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PROTOTYPE DEVELOPMENT OF MICRO-MILLING MACHINE FOR MICRO-PRODUCT

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ABSTRACT

Micro-milling technology is improving to fulfill the micro-product demand in term of shape, accuracy, complexity, etc. Although commercial micro-milling machines are available, however a low-cost micro-milling machine is still required to enhance the micro-milling technology. Hadia Micromill-5X is a NC micro-milling machine prototype. Each axis of the machine are moved by a stepper motor. The motor is driven by sending pulses corresponds to NC point. The linear axes movement accuracy was measured by using a Laser Interferometer. In producing micro-parts, an integrated CAD/CAM software is used to design the micro-part and planning the manufacturing process. The CAD/CAM software produces a CL file which then transformed to NC file through a postprocessor. Then, the NC file executes by Hadia Micromill-5X to perform a micro-milling cutting process. Contoured thin-wall with maximum thickness of 50 µm and 150 µm, micro-impellers with a diameter of 2 mm and 3 mm were successfully machined.

Keywords: micro-milling machine, micro-product, CAD/CAM.

INTRODUCTION

The word of "micro" in the Oxford dictionary is defined as "extremely small" and denoting a factor of one millionth (10^{-6}). Micro-milling is one of micro-manufacturing process to manufacture products and/or features that have at least two dimensions within the sub-millimeter range [1]. Micro-milling is a "scaling down technology" from macro-milling to produce products with dimension around of 100 µm – 10.000 µm [2] by using tools with diameters less than 2 mm [3]. Due to the small dimension of tool and workpiece, micro-milling technology has faced many difficulties which known as the "size-effect". However, up till now micro-milling is still a preferable process to produce a micro-product especially for a complex product.

The micro-milling technology is improving due to the requisite of micro-product complexity, such as micro-impeller, micro-mold, micro-dies and micro-tool to support the other manufacturing process. Although micro-milling machines are available in the market, however, some researchers have developed low-cost micro-milling machines as shown in Figure-1. These machines have proven capable of producing micro-products.

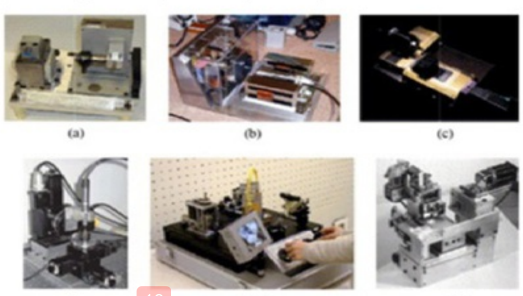


Figure-1. Miniaturized micro-milling machine.

Most of the problems in designing micro-milling machine are the same problems as in designing macro/conventional milling machine. According to Huo [4, 5], there are three main problems in designing a micro-milling machine which are movement accuracy, dynamic stiffness and thermal stability. Therefore, the developed prototype must able to overcome the problems.

Several researchers have successfully developed micro-milling machine. Bang *et al* [6] developed a 5-axis micro-milling using the available component in the market. Tanaka [7], Brecher *et al.* [8] and Kimman *et al.* [9] successfully developed 3-axis micro-milling, while Park *et al.* [10] developed 4-axis ultra-precision machine tool for large surface machining. However, there are not enough information about the development and its problems.

This paper explained the prototype development of a low-cost numerical controlled micro-milling machine. The micro-milling machine, Hadia Micromill-5X, was built using available components and controllers to minimize the error and optimize the machine performance. The machine performance was analyzed by comparing the conformity of micro-product design with the cutting result. The explanation is arranged into three sections, which are construction's development, control system development and results of machining process.

CONSTRUCTION'S DEVELOPMENT

Hadia Micromill-5X was designed as a table/spindle tilting micro-milling NC-machine with three linear axes of XYZ and two rotational axes of AC. The strength, stability and rigidity analysis were performed by FEM software, with 5.5 N of cutting forces [11]. Figure-2 shows that the maximum tension is on Z-axis, in range of 19.78 MPa up to 26.37 MPa. It is represented in light blue, which means the machine design is safe.

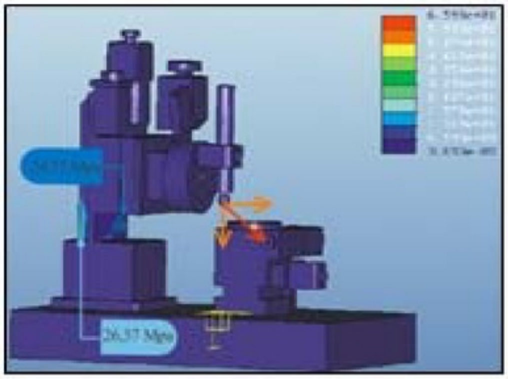


Figure-2. The design of micromilling machine.

Each axis are moved by a controlled stepper motor with 5 μm positioning accuracy for one direction of linear axis and 0.05° for rotational axis. Pulses are sent to initiate the motor movement which is controlled by a PC via a suitable controller for the stepper motor. Figure-3 shows Hadia Micromill-5X, the direction of each axis and the machining process.

Working envelope is defined as the working area in space within the tool able to perform cutting process. Due to the certain range of travel distance for each stepper motor, the working envelope of Hadia Micromill-5X covers an area as shown in Figure-4. The working envelope defines the confines of part shape and dimension.

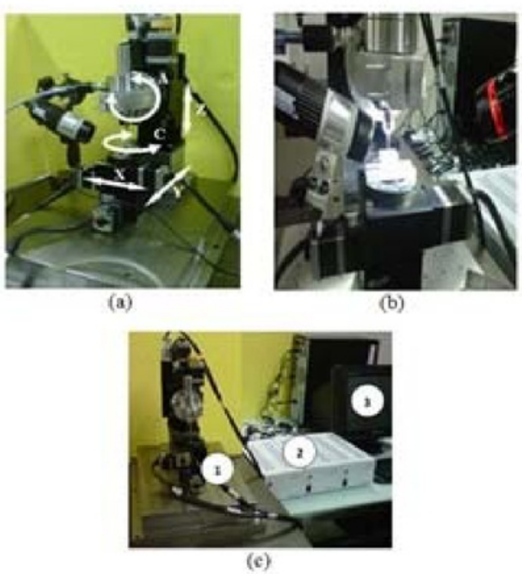


Figure-3. Hadia Micromill-5X (a) Axis direction (b) machining process (c) Machine components

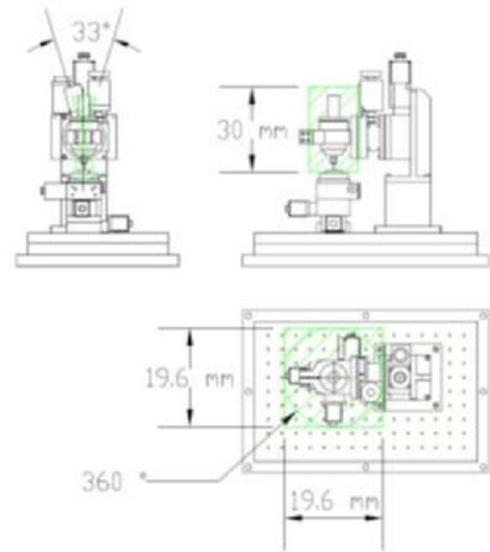


Figure-4. Working envelope of Hadia Micromill 5-X.

To assured movement accuracy, the linear movement was measured by using a Laser Interferometer, Renishaw ML10, which has the capability to measure 1 nm of minimum distance movement. The measurements were performed by two different cycles, uni-directional and bi-directional, as shown in Figure-5. The measurement result is detailed in Table-1.

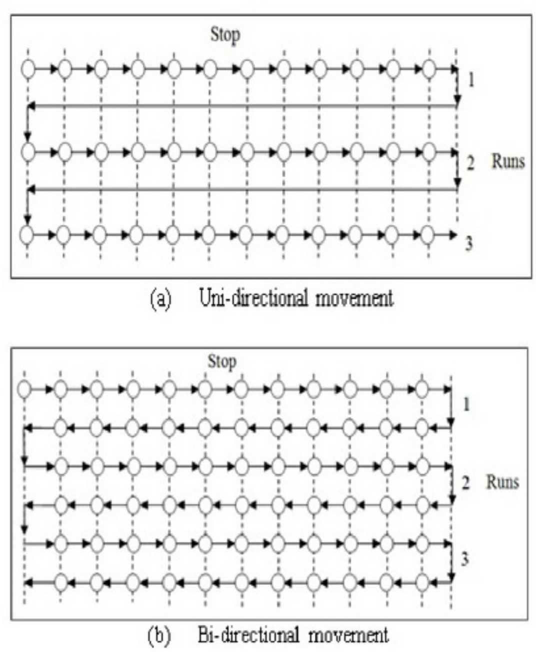


Figure-5. Movement cycle of linear accuracy testing.

An air bearing spindle is used to rotate the spindle up to 150,000 RPM, with operating air pressure between 42~71 psi and volume of airflow ±90 l/min. The air bearing of spindle type was chosen in order to reduce the effect of temperature, which is caused by an electric spindle. However, to reach the stability of spindle rotation, the spindle must be warm up about 25 minutes before performing the cutting process.

CONTROL SYSTEM DEVELOPMENT

The control system of Hadia Micromill-5X consists of a PC and three units of DS102/122. Each DS102/122 controls two motor steppers. Figure-6 shows the Hadia Micromill-5X control system.

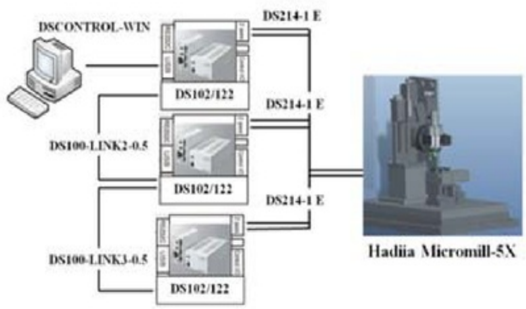


Figure-6. Control system.

The stepper motor is driven by sending pulses correspond to the destination points which saves in the Numerical Controller file (NC file). Points definition in NC file is occupying Machine Coordinate System (MCS) which has the origin point (0,0,0) appropriate to the origin position of each stepper motor. A particular point in NC file is calculated from Cutter Location file (CL file) that produced by the CAM software. The CL file contains series point of tool position to deliver the cutting process occupying the Work piece Coordinate System (WCS). The calculation of CL file to NC file is performed in a postprocessor.

There are two functions of postprocessor which are:

- Kinematic calculation to generate a NC-file from a CL file. It transforms WCS to MCS and includes the machine offset geometry. There are two methods to calculate the machine kinematics, which are forward and inverse kinematics. The inverse kinematic method is used in this research. The equations as a result of inverse kinematic calculation [12] are as follows:

$$A = \varphi_A = \arccos(K_Z) \qquad (-\pi/2 \le \varphi_A \le \pi/2) \qquad (1)$$

$$C = \varphi_C = \arctan(K_x, K_y) \qquad (-\pi \le \varphi_C \le \pi) \qquad (2)$$

$$X = (Q_x + L_x)C\varphi_C - (Q_y - L_y)S\varphi_C + L_x \qquad (3)$$

$$Y = -(Q_x - L_x)S\varphi_C + (Q_y - L_y)C\varphi_C - S\varphi_A.L_t + L_y$$

$$Z = Q_z - C\varphi_A.L_t + L_t + L_z \qquad (5)$$

Whereas X, Y and Z are linear axis, A and C is rotary axis, Q_x Q_y Q_z is the point vector of the cutter tip center, L_x, L_y, L_z are offset vector calculated from the origin of the work piece, K_x K_y K_z are the relative orientation and the position of the cutting tool with respect to the workpiece coordinate system. Meanwhile, L_t is the effective cutter length.

- Format exchange from TXT file format of CL file to PRG file format of NC file. It is necessary to change the format in PRG file format, since the DS102/112 only read PRG file format. The exchange includes command syntax and file extension.

The NC file is executed using Program Drive menu of DSControlWin or using Micro Machining Communication Command Software (MMCC Software). MMCC Software was developed in this research. It was used to perform cutting process with more than 1,000 points. The execution moves the motor stepper simultaneously and continuously. It results in the movement of the machine tools table and tool, which perform a machining process.

MACHINING THE PRODUCTS

A micro-milling process begins from product design until machining process. Figure-7 shows the flowchart of a micro-milling process using Hadia Micromill-5X. It is necessary to consider the dimension and shape of micro-product when designing the product. The micro-part must be applicable to the machine working envelope and the tool type and dimension.

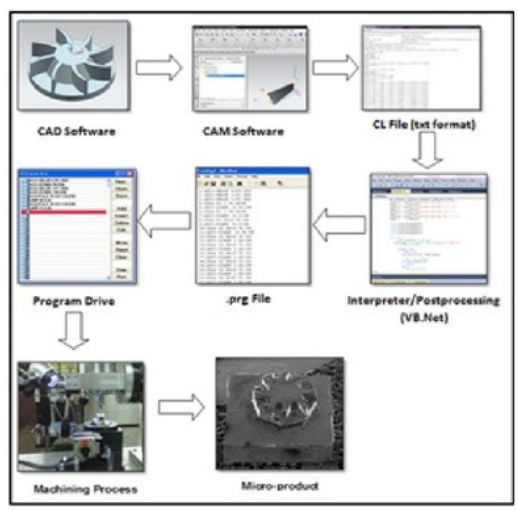
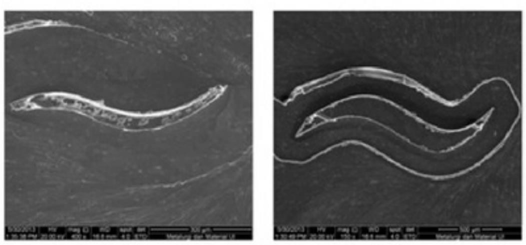


Figure-7. Sequence of micro-milling process.

The design process was performed in an integrated CAD/CAM software. It was selected for an easier file exchange between parts design (CAD) and manufacturing design (CAM). 3D-design of micro-product was made in CAD software which becomes a reference to plan the cutting process (or manufacturing process) by using CAM software. The result of manufacturing CAM design software was a CL file. Once a CL file generated, the postprocessor transforms it to a NC file in PRG format. The NC file executes through a Program Drive menu or MMCC Software to perform a machining process.

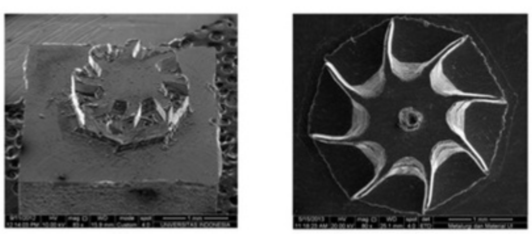
Hadia Micromill-5X was proved capable of producing thin-wall product with aspect ratio of 25, which are 12 μm in thickness and 300 μm in height. However, a perfect thin wall with higher aspect ratio is difficult to achieve due to component vibration, thermal rise, tool wear, tool rigidity and thin-wall deflection. Figure-8 (a) shows a contoured thin-wall with 50 μm thickness and (b) with 150 μm thickness. A solid carbide nACro coated flat-end mill tool with a diameter of 200 μm was used to cut AA-1100. The cutting parameter of the feed-rate was 0.1 mm/s, spindle speed was 80,000 RPM and depth per-cut was 5 μm. By comparing the design dimension with the machined part, it was found that there are ± 0.15 μm deviations between design parts and machined parts.

Figure-9 shows the micro-impeller with a diameter of 2 mm and 3 mm. The micro-impeller material was AA-1100 which cut with 0.2 mm diameter of End-mill Solid Carbide TiAIN coated. The machining process was performed with feed-rate of 0.5 mm/s, spindle-speed of 70,000 RPM and depth per-cut of 4 μm.



(a) (b)

Figure-8. Contoured thin-wall with thickness of (a) 50 μm (b) 150 μm.



(a) (b)

Figure-9. Micro-impeller with diameter of (a) 2 mm (b) 3 mm.

CONCLUSIONS

In this research, a low-cost micro-milling machine Hadia Micromill-5X have been developed successfully. It is adequate of producing complex micro-product. Micro-milling process to produce micro-parts are throughout following steps, part design by using CAD software, tool-path planning by using CAM software, transforms a CL file to a NC file in a PRG file by using a postprocessor, and then the NC file execution by using a program drive menu or MMCC Software.

The experiment results show that Hadia Micromill-5X capable of producing contoured thin-wall with maximum thickness of 50 μm and 150 μm, ± 0.15 μm deviations. Hadia Micromill-5x also proved to have the capability of producing micro-impellers with a diameter of 2 mm and 3 mm.

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