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A preliminary study of micro thin wall fabrication on PMMA using an in-house developed micromilling machine

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Abstract— **Micromilling has been increasingly employed for fabrication of micro geometrical features in many miniature parts, but the machining of micro thin walls is considered as difficult due to low material rigidity, and easy deformation by cutting force. In this study, a low-cost and reconfigurable 3-axis micromilling machine was developed by integrating a XYZ precision motion stage with a high-speed spindle. The development and configuration of the micromilling platform is introduced, along with a calibration of the motion accuracy and a vision-assisted tool tip positioning approach. Preliminary experimental study was conducted to fabricate micro thin walls on PMMA workpiece under different conditions. While the thin walls with a target thickness of 300 µm were successfully machined, it was found that there were many issues encountered in the machining of the 30 µm thin walls. The defects were analyzed to identify the root-causes and future research directions.**

Keywords- micromilling; micro thin wall; PMMA; positioning; machine

I. INTRODUCTION *(HEADING 1)*

The demand for the manufacture of miniaturized devices or components with high aspect ratio micro features has been increasing globally over the last decades, with broad applications in the medical, aerospace, automotive, and electronic / communications industries. The miniaturization of products grows in complexity and shrinks in microsize, and the work materials span a wide range of materials including polymers, metals, and composites. The lithographic processes cannot be used in the fabrication of these micro-featured devices on materials rather than silicon compounds or other semiconductor materials. Instead, mechanical micromachining, especially micromilling, has found extensive applications across many industries due to its flexibility, capability, and efficiency in many materials [1], [2].

Micromilling is considered as one of the most efficient manufacturing methods for micro feature fabrication, such as for the precision fabrication of micro-featured devices with deep channels or thin walls as required for microfluidic devices [3]. However, there are many issues in tool-based machining that can affect the micro structure shape and dimensional accuracy of machined work pieces, such as burr formation, cutting tool geometry, chip formation, tool-workpiece vibration, tool-path strategy, material properties, occurrence of tool problems like tool wear or tool breakage, etc. [4]. For the micromilling of deep channels or thin walls, especially on some hard or brittle materials, the challenging is even high.

Extending conventional mechanical machining into the micro-scale (typically within 1000 µm in the dimension of part geometrical features) has not been straightforward due to the significant size effects, which present limitations to the down-scaling process. In micromilling, the radius of curvature of the cutting edge (~1-2 µm) is around the same order of the chip sizes (~0.5-5 µm). The workpiece does not see a sharp cutting edge. This results in the cutting edge rubbing or ploughing the workpiece rather than cutting, causing a significant increase of cutting force as the frictional forces are increased. This can lead to the onset of vibrations causing the surface roughness of machined products to increase [5]. Ploughing also causes plastic side flow and burr formation resulting in unevenness on the machined surface. Formation of the chip is influenced by the minimum chip thickness to successfully remove the work-piece layer as a single chip. When attempting to cut less than the minimum chip thickness, the work-piece material preferentially compresses and springs back after the passage of the cutting edge. If the cutting edge attempts to take exactly the minimum chip thickness, a chip less than the minimum chip thickness is formed as part of the surface is compressed during cutting and this springs back up after the cutting edge has passed. A fully formed chip is produced only when a chip larger than the minimum chip thickness is removed in a single cut [6].

Micromilling requires both high speed and high accuracy in order to economically produce parts with features on the scale of micron. High positioning precision is required in micro milling since even small vibrations in the tool-workpiece are problematic. On the other hand, micro mills are smaller and more flexible than traditional large-scale machines. Therefore, vibration of the machine structure is a significant problem. In micromilling operations, the low stability of microtools and their manufacturing can lead to poor surface qualities and undesirable surface location errors. Due to the decreasing stiffness of the tool with decreasing diameter, small end mills have a low resistance to forces and torques. This leads to an increased tool deflection and, therefore, to a reduced precision of the machined contour [7].

Micro thin wall is a typical geometrical feature in some miniature parts such as MEMS devices, micro molds, microfluidic systems. It is considered as a difficult-to-machine geometry due to low rigidity, low and uneven strength, easy deformation by force and heat, and bad machinability, etc. [8]. The cutting forces and tool-workpiece vibration have significant influence on machining deformations and thus the geometrical integrity of the resultant thin walls. There were controversial results published regarding the influence of the moving path or the milling strategies. Llanos et al. [9] reported that by employing a down-milling cutting direction, high spindle speeds and low feed rate values, better surface roughness can be obtained on thin walls made by brass and aluminium. Liu et al. demonstrated that down milling of a copper thin wall structure resulted in better quality and smaller deformation and burr sizes than up-milling. However, Annoni et al. reported that using up-milling strategy instead of down-milling can achieve low absolute cutting force value in high aspect ratio wall micromilling [10]. Han et al. showed that the top-burrs formed on the down-milling side are always more numerous than those on another side [11].

PMMA, or Poly (methyl methacrylate), a transparent thermoplastic, is widely used as a substitute for inorganic glass, due to its high impact strength, lightweight, scratch resistance, and favorable processing conditions [12]. It has found applications in biomedical, optical, solar, sensors, nanotechnology, etc. PMMA has served as molds for enabling fabrication of final parts with micro-scale features [13]. There is a need for rapid, economic, accurate, and reliable fabrication of polymer parts with miniatured features. A major challenge in the rapid and mass scale fabrication of PMMA-based biomedical devices such as microfluidic devices is the large number of microfeatures with high aspect ratio to be reproduced on the same substrate with tight tolerances [14]. Mechanical micromilling is a fabrication method for such purpose due to its capacity of creating complex 3D micro-scale features on many engineering materials [13]. It has been reported that polymer machining is actually a challenging operation to achieve a good surface finish, since it can be affected by viscoelastic, thermal, and mechanical properties of polymers.

Meanwhile, although there are different types of ultraprecision micromilling machines commercially available on the market for the machining of high precision micro-sized features, these machines are too expensive and are inaccessible to many researchers with limited budget [15]. Some of the complex functionalities on the high-end machines might be not needed for some researchers. Therefore design and development of low-cost and reconfigurable micromilling machines with the required specific capabilities would be an inspiring options for researchers even if there are many challenges in the course, and some researchers have presented their development work such as [15]–[17].

This paper presents a preliminary study of micro thin wall fabrication on PMMA using an in-house developed micromilling machine. The main feature of this machine is low-cost and reconfigurable. The development and configuration of the micromilling platform is introduced, along with a calibration of the motion accuracy and a vision-assisted tool tip positioning approach. Preliminary micromilling tests are conducted to machine micro thin walls on PMMA workpiece panels under different conditions with reasonably high aspect ratios. The resultant thin walls are examined using microscope and the results are presented and discussed.

II. MICROMILLING MACHINE

A. System integration

The micromilling machine was developed by using an ALIO XYZ precision linear motion stage, as shown in Fig. 1(a). The XY-axis feed drive, Model AI-LM-500-XY integrated linear stage, was used as work table to mount the workpiece and carry out feeding movement in the horizontal plane. It has a travel range of 50 mm × 50 mm. The motion was driven by DC servo motors, and the feedback was from Linear Optical Encoders with 1Vp-p analog output, encoder resolution peak to peak 5nm with 4096x interpolation. The Z-axis linear stage has also a travel range of 50 mm, DC linear motor, Linear Optical Encoders with 1Vp-p analog output, encoder resolution peak to peak 5nm with 4096x interpolation. The Z-axis stage was to mount a high-speed spindle as the cutting tool holder and move in the Z-direction. The Z stage can handle 5.5 kg load. It uses pressurized air for a counterbalance. Both the XY-stage and the Z-stage are made of anodized aluminium stage structure. The XY integrated linear stage was mounted on a granite base, with a granite vertical post on the base to hold the Z Stage.

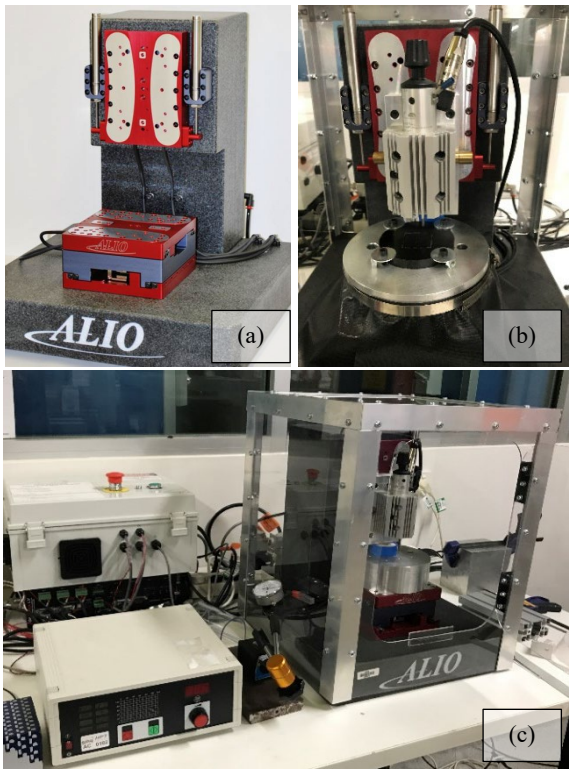

Figure 1. Development of the micromilling machine. (a) XYZ precision linear motion stage; (b) with the high-speed spindle system mounted on the Z-stage; (c) Integrated micromilling machine

A Delta Tau Geo Brick LV controller was employed to implement precision motion control of the XYZ stage. This was a 4-Channel Low Voltage PMAC Controller with 4-Axis Sin/Cos Interpolation, and 4-Axis PWM Amplifiers 5A Continuous/10A Peak. It was believed that the modular Geo Brick LV provides more flexibility and a better performance than the conventional CNC system to meet the highest requirements of 3 axis micro/nano milling machine. The controller was connected to a computer, and a software package called PMAC Executive Pro2 Suite was used to control the motion of the XYZ stage.

The high-speed spindle was made by Alfred Jaeger Gmbh, with a weight of around 0.6 kg. The rated rotational speed is in excess of 100,000 rpm and the rated power is 0.30 kW (S1-100%). This is a maintenance free spindle, with 2 pieces of ceramic hybrid ball bearings installed. It is suitable for high-speed milling, grinding, and drilling. The clamping range is up to 3.5 mm. This spindle is uncooled, so the heat must be dissipated via the spindle holder of a heat sinker. A spindle mounting plate was designed and fabricated to mount the spindle to the Z-stage through a few mounting holes. A photo of the spindle system fixed on the Z-stage is shown in Fig. 1(b). A BMR Frequency Converter Mod. SFU0102AC was used to drive the spindle. It was connected to the computer to control the spindle operation and speed manually or remotely.

A power supply / controller system was also developed in-house by integrating the two main power supplies and installing an emergency stop button and a set of on/off switch. A fixture was designed and installed on the XY stage to mount a workpiece. In addition, a chamber for the machine stage was also made to provide a safe working environment. The integrated micromilling machine is shown in Fig. 1(c).

B. Motion calibration

The positioning accuracy and repeatability of the motion stage along the 3 directions were calibrated by using a Keyence CCD laser displacement sensor. The model of the laser sensor was KEYENCE LK-G87, and the sensor controller was LK-GD500. The repeatability of this sensor is 0.2 μm, the measuring range is ±15 mm, and reference distance 80 mm.

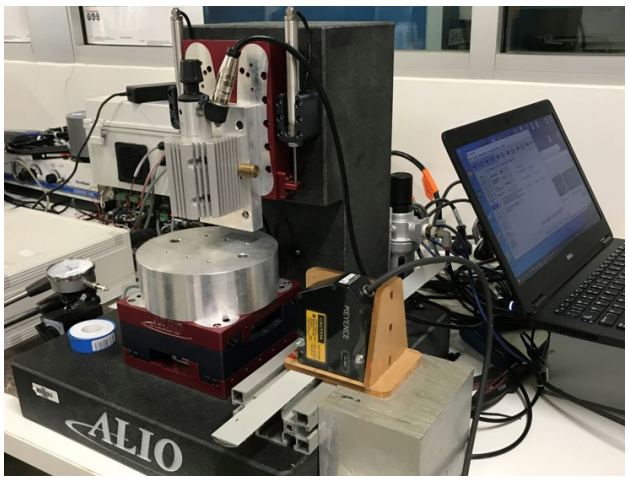

Figure 2. Motion calibration measurement setup

For the motion calibration, the machine was programmed to run a 2 mm step motion repetitively on each axis, and the laser sensor was placed close to the stage within the reference range to measure the displacement of the stage at each axis respectively. The controller was connected to the computer via a USB interface. The controller software, LK-Navigator, was used to acquire and record the measurement results. The measurement setup is shown in Fig. 2, and a typical measured displacement graph is shown in Fig. 3.

The measurement results showed that over a 2 mm motion, the positioning error in the x, y, and z directions was -0.8 μm, 0.7 μm, and -2.3 μm respectively. It can be seen that among the 3 directions, Z-axis is the most vulnerable one in the accuracy, perhaps related to the load of gravity it has to take. As to the repeatability, the measured values were all in the sub-micrometer range for all three directions.

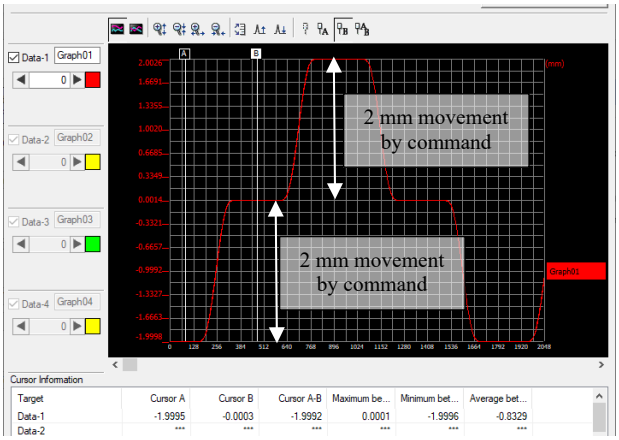

Figure 3. A typical measured displacement graph

C. Vision-assisted tool tip positioning

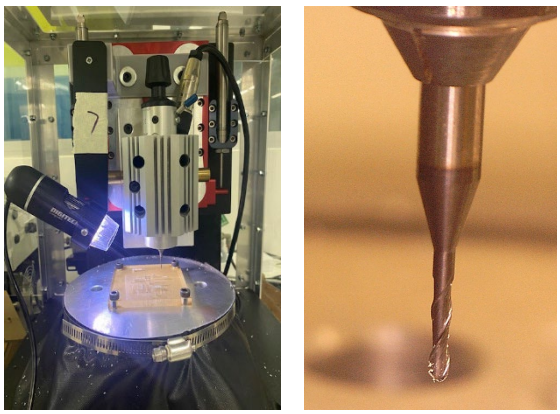

Figure 4. Setup of the vision-assisted tool tip positioning

For accurate motion control of a linear motor stage, the motor must commutate with the encoder position. The ALIO XYZ stage performs the critical steps for setting the phasing position as part of the phasing and homing procedures. For motion control in the X- and Y- axes, knowing the home position is usually enough in the setup of a micromilling operation. However, the Z-axis is an exception. Due to the size variations of the fixture, workpiece, and cutting tools in the X-direction, it is more

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important to have a knowledge of the actual gap between the tool tip and the top surface on the workpiece in the Z-direction. In this study, a vision-assisted tool tip positioning approach is developed. A DigiTech 5MP USB digital microscope camera was mounted on the Z-stage using a 3D printed arm to detect if the tool tip is close enough to the workpiece surface, as shown in Fig. 4. Such a simple setup facilitated the tool tip positioning in micromilling dramatically and avoided the possible clash between cutter and work.

III. MICRO THIN WALL MACHINING AND RESULTS

Preliminary cutting tests were conducted on the developed micromilling machine to machine micro thin walls on PMMA panels. The PMMA workpiece was prepared to small rectangular pieces with a dimension of 75 mm × 45 mm × 6.2 mm and was mounted on the XY table. The micromilling cutter used was SUTTON E6030100 2-flute VHM carbide endmill, with Helix Angle R30 and rake angle 12°. The diameter on the cutting side was 1 mm.

A. Thin walls with a target thickness of 300 μm

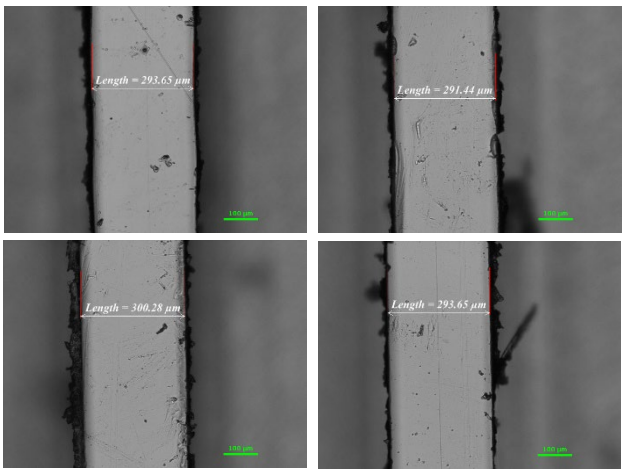

Figure 5. Microscopic photos of the machined thin walls top surface with a target thickness of 300 μm

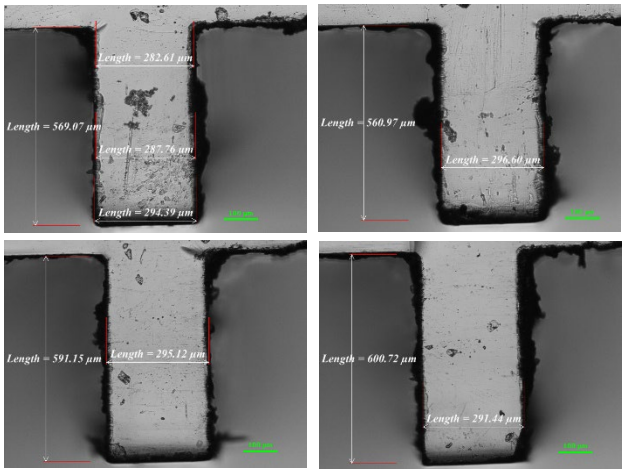

Figure 6. Microscopic photos of the machined thin walls side surface with a target thickness of 300 μm

For the first set of micro thin wall machining, the micro wall thickness was set as 300 μm. Up milling strategy was used. The spindle speed used included 25,000 rpm, 50,000 rpm, and 75,000 rpm. The feed per tooth was 0.015 mm/tooth. A Nikon ECLIPSE E200 Microscope was used to examine the machined thin walls. The microscopic examination of the machined parts showed that the micro thin walls with a thickness close to 300 μm have been successfully fabricated, as in Fig. 5. With a wall height close to 600 μm achieved, the aspect ratio for the fabricated walls was around 2. It is noted that there some variation in the wall height, which might be caused by some unevenness on the workpiece panel, or some errors in the vertical positioning. The influence of spindle speed on the fabrication was not significant. Some burrs on the edges of the thin walls can be observed. Overall, the quality and integrity of the micro thin walls are good and acceptable.

B. Thin walls with a target thickness of 30 μm

The next set of tests was designed to make much smaller thickness of the thin walls, which was targeted at 30 μm. Again, up milling strategy was used. The same spindle speeds of 25,000 rpm, 50,000 rpm, and 75,000 rpm, and the same feed per tooth of 0.015 mm/tooth, were employed. The wall height was set as 150 μm. Each machining condition was repeated for 5 times, and the fabricated walls were checked using microscope. In comparison with the 300 μm thin walls, the quality of this set of 30 μm thin walls was overall poor. The noticed issues are summarized as follows.

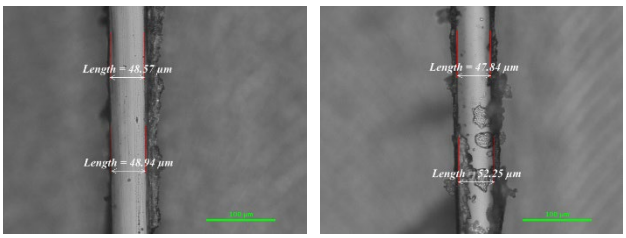

Figure 7. Microscopic photos of the machined thin walls top surface with a target thickness of 30 μm

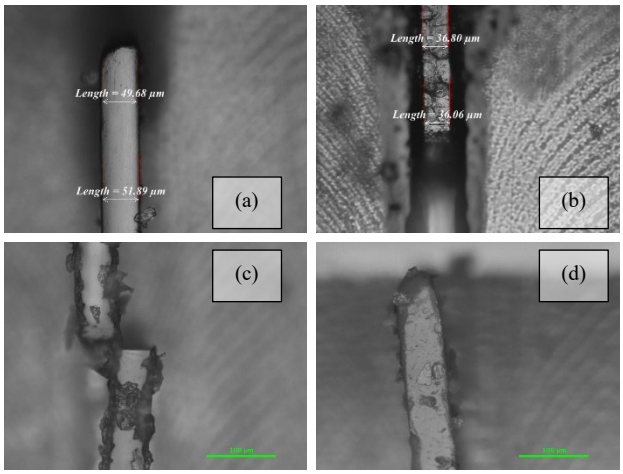

Figure 8. Microscopic photos of the machined thin walls top surface with a target thickness of 30 μm – defects shown

Incorrect thickness on the top of the thin walls. Two representative photos showing a segment of the fabricated walls are presented in Fig. 7. It can be seen that the thickness of the thin walls varied from 48 μm to 52 μm,

which was about 70% greater than the expected thickness of 30 µm. It is believed that the inaccuracy was caused mainly by the deflection of the micro thin wall during machining, which was evidenced when checking the broken wall segments.

Broken or sheared-off thin wall segment. This defect is especially severe close to the starting position of the wall, as shown in Fig. 8. In Fig. 8(a), a segment of the thin wall top surface is shown, and the thickness was measured as around 50 µm. When the microscope was focused close to the bottom of the thin wall, the surface of the broken section of the wall was clearly shown, as in Fig. 8(b). The thickness of the broken wall was about 36 µm. The cross-section of the thin wall was in fact a trapezoid shape. This can be further supported by the microscopic photos taken from the side view of the thin walls, as shown in Fig. 9. The Fig. 9(a) and (b) was taken from the same wall which was broken, with a focus on the workpiece side surface and on the wall broken face, respectively. In Fig. 9(c) and (d), two walls which were sheared off from the base workpiece were shown. But they were not totally broken. The sheared-off segments were with a limited length starting from the side surface of the work.

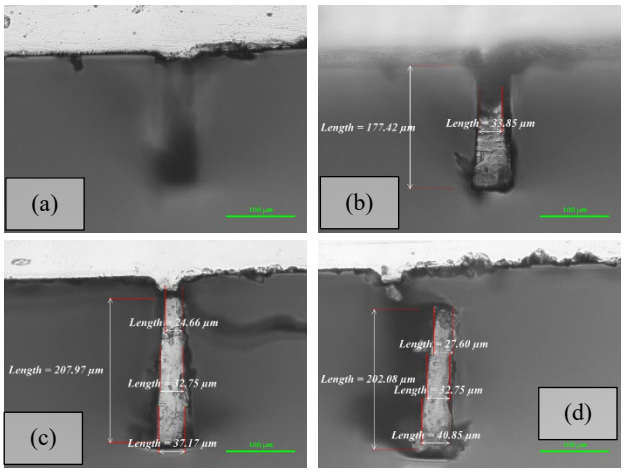

Figure 9. Microscopic photos of the machined thin walls side surface with a target thickness of 30 µm – broken or sheared off

Burrs. It can be observed that burrs formed along the wall side were quite common. Sometimes very long burrs can be seen, as in Figs. 7 and 8. Plastics materials like PMMA are prone to burr formation in machining [18]. It was noted that the burrs formed on the wall side and sometimes on the wall top. The formation of burrs was possibly caused by rubbing and ploughing in the undeformed region during cutting. Burrs can be a big issue affecting the functionality of a mold for micro feature fabrication.

C. Discussions

In the preliminary experimental study of thin wall machining, although similar cutting conditions were used, the micro thin walls with a target thickness of 300 µm were mostly with acceptable quality, but in contrary, there were many issues encountered in the machining of the 30 µm thin wall as shown in the above section. The success of 300 µm thin wall demonstrated the good positioning accuracy of the micromilling machine. The defects for the 30 µm thin wall, including the poor resultant geometric dimensions and the broken /sheared off wall segments, can be attributed to the milling force and perhaps vibration between cutting tool and the workpiece (thin wall), which caused the deflection of the thin wall due to limited wall stiffness when the thickness was so small, and also the shearing-off due to limited strength. Further research will be conducted to improve the quality of the 30 µm thin wall machining, including optimization of machining conditions and strategies to reduce the lateral cutting force, and to design and deploy a supporting fixture which can be applied to the other side of the thin wall to minimize the deflection. Burr reduction also needs to be investigated. Control burr formation can be through optimization of the cutting conditions such as to use a larger feed and a higher cutting speed. It has been suggested that uncoated cutting tools can help to reduce the burr formation [18]. Other strategies include to use a taper tool or to apply targeted cooling to reduce plastic sideflow and burr formation in the micromilling operation.

IV. Conclusions

Micro thin wall is a typical geometrical feature in some miniature parts but is difficult to machine due to low rigidity, and easy deformation by cutting force. In this study, a low-cost and reconfigurable 3-axis micromilling machine was developed in-house by integrating a XYZ precision motion stage with a high-speed spindle. Calibration of the motion stage by using a laser displacement sensor showed that the positioning accuracy and repeatability of the X- and Y- axis were in sub-micrometer level, while the error in Z direction was up to 2.3 µm. A vision-assisted tool tip positioning approach was developed by employing a small digital microscope camera. Preliminary experimental study was conducted to fabricate micro thin walls on PMMA workpiece under different conditions by using the developed micromilling machine. The resultant thin walls were examined using microscope. It was shown that thin walls with a target thickness of 300 µm were successfully machined, but there were many issues encountered in the machining of the 30 µm thin wall, including the incorrect thickness on the top surface and trapezoidal shape of the obtained thin walls, and broken or sheared-off thin wall segments. The defects could be attributed to the thin wall deflection in machining due to cutting force applied. Further research will be conducted for optimization of machining conditions and strategies to reduce the lateral cutting force and to reduce the thin wall deflection.

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