Single Point Micro Incremental Forming of Miniature Shell Structures

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Abstract:
This paper describes single point micro incremental forming (SPMIF) applied to the fabrication of meso-scale shell structures. The authors have developed SPMIF without using any die and backing plate for flexible micro forming of miniature 3D products in a range of micro meters to sub-millimeters. A desk-top type of CNC milling machine was constructed as an experimental apparatus. Thin aluminum foils of different thickness and thin round tip bars of different diameters were utilized as blanks and forming tools, respectively. Some basic shapes and complex shell structures of micro shell structures were formed in the established SPMIF system. Through the experiments, it was proved that the SPMIF system established in this study can be widely applied to the forming of micro shell structures in various shapes.

Keywords: Micro incremental forming, Thin film, Miniature product

1. Introduction
Energy-saving and environment-friendly technology is aspired in today’s society. It is well known that miniaturized elements with useful features can contribute to the development of energy-saving and environment-friendly technology. From the standpoint of energy and environment, micro-fabrication to realize advanced technology has been rapidly expanded in many areas such as optoelectronics, MEMS, and surface texturing. In addition, various research projects on micro-fabrication are running in order to develop innovative fabrication methods.

These days, tiny surface structures on micro systems are usually made using silicon chip processes with lithography and etching, whereas other types of micro processes have been reported: nanoimprinting, nano precision ELID, micro EDM, etc. However, the processes to make various shapes of micro 3D structures are still immature. In this paper, novel micro-fabrication using incremental forming is described.

Incremental forming is known as a sheet forming process with favorable potentiality for energy and environment. In this process, a variety of sheet parts can be flexibly formed using a forming tool with a round tip. Iseki et al. [1] first reported dieless incremental forming as a forming process with high formability. After that, much effort has been made by Japanese researchers to make incremental forming versatile technologies [2-4]. Even today, many studies related to incremental forming are being reported [5, 6].

Although incremental forming has superior features, application of incremental forming to micro-fabrication has scarcely been studied. One of the few studies related to micro incremental forming was reported by Obikawa et al. [7]. With the dual aims of enhancing the study and establishing an innovative micro-fabrication method, a desk-top type of computer numerically controlled (CNC) single point micro incremental forming (SPMIF) system was newly made. Using the SPMIF system, miniature 3D shell structures were made by superposing planer tool paths based on fundamental geometry such as triangle and quadrangle. Finally, several complex shell structures were formed through elaborate tool paths.

2. Experimental Apparatus and Procedure
2.1 A Desk-top Type of CNC SPMIF System
A desk-top type of CNC SPMIF system and its appearance are shown in Figs. 1 and 2, respectively. It is composed of six main elements: an x-y table with closed loop control, a z-stage with harmonic drive, $\theta_x$ and $\theta_y$ swivels on the x-y table, a spindle, a manual height stage for rough positioning and a base. An x-y table, a z-stage, and $\theta_x$ and $\theta_y$ swivels are numerically controlled through digital signals from a personal computer. The resolution of motion is 10 nm for the x-y table, 10 nm for the z stage, and 0.001 deg. for the swivels. The upper limit of rotational speed of the spindle was 25000 rpm. Pure water was used as lubricant. As shown in Fig. 2, a vessel

![Figure 1: A schematic of CNC SPMIF system](image-url)
to receive splashes of pure water is put on the swivels in SPMIF system.

2.2 A Blank Holder

Elements of a blank holder are illustrated in Fig. 3. The blank holder is composed of eight parts: top plate, spacer, rubber plate, backup plate, adjustment plate, o-ring, tensioner and base plate. Six parts except for rubber plate and o-ring were made of stainless steel. A blank was put on between the tensioner and o-ring. Then, whole parts of the blank holder with a blank were fastened to assure the flatness on the forming surface of the blank. This system of the holder can avoid the wrinkles of the blank and improve the flatness by applying slight tension to the blank. The blank holder was fixed on swivels. Figure 4 shows surface conditions of a blank using the above blank holder.

2.3 A Forming Tool

A forming tool with the tip radius of 100 μm is shown in Fig. 5. The tool was chucked to an end of the spindle. The length of a protruding part of the tool was approximately set to 15 mm. The tool rotational speed was controlled with a spindle controller. To adjust the forming tool vertical to a forming surface, a rotational table was placed on the z stage. The contact point between the tool and the blank was detected accurately with an ammeter. That is, the tool and the blank were incorporated into an electric circuit. A forming tool was approached mechanically and slowly very close to a forming surface. When they came in contact, current, which began to pass through them, were detected with an ammeter. After the contact point was detected, the tool was moved to the starting point which was 1μm above the blank surface.

2.4 Foil Blank and Experimental Procedure

A household aluminum foil was used as a blank. The blank was 12 μm thick, and its chemical composition was 0.12 mass % Si, 1.5 mass % Fe, and 98.45 mass % Al. To avoid adhesion and abrasion occurred between a forming tool and blank surface, pure water was used as lubricant in all experiments. A view of SPMIF experiment is shown in Fig. 6. The SPMIF system enabled us to form a shell structure at anywhere of the blank. Unlike ordinary sheet forming process, tool path is needed to form a designed shape in SPMIF. Figure 7 shows a schematic of tool paths and foil deformation during forming of a pyramid. In Fig. 7, X, Y and Z are Cartesian coordinates; \( L \) is the diameter of a base circle; \( t \) is the thickness of a blank; \( h \) is the height of a forming shape; \( \alpha \) is the half apex angle; \( \omega \) is the tool rotational speed; \( dy \) and \( dz \) are the movement of initial position per planar tool path. A forming shape is mainly defined by the diameter of a base circle \( L \), half...
3. Experimental Results and Discussion

3.1 Polygonal Shell Structures

Several miniature polygonal shell structures through a SPMIF process were formed to investigate their fundamental forming characteristics. The forming conditions were as follows: $L = 1 \text{ mm}$; $dy$ and $dz = 10 \mu\text{m}$; $h = 0.50 \text{ mm}$; $t = 12 \mu\text{m}$; $\theta = 45 \text{ deg}$; $\omega = 4000\text{rpm}$; tool radius $R = 100 \mu\text{m}$; table speed $f = 80 \mu\text{m/s}$. Figure 8 shows schematics of planar tool paths for three polygonal shell structures, and their CCD micrographs: (a) triangular pyramid, (b) pentagonal pyramid and (c) nonagonal pyramid. In their bottom views, tool marks, which are the traces of local deformation along tool paths, are observed on the tool contact surfaces.

As shown in the bird’s-eye views, these pyramids were able to be formed on arbitrary places on a blank without any die or any backing plate. It was found that an aluminum foil had large enough elongation to complete the formation of polygonal shell structures without forming pinholes or fracture, though its elongation was usually very small in tensile test.

3.2 Complex Shell Structures

Several complex shell structures were formed under
In the inside of shell structures, a set of tool marks with small intervals was observed clearly. This proved that the shapes of complex structure were formed step by step through localized deformation process. These experimental results suggested that miniature shell structures with various complex shapes were able to be made through elaborate tool paths.

4. Conclusions
In this study, single point incremental forming was applied to forming miniature shell structures. A desk-top type of CNC SPMIF system was newly composed to establish an innovative micro-fabrication method. Several polygonal shell structures were formed by superposing fundamental geometries hierarchically. Complex shell structures were able to be formed using the SPMIF system. Through the experiments, it was proved that the SPMIF system established in this study can be widely applied to the forming of miniature shell structures in various shapes.

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