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Study on the micro-machining process with a micro three-sided pyramidal tip and the circular machining trajectory

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ABSTRACT

In this paper a three-sided pyramidal tip was driven in a circular trajectory to perform micro-machining process. The circular trajectory was achieved by rotating the tip around a center point. Because of the asymmetry of the three-sided pyramidal tip, machining micro channels along different feeding directions would cause different cutting tracks, which influences the finish of channel sides. It was found that the variations of cutting rake angle and uncut chip thickness in each revolution mainly affected the burr formation. By studying effects of tip edge radius and tip geometry on machining process, a channel with slight burr at two sides was obtained. Using the optimized machining method and coordinating with feed motion of the work stage, perfect three-dimensional structures with well-finishing edges were obtained on aluminum alloy and polymethylmethacrylate (PMMA) surfaces. The dimension of fabricated 3D structures can be controlled in three dimensional directions, ranging from ten microns to several hundred microns.

1. Introduction

Miniaturization has greatly pushed forward the development of the micro and nano researches, and is widely used in various industries, such as information technology, medical engineering, bio-chemistry and automotive. To meet the continuously improved requirements posed by the microparts and micro-structures, the corresponding micro-fabrication technologies, such as lithography-based techniques, micro non-traditional machining and micro mechanical machining, have been developed rapidly. Brousseau et al. (2010) reviewed the state of the art of 1D and 3D processing technologies in recent years, such as micro-EDM, micro-milling, nano-imprint lithography, hot embossing and so on. With the advantages of the broad range machinable materials and the flexible processing system, micro mechanical machining methods are topics of active research. Dornfeld et al. (2006) reviewed current research state of micro-machining from the aspects of processing mechanism, numerical simulation, machine tools and sophisticated machining results applied to other research fields.

Among the mechanical processing techniques micro-milling is the best candidate for creating 3D structures with dimensions from tens of micrometers to a few millimeters. By the focused ion beam method, Friedrich and Vasile (1996) fabricated micro-milling tool with about 22 μm diameter to machine the micro-scale trench structures on the polymethylmethacrylate material. Denkena et al. (2006) used milling cutters respectively made of tungsten carbon and diamond materials to process 3D structures and found that the diamond cutter could machine smaller dimension structures. Though a lot of studies have been invested to promote this technique, there are also some obstacles to be overcome. Chae et al. (2006) discussed the state of the art of micro-milling operations in detail. One focus of attention is the limit of processing capacity to the smaller scale. Reducing the tool diameter may be the only solution. For machining less than 50 μm grooves, Schaller et al. (1999) ground hard metal tools by diamond grinding disks and obtained the end mills with diameter ranging from 35 μm to 120 μm. However, not only increase the difficulty of manufacturing the milling tool with the smaller size, but also the chance of tool wear and breakage. Tansel et al. (1998) studied the tool failure mechanisms through machining different materials and proposed the methods for predicting tool breakage. Meanwhile, to attain sufficient cutting speeds in milling process with reduced tool diameter, higher rotational speeds are required, which aggravates the problem of tool run-out and raises the cost of the machine tool. Some

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modified micro-milling techniques, such as laser-assisted micro milling (Kumar and Melkote, 2012) and vibration-assisted micro milling (Shen et al., 2011), have been proven to be effective on reducing tool wear, but restricted by the complexity to the set-ups and lower the quality of the machined surface. Heamawatanachai and Bamberg (2009) developed a novel machining technique based on orbital motion of a single point tool tip. In their studies, a conical single crystal diamond tip with about several microns radius was rotated by a piezoelectric tube scanner instead of a high speed spindle to mill features. Not only feasibility for machining 3D structures on various kinds of ductile materials has been verified, but also the ability to fabricate brittle materials due to an extremely negative rake angle. They presented the cutting force model for this processing method based on the modified grinding force model and performed machining experiments to verify this model (Heamawatanachai and Bamberg, 2010).

AFM-based mechanical fabrication has been a sophisticated processing technique which can create smaller features ranging from several nanometers to a few micrometers, with the recipe that applying a small force is measurement and a large force is manufacture. Fang and Chang (2003) conducted AFM nanolithography using tip-based scratching on the aluminum film and optimized the quality of machined surface. Li et al. (2005) developed an equipment of nanoindenter integrating with AFM to cut the ZnS nanobelts into the prescribed length and fabricated pyramidal indentations and nanochannels on the top surface of the nanobelt. Because the original purpose of AFM is used for measurement, there are some shortcomings existing in manufacture. To eliminate shortcomings of the range and resolution limitations, and nonlinearity and hysterics of the piezo scanner, Yan et al. (2010) developed an AFM processing system integrated with a nanometer scale precision-stage in which the scanner was not employed during the machining. They machined a 3D human face by the stages combining motion of z-direction extension and x- and y-feeds in the AFM height mode. To obtain the prescribed removal depth and shearing removal mechanism, Gozen and Ozdoganlar (2010) presented a tip-based nanomilling technique: an AFM tip was directly motivated by a piezoelectric actuator to rotate in horizontal or vertical plane, and by the rotational motion of the tip the milling process was achieved. Without utilizing the tip cantilever during the machining process, a high-stiffness processing method was realized with a controlled machining depth (Gozen and Ozdoganlar, 2012). Combining the tool rotation with stage feeding motions, some 2D and 3D structures were machined in the cutting state.

In the current research, there is a gap of processing scale from ten microns to one hundred microns. Downsizing the micro-milling and upsizing AFM machining both result in the new technical problems and high-cost of set-ups. Therefore, a novel processing method is urgently required. In this study, a new set-up was established to perform micro-machining similar to the set-up established by Heamawatanachai (2010). In their studies the conical tip was employed as a tool for machining, which would cause serious burr formation upon machining ductile materials and need the deburring methods (Heamawatanachai, 2010). Moreover, due to the orbital motion achieved by the piezo tube whose length in z-direction would change during moving, the height compensation is needed to obtain the planar orbital motion of the tip. The differences between our work and theirs are the use of the three-sided pyramidal diamond tip and a three-axis piezoelectric translation stage which can achieve planar revolution without height compensation. Because the pyramidal tip has three cutting edges and the mean radius of the three edges was about several tens of nanometers, smaller features could be processed than the previous researches. Due to the asymmetry of the three-sided pyramidal tip, the variations of cutting thickness were different along different feed directions. For machining the micro channels, four processing directions were studied to analyze tip geometry effect on the machining results. Under different feeds per revolution the influence of tip edge radius on machining was analyzed. Finally, channels with fewer burr and better bottom surface quality were obtained. By the piezoelectric actuator extending coordinating with two-dimensional nano-positioning stages feeding, some 3D structures were machined on different materials successfully.

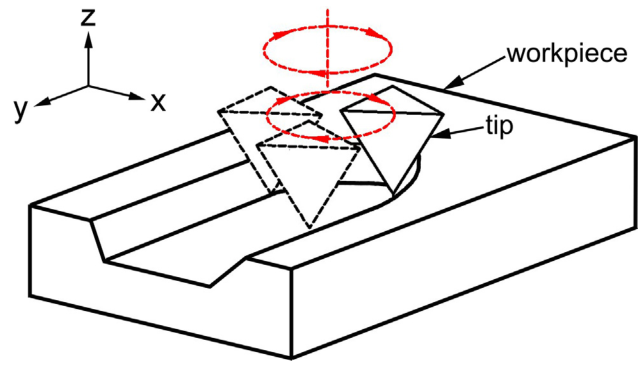

Fig. 1. Schematic of machining process.

2. Experimental details and methods

A tool tip is driven by the piezoelectric actuator to conduct the milling process on the workpiece in our machining system, which is not the rotation of tip but the revolution, the principle as shown in Fig. 1. The tool is the three-sided pyramidal diamond tip (cube corner, Synton-MDP, Switzerland) which is commercially used for nanoindentation. Fig. 2(a) shows the SEM image of the diamond tip with three very sharp edges. By AFM scanning for the three edges, the radii of the cutting edges can be estimated to 50 nm approximately, as shown in Fig. 2(b). But due to the radius of AFM tip (~10 nm), the true value of edge radius would be about 40 nm or less. The actuator is a three-axis piezoelectric translation stage with a moving range of 100 μm, a closed-loop resolution of 2 nm. It could provide both horizontal orbital motion and vertical extension. In the horizontal plane the x- and y-axes were actuated by a pair of sinusoidal excitations (a phase lag of 90°) to revolve the tip, and in the vertical the z-axis was used to make the tip approach the workpiece surface. Due to independent movement of three axes, the compensation for z-direction during x- and y-axes moving is not needed. Nanometer-precision linear stage (M-714.HD, PI Company, Germany, 7 mm range and 2 nm resolution) and Nano-precision heavy-duty stage (M-511.HD, PI Company, Germany, 100 mm range and 2 nm resolution) were combined to perform feeding motions along x-direction and y-direction, respectively. The schematic for the machining system is shown in Fig. 3. With the tip revolving the sample is moved by the two stages to obtain the prescribed feature. The sample materials were aluminum alloy (2A12) machined by ultra-precision turning with the surface roughness R_a of 5 nm, and injection molding polymethylmethacrylate (PMMA) with R_a of 2 nm approximately. All the processing experiments were preformed under the ambient conditions and free of the cutting fluid. After processing, the surfaces were ultrasonically washed in ethanol solution for about 3–5 min to remove the chips for subsequent imaging.

3. Results and discussion

To validate the moving path of the tip circular motion, a ring was machined directly by the tip revolution with 10 Hz frequency and 10 μm diameter, and then measured by AFM as shown in Fig. 4(a). The tip orientation and its revolution direction during the