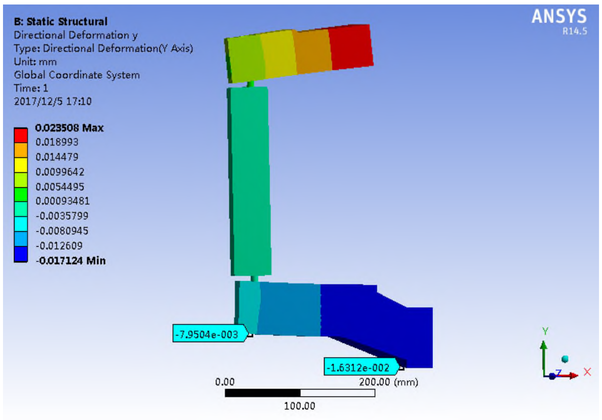

(c)

Figure 3: Contours of the structure deformations; (a)0.4MPa; (b)0.5MPa; (c)0.6MPa

The structure deformations are extracted and arranged as Figure 4, the difference between the edge of the cutter head and the centre of the cutter head is regarded as the deformation of the cutter head, and the difference between the upper bolts and lower bolts is regarded as the deformation of the total tensile deformation of bolts. In this way, when the input pressure increases from 0.4MPa to 0.5MPa, the deformation of the cutter head increases by 0.69µm; the deformation of the bolts increases by 0.96µm. And when the input pressure increases from 0.5MPa to 0.6MPa, the deformation of the cutter head increases by 0.33µm; the deformation of the bolts increases by 0.65µm.

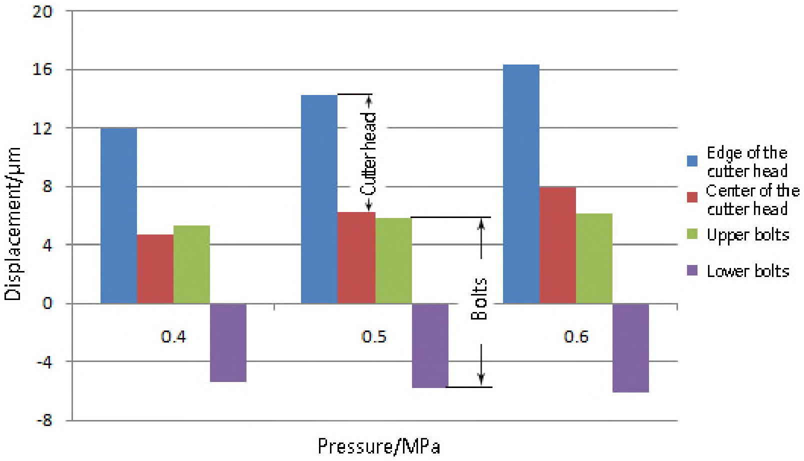

Figure 4: Displacements of the cutter head and the bolts

3 Experiment

3.1 Static measurement

Static measurements and analyses of the spindle system are carried out for validation. The precision capacitive displacement sensors and the supporting equipment are used in the experiment. As shown in the Figure 5, three capacitive displacement sensors are arranged in the centre of the upper of the spindle, the centre of the cutter head and the edge of the cutter head respectively to perform precision measurements. A precision electric proportional valve from SMC is introduced to adjust the supplied air pressure, and the pressure value is monitored by precision pressure indicator produced by GE Druck with the precision of 0.01% F.S.[11].

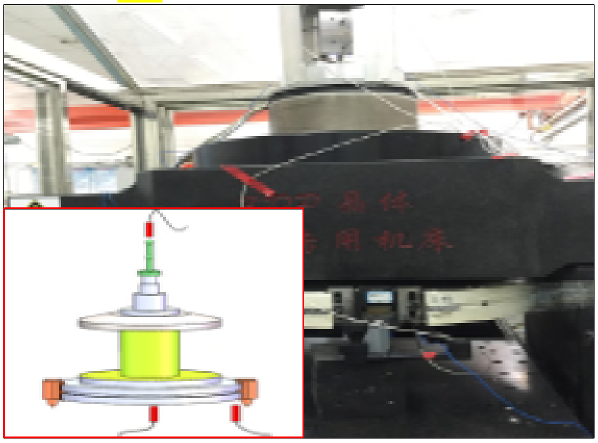

Figure 5: Sensors installation instructions

In the experiment, the gaps between the capacitive displacement sensors and the measuring positions are controlled within 50μm to ensure the measurement accuracy. The input air pressure is changed manually from 0.2MPa increased gradually to 0.6MPa, each step increases 0.1MPa, and measurements are repeated several times. The results of measurements have the same trend shown as Figure 6. It can be seen from the figure that with the increase of the air pressure, the central position of the spindle is floating, and the increment of the unit pressure decreases; both the centre of the cutter head and the edge of the cutter head are floated up first and then sank.

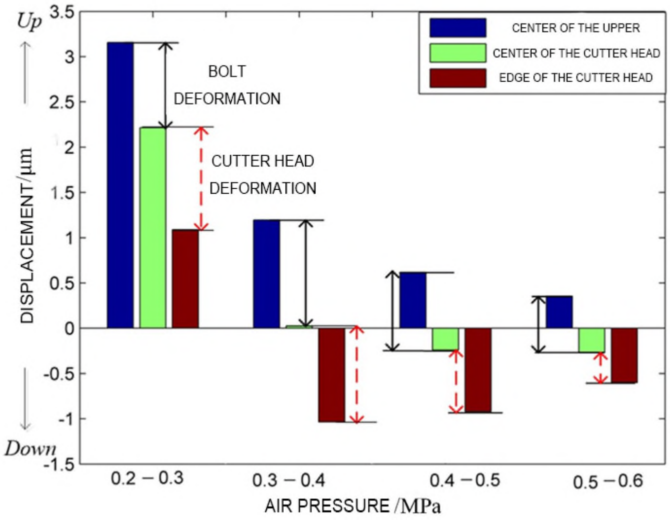

Figure 6: Displacements of the spindle system with various air pressures

From the above experimental results, it can be found that when the working pressure is between 0.4MPa-0.6MPa, the tool position will increase with the decrease of the air pressure. In addition, the upper position is larger than the centre position of the lower, which indicates that the axial length of the spindle increases with the incensement of the air pressure. The main reason is that the spindle thrust plates are combined by the bolts; with the increase of the pressure, the bolts are stretched. At the same time, the displacement in the edge of the cutter head is larger than the displacement in the centre of the cutter head, which indicates that the cutter head deforms with the increase of the air pressure. Compared with the simulation results, the deformations of the cutter head and the bolts are high consistent.

3.2 Flycutting experiment

Flycutting is a dynamic machining process so that the static data can only explain the trend. Thus it is necessary to measure the displacement of the tool dynamically with the influence of air pressures. It is very difficult to measure the displacement of the tool directly at work. Therefore, the dynamic information of the flycutting process should be measured by the reverse method through the machined surface [12]. The flycutting machine tool is employed to process the workpiece. Processing parameters for the fine cutting are set as feed speed of 60μm / s, cutting depth of 3μm, spindle rotation speed of 400rpm; the input air pressure is set as 0.46MPa. After 5 minutes for cutting, stop feeding and increase the air pressure by 0.01MPa. Then the table continues to feed for 5 minutes. Repeat above steps until the air pressure increased to 0.56MPa.

According to the previous experiment and analysis, the machined surface will show a stepped structure. The surface of the component is tested by surface roughness measuring instrument and microscope shown as Figure 7. It can be seen that the width of every step is about 4mm as it takes 6 steps from 16mm to 40mm, while the depth is about from -100nm to 70nm. Since the pressure increased 0.01MPa per step, the depth increased about 170nm when pressure increased 0.06MPa.

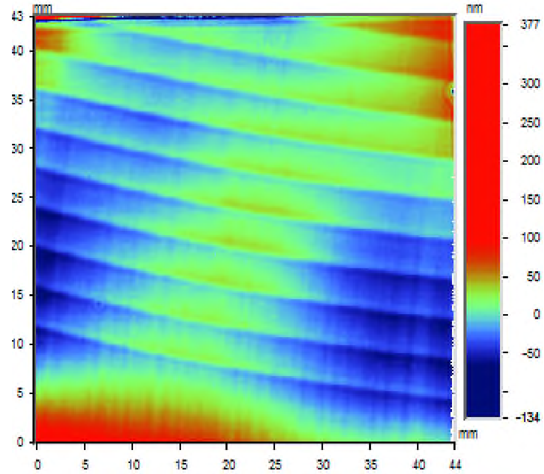

Figure 7: Surface with stepped structure machined with various pressure

The data of static measurements and dynamic measurements are arranged as Figure 8. It is easy to find that the displacement of the tool is approximately linearly increased and they are repeatable when the pressure increases from 0.46MPa to 0.56MPa. The dynamic data have the same tendency with static data; while the dynamic data are smaller than static data in the same pressure due to the workpiece exerts a reaction force to the tool when processing.

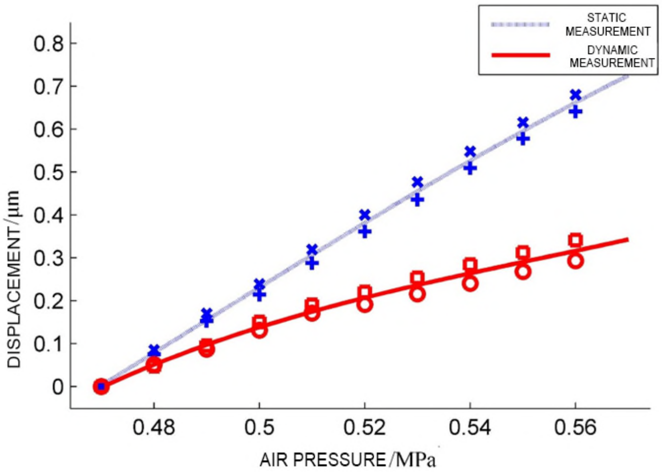

Figure 8: Displacements of the tool with static measurements and dynamic measurements

4 Conclusion

The change of the inlet air pressure allows the tool displacement changing at the submicron level. This phenomenon may reduce the quality of the machined surface in a complete process which should be avoided. However, it could be exploited between two processes to achieve a subtle feed at submicron level. After one cutting process is completed, adjusting the pressure to achieve a subtle feed would be practical according to the analyses above. For instance, adjusting the pressure from 0.52MPa to 0.56MPa could achieve a cutting depth of about 100nm.

Acknowledgement

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