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A MACHINING PROCESS CHAIN SYSTEM FOR PRECISION MANUFACTURE OF POLAR MICROSTRUCTURES

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Abstract
Polar microstructures are three dimensional (3D) structured surfaces possessing a pattern of distribution of latitude and longitude micro-topographies with geometrical characteristics which is similar to that in earth's north or south pole. The spacing of its texture can achieve micrometer level. Polar microstructures have great potential of applications in many areas such as polar coordinate system, datum for precision measurement, etc. They are usually machined by Fast Tool Servo (FTS) machining after complicated generation of tool path. However, FTS machining method suffers from complicated program coding, low machining efficiency, limited size of the workpiece and dynamic characteristics of FTS. This paper presents a study of machining process chain system which combines turning and broaching machining processes together to precision manufacture of polar microstructures. A framework of machining process chain system is presented which is composed of input module, deign module, metrology module and output module. Based on the design principle of polar microstructures and a series of machining process steps, a series of experiments are conducted to ultra-precision machining various types of polar microstructures. The machining results show that the machining process chain system is technical feasible and effective in precision manufacture of polar microstructures. The technological advantages of the system are also realized.

INTRODUCTION
Polar coordinate has been applied in many fields such as modeling, position, navigation, etc. [1]. For example, figure 1 shows the Antarctic navigation map, the earth latitude and longitude form a polar coordinate which is convenient for accurate positioning. In precision engineering field, polar coordinate is also vital which provides a potential method as positioning for precision measurement. Currently, polar microstructures are usually machined by Fast Tool Servo (FTS) machining after complicated generation of tool path. However, FTS machining method suffers from complicated program coding, low machining efficiency, limited size of the workpiece and dynamic characteristics of FTS.

This paper presents a study of machining process chain method which combines turning and broaching machining processes together with the precision manufacture of the polar microstructures. In this paper, a polar microstructure was fabricated based on purposely designed machining process chain which is both effective and efficiency as compared with FTS machining. Firstly, a process chain system in ultra precision machining was presented, followed by designing and machining polar microstructures through a series of cutting experiments. Hence, experiment results were discussed.

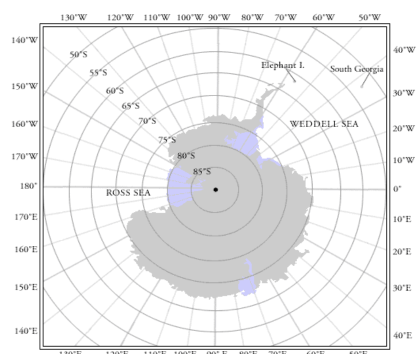

FIGURE 1. The distribution of the earth latitude and longitude lines from the perspective of the Antarctic [2]

MACHINING PROCESS CHAIN SYSTEM
Machining process chain is an emerging area in precision manufacturing. Thompson [3] applied it for the selection of an additive manufacturing context, Uhlmann [4] gave a review of process chain research for high-precision components with micro-scale features. Zhao et al [5] firstly

proposed a process chain optimization system in ultra-precision machining, and then a process-chain based study [6] was conducted to investigate the influence of machining parameters in ultra-precision raster milling. A framework of a machining process chain system is shown as Figure 2. This system consists of four modules which are input module, design module, output module and metrology module respectively.

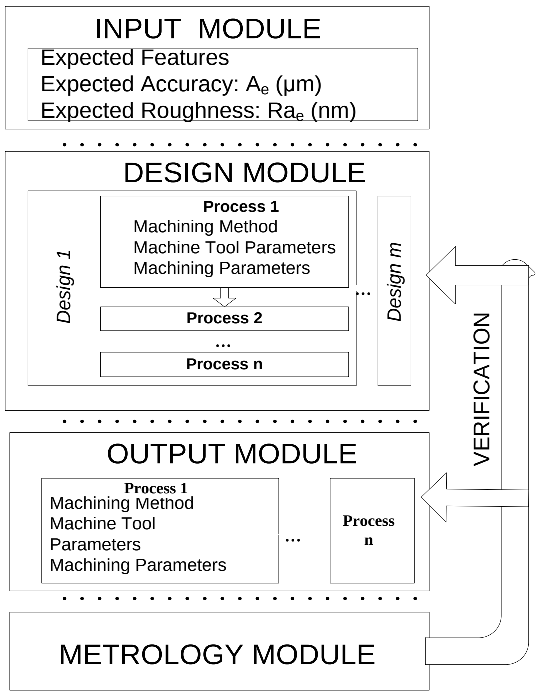

FIGURE 2. Framework of machining process chain system.

In the input module, expected features of workpiece should be entered. Moreover, accuracy and surface quality are also needed to be limited. Afterward, some initial machining process chains are presented in the design module, considering the limitation of each designated process chain such as its accuracy surface roughness, machining efficiency, etc. An optimal machining process chain including machining methods and relevant parameters which are selected for the output module and followed by corresponding simulation. The simulation is undertaken based on the modeling of the machining processes so as to obtain the predicted performance of the selected process chain. The workpiece is then machined based on the parameters in the output module. In the metrology module, the processed workpiece is measured so as to verify whether the results meet the requirements. If it is not, a repeated cycle from design module to metrology module should be conducted until all indicators are acceptable.

DESIGN OF POLAR MICRO STRUCTURE

Based on abovementioned process chain system in ultra-precision machining, there are different methods to machine polar microstructure, three possible machining chains are shown as Table 1. In machining process chain 1 (MPC1), fast tool servo (FTS) machining is suffered from complicated program coding. Moreover, the FTS is usually limited by size of the workpiece which should not be too large. Machining process chain 2 (MPC2) makes use of both Single Point Diamond Turning (SPDT) and Ultra-precision Raster Milling (UPRM) which overcomes the shortcomings of MPC1.
However, it is difficult to coincide with two machining centers due to repositioning error. Comparatively, Machining process 3 (MPC3) combines SPDT with diamond broaching together, its machining principle is shown in Figure 3. The concentric grooves are machined by SPDT and the straight grooves are machined by diamond broaching with the same machine tool (Moore Nanotech 350FG) as that of SPDT. It overcomes the above shortcomings in MPC1 and MPC2. More importantly, MPC 3 has the ability to machine large-size workpiece with high efficiency. Hence, the process chain of machining polar microstructure is chosen.

TABLE 1. Different machining process chains of manufacturing polar microstructure.

Process Chain 1	Fas Tool Servo (FTS) Machining
Process Chain2	Single Point Diamond Turning (SPDT) + Ultra-precision Raster Machining (UPRM)
Process Chain 3	Single Point Diamond Turning (SPDT) + Diamond Broaching

The next step is to determine machining parameters. Based on the models of SPDT and diamond broaching which have been built up, a series of simulation experiments were conducted using different machining parameters. A group of optimal parameters are shown in Table 2 and the simulated surface texture of the polar microstructure is shown in Figure 4. The distance and angle spacing of its texture are chosen to be 50 μm and 10° respectively after considering both machining tool accuracy and material properties of workpiece.

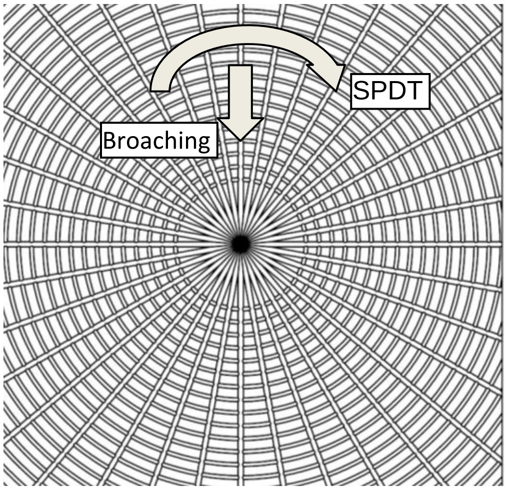

FIGURE 3. Optimal process chain (Combing SPDT and diamond broaching process) of machining polar microstructure

TABLE 2. Primary machining parameters in manufacturing of micro polar structure.

Radius of diamond tool	0.043 mm
Spindle speed of SPDT	2000 r/min
Feed rate of broaching	600 mm/min
Depth of cut (Both)	0.65 μm
Spacing (Both)	50 μm

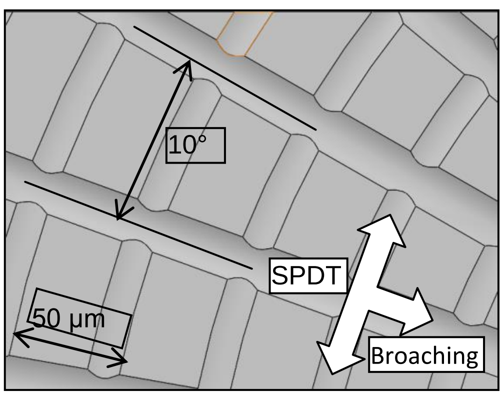

FIGURE 4. Enlarged top view of process chain model of machining polar microstructure

EXPERIMENTAL RESULTS

A series of cutting experiments with the machining parameters based on the optimal designed ones by process chain system have been conducted. The experimental results are shown as Figure 5. As shown in Figure 5(a), the intersection of the straight grooves coincides well with the center of concentric grooves. There are 36 straight grooves evenly distributed on the surface of polar microstructure.

Moreover, the distance between each adjacent concentric groove is 50 μm. To clearly observe micro polar structure, the workpiece was measured with a Scanning Electron Microscope (Hitachi Electron Microscope TM3000) as shown in Figure 5(b). The surface quality of workpiece is good including cutting grooves as well as the protruding surface parts (such as the 'PSP' marked in Figure 5(b)) which were not machined in this process chain.

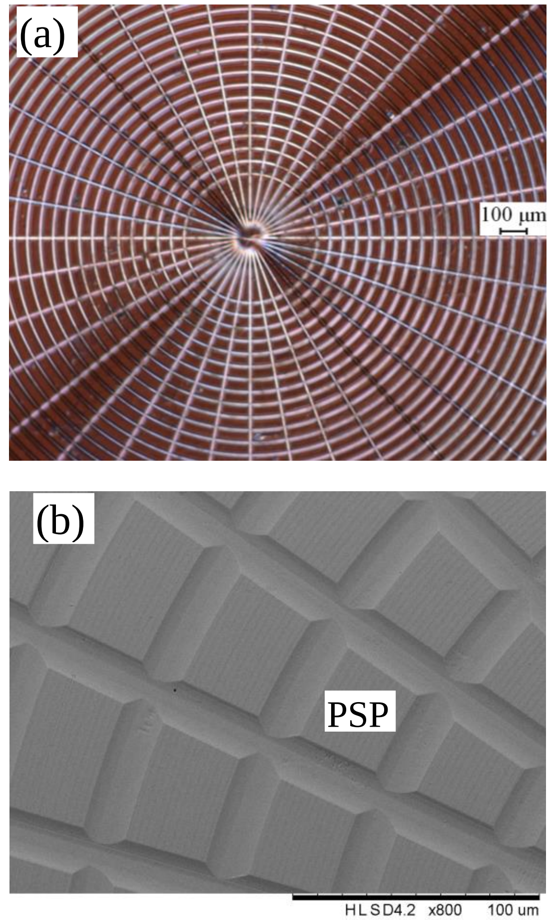

FIGURE 5. Micro polar structure measured by (a) Pearl Centering Microscope (b) Hitachi Electron Microscope TM3000.

To illustrate the experimental results through the specific data, the workpiece was also measured with a laser interferometer (Zygo Nexview™ 3D Optical Surface Profiler) as shown in Figure 6. To study the following factors affecting the accuracy of polar microstructure: 1) the cutting depth of machined grooves; 2) spacing between adjacent grooves; 3) surface roughness (Ra) of PSP, the above parameters of 50 straight grooves, 50 round grooves and 50 PSP were recorded as shown as Table 3.

Compared with the designed machining parameters in Table 2, SG_A is 0.02 μm less than designed spacing distance, DCS_A and DCR_A are 22.3 nm and 34.6 nm respectively more than designed depth of cut, DCS_S and DCR_S are 20.5 nm and 28.9 nm separately. Moreover, Ra of PSP is 14.6 nm which infers a high surface quality of micro polar structure.

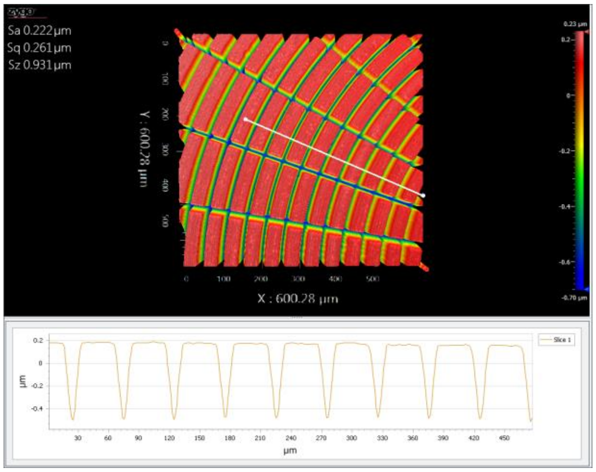

FIGURE 6. Surface topography of micro polar structure and its sectional view to show the structure space and depth of cut.

TABLE 2. Experimental parameters influencing machining quality of micro polar structure

Average depth of cut in straight grooves (DCS_A)	672.3 nm
Standard deviation of depth of cut in straight grooves (DCS_S)	20.5 nm
Average depth of cut in round grooves (DCR_A)	684.6 nm
Standard deviation of depth of cut in round grooves (DCR_S)	28.9 nm
Average spacing between adjacent grooves (SG_A)	49.98 μm
Arithmetic Roughness (Ra) of PSP	14.6 nm

CONCLUSION

This paper presents a machining method for precision manufacturing polar microstructure based on process chain system in ultra-precision machining. Polar microstructure has potential applications for precision measurement, while the machining accuracy and surface quality are also key factors needed to be considered. In this paper, a framework of machining process chain system is presented and design flow was described. Based on process chain system, the optimal process chain of machining polar microstructure was selected, followed by determined machining parameters. A series of experiments were conducted according to the designed machining parameters. The experimental results show that the accuracy of different primary parameters which influencing the future performance of polar microstructure is found to be in nanometer level. The result shows a machining process chain method which combines single point diamond turning together with diamond broaching is technically feasible and efficient to precision manufacture polar microstructure. The results also infer that the machining process chain system plays an important role for designing and optimizing machining processes in ultra-precision machining.

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