3D Tool Path Generation for Micro-abrasive Jet Machining on 3D Curved Surface

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Micro-patterns can be carved by jetting fine particles onto the surface of a workpiece. A mask structure is required to classify the surface regions to be machined. This mask is a plate with a hole that corresponds to the pattern to be carved. Abrasive particles are used to erode the workpiece through the hole in the mask. Recently, abrasive jet machining technology has been applied to workpieces with three-dimensional curved surfaces. To utilize the technology for a three-dimensional workpiece, a mask structure needs to be built on the workpiece. Microstereolithography can be used to build this three-dimensional mask for the workpiece. Consequently, process planning technology for the movement of the abrasive jet nozzle should be developed. It should follow the three-dimensional mask and workpiece at a specific distance to achieve uniform machining and a better surface finish. This paper introduces a process planning technique that can automatically generate a three-dimensional machining path for a three-dimensional mask and workpiece. A verification example and an application example are also shown.

1. Introduction

Abrasive jet machining is known to be a good machining process for making holes or grooves in brittle or heat-sensitive materials. It erodes the material away by blowing abrasive particles onto the surface of the workpiece. This technique is primarily used to remove the flash or reduce the surface roughness of cast or pressed products.1,2 Recently, the materials for machining have become more diverse. Therefore, the need for an effective machining technology for thin or thermoplastic materials has been increasing.3-8

In abrasive jet machining, the sprayed particles gradually scatter as they move away from the nozzle. Thus, for precise machining, there is a need for a mask structure that can assign the area to be machined. In general, this mask is fabricated by photolithography and chemical etching on a metal plate. Recently, a direct mask fabrication technique has been developed, which fabricates a mask structure on the workpiece by using a photocurable resin and a UV light source.9 This is very effective when the production volume is small. Some studies have attempted to apply micro-abrasive jet machining (μAJM) to a workpiece with a curved surface. In addition, a mask modeling technology for a workpiece with a three-dimensional curved surface has also been developed.10,11 Moreover, a nozzle path planning technique has also been introduced for a curved workpiece, but it makes still a planar jetting path.12 However, for a workpiece and mask structure with a three-dimensional curved surface, it is better to use a machining path that is also three dimensional. This is because a constant SOD (standoff distance) between the nozzle tip and the workpiece should be maintained for uniform machining.3 Therefore, the development of a process planning technique for a three-dimensional jetting path is required. This paper introduces the algorithm and some application examples for such a technology.

2. Micro-abrasive jet machining on curved surface

2.1 Abrasive jet machining

Abrasive jet machining typically uses fine abrasive particles with diameters of approximately 25 μm, which are injected at a high speed by using air or an inert gas at a pressure of around 170-900 kPaG and a speed of up to 300 m/s.1,2 Fig. 1 shows a conceptual schematic. The grinding particles are fired through the nozzle with the compressed gas, and the nozzle or table is moved to change the machining position. At
this time, the distance between the workpiece and the nozzle is one of the main factors for determining the size of the machining point and the material removal rate. Although abrasive jet machining is a good method for patterning thin plates or heat-sensitive materials, it has a low material removal ratio and produces a tapered cut at the boundary of the patterns.\textsuperscript{2,3}

In abrasive jet machining, fine patterns can be fabricated using a mask, which sets the machining region and reduces the tapering of the cut at the boundary.\textsuperscript{13} There are two mask fabrication methods commonly used: photolithography and stereolithography.\textsuperscript{9} In photolithography, the mask plate is fabricated by the irradiation of light on a film, which transmits the light through a pattern but not through the background or vice versa. The irradiated region will either remain or be removed when it is developed. Although fabricating a mask by this method is a lengthy and costly process and is hard to automate, the mask is hard enough to use several times. Thus, it is suitable for mass production. However, because the mask is flat, it cannot be applied to a workpiece with a curved surface.\textsuperscript{12} In contrast, stereolithography can be used to fabricate three-dimensional mask structures by the selective solidification of a liquid photocurable resin after the workpiece is dipped into the resin in a layer-by-layer manner.\textsuperscript{9} A fine pattern can be carved by moving the abrasive jet nozzle along the pattern by using a mask fabricated by stereolithography while maintaining its distance from the workpiece. The moving path can be generated using the process planning algorithm introduced in this paper.

2.2 Process planning

The process planning for the abrasive jet machining of a workpiece with a curved surface can be carried out by inputting the pattern image to be carved and the three-dimensional CAD (Computer Aided Design) data for the workpiece, as shown in Fig. 2. The technique used to generate the three-dimensional mask CAD data from these inputs was developed in a previous study, wherein the mask was modeled by projecting the pattern image on the curved surface of the workpiece.\textsuperscript{10,11} By applying the mask fabricated in the previous work, one can carve patterns on the curved surface by moving the nozzle, and the moving path can be generated on the curved surface by the projected region of the patterning image. The algorithm shown in Fig. 3 can generate the moving path for the abrasive jetting nozzle. The boundary contours are extracted from the image marking the machining region. Parallel scanning lines are generated using an offset of the machining hatch distance, which covers the entire region of the image. The scanning lines are divided at the points of intersection with the boundary contours. Then, the lines outside the machining region are removed, and the line segments are projected onto the curved surface of the workpiece to position the segments on the workpiece while breaking the lines sufficiently to keep the sagging height within bounds. Finally, the lines are connected to generate the tool path for the abrasive jetting nozzle, and the results are exported in G-code. Jetting abrasive particles onto the masked workpiece following the generated nozzle path will produce a three-dimensional pattern on the curved surface of the workpiece after removing the remaining mask structures.

2.2.1 Extracting boundary contour

To carve a pattern similar to that shown in Fig. 4(a), a mask image