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A study on initial contact detection for precision micro-mold and surface generation of vertical side walls in micromachining

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ABSTRACT

The surface quality and the dimensional accuracy are important criteria for micro-mold production, specially for micro-fluidic devices. Important cutting parameters that affect the quality of vertical side walls created by the peripheral cutting edge in micro-end-milling operations were identified. Surface roughness and form error were used to define the quality of side walls on stainless steel and aluminum workpieces. An acoustic emission sensor was used to detect initial contact between a tool and a workpiece for higher dimensional accuracy where the referencing is a critical element for precision micromachining feature creation.

1. Introduction

The micro-fluidic device, one of high accuracy miniaturized components in demand, is emerging as a representative application for mass production of such small parts (typically ~100 μm). Various manufacturing technologies are competing to achieve the required level of precision on a wide range of materials. Unlike the conventional semiconductor technologies, the mechanical micromachining has fewer limitations on materials and offers 3-D flexibility and environmental benefits [1–3].

Dimensional accuracy and surface quality are two critical aspects of manufacturing such devices. Dimensional accuracy is governed by almost the same parameters as in conventional machining. However, due to the feature size used, referencing the tool tip position to the workpiece is a big challenge to deliver the required dimensional accuracy. Surface quality is another important factor because it affects the functional characteristics of the parts. The issue is that the surface quality generated by micromachining has to meet the requirements without further processing, since surface-finish processes like grinding or lapping are difficult to apply for features on the microscale [1,4,5].

In this study, the effects of process parameters on the form error of vertical side walls and the surface roughness created in step-milling were investigated. A series of cutting tests were carried out with a variation of parameters such as depth of cut, width of cut, and feed per tooth. An acoustic emission (AE) sensor was the method of choice to detect the initial contact between a tool and a workpiece to find the coordinate system in the machine tool. While a microscope has been usually used for this purpose, it has a long setup time and induces errors during the setup. Currently several other methods are being developed; however, some are expensive or impractical in production, and others fail to meet required resolutions. The AE sensor fits well for this application due to its good sensitivity and ease of setup [6,7]. This study also investigated the applicability of the AE sensor and developed an automated end point detection system for the machine tool.

2. Surface quality and form error of vertical side walls

2.1. Experimental setup

The experiments were performed on a CNC high-precision machine center with a maximum spindle speed of 24,000 rpm. Two-fluted micro-end-mills with 254 μm diameter were used for all the tests. The tool material was WC-Co-Carbide with 8% cobalt. A cantilever tool length (distance from the collet to the tip of the tool) of 13 mm was set for all the experiments. The edge radii of all the inspected tools (new) varied in the range of approximately 0.5–1 μm.

Austenitic stainless steel 304 in annealed condition and aluminum 6061-T6511 were used for the experiments because they are commonly used for micro-mold manufacturing. The grain size of both materials varied between 5 and 25 μm.

The parameters depth of cut (DOC), width of cut (WOC), and feed rate were varied in the experiments to analyze the effects of different cutting parameters on the surface roughness and form error of vertical side walls, Table 1. Additionally, the different cutting parameter combinations were applied for up and down-milling operations, while the spindle speed was constant at 24,000 rpm to reach the maximum cutting velocity. All the milling tests were performed without using a cutting fluid. A constant width of cut of 64 μm for stainless steel and 127 μm for aluminum were used because preliminary tests showed that the width of cut had a negligible effect on the surface roughness.

For both materials, one cutting tool was used for a cutting length of 12 mm. Preliminary tests showed that the surface roughness varied in the small range of 10 nm for a cutting length of

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Table 1
Cutting parameters

	Stainless steel 304	Aluminum 6061
v_c [a] (m/min)	19	
WOC (μm)	64	127
WOC/D (1)	0.25	0.5
DOC (μm)	25/64/127/191/254	
DOC/D (1)	0.1/0.25/0.5/0.75/1	
f_t (μM)	0.25/0.5/1/1.5/2/3	0.25/0.5/1/2/3/5
Milling method	Up/Down	

[a] n = 24,000 rpm, D = 254 μm.

13 mm before it started to increase with increasing cutting length. Therefore, the surface roughness was not influenced by tool wear.

2.2. Effects of the cutting parameters on surface roughness

Fig. 1 shows the effects of feed rates and depths of cut on the surface roughness for down-milling. For stainless steel, the surface roughness (R_a) values vary in the range of 190–300 nm. For the two smallest depths of cut (DOC = 0.1 D, 0.25 D), R_a generally increases with feed rate and was the lowest at an optimum feed (f_t = 0.5 μm). If the feed is chosen too small (f_t = 0.25 μm), the surface roughness gets worse because the effective rake angle of the cutting tool becomes negative due to a small ratio of feed per tooth to cutting edge radius ($f_t/r_{ma} < 1$), which causes plowing with elastic recovery instead of shearing, resulting in a rougher surface [8]. The effect of feed per tooth on the surface roughness is less pronounced for larger depths of cut.

The modulus of elasticity of aluminum is roughly one-third that of stainless steel, and thus plowing is more dominant at lower engagement of the cutting edge [5]. Therefore, the minimum surface roughness appears for all the depths of cut and plowing effect is significant at lower feeds.

The up-milling exhibited much worse surface quality than the down-milling, Fig. 2. To understand this effect, it is necessary to consider the kinematics for up- and down-milling. The final surface is produced at the beginning of the chip formation process in up-milling ($T = t - \Delta t$), Fig. 3. Due to the radius of the cutting edge and the negative effective rake angle in the period of $T = t - \Delta t$ to $T = t$, the minimum chip thickness is not met and the cutting edge only elastically deforms the material by plowing or rubbing, while the shearing of a chip begins later than $T = t$. After that, the tooth continues to cut until the chip finally breaks off ($T = t + \Delta t$). In contrast to up-milling, the chip formation in down-milling starts with the maximum chip thickness, far away from the final surface. When the final surface is generated, the chip thickness is also at its minimum but the chip simply breaks off the surface. Hence, the surface finish is much better in down-milling.

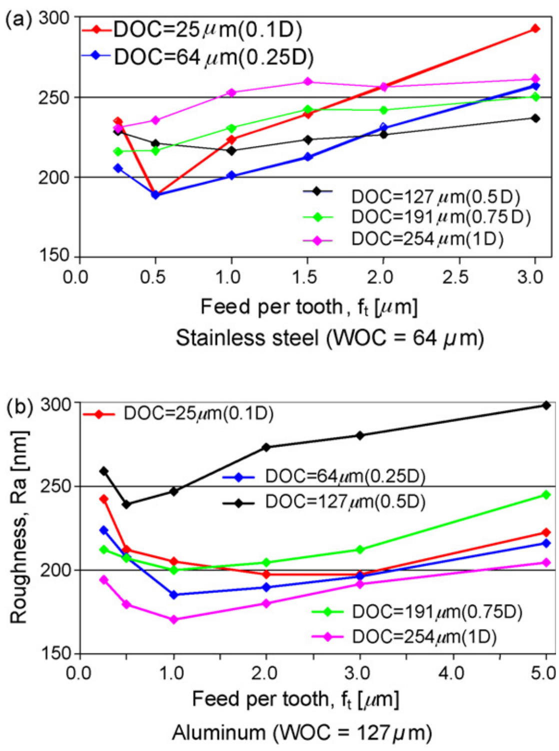

Fig. 1. Surface roughness in down-milling.

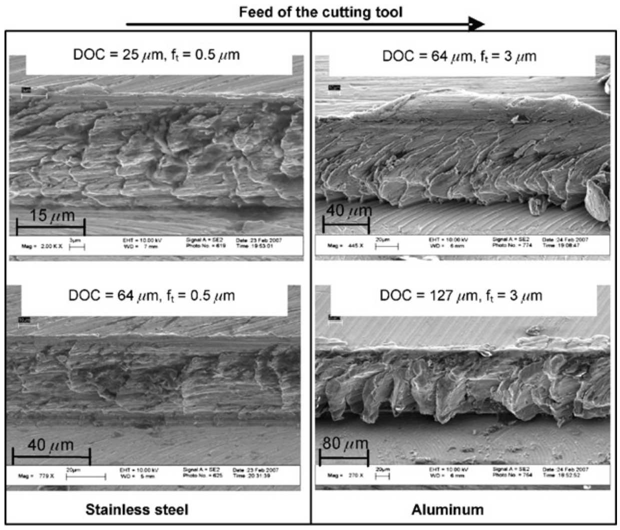

Fig. 2. SEM images of the up-milled surface.

In aluminum, huge protrusions appeared on some up-milled surfaces, Fig. 2. The shape of the protrusions is always more or less parallel to the locus of the back cutting edge, which possibly explains that the protrusions could be deposited material such as chips that have been reattached on the surface by the trailing edge and the flank of the micro-end-mills.

Some tools were broken during up-milling and this indicates that the chips might have clogged the flutes before they were either deposited on the surface of the vertical wall in the next engagement of the tooth, or led to breakage of the cutting tool. Effects of built-up edges or inhomogeneity of the workpiece material cannot be excluded as well.

2.3. Effects of the cutting parameters on form error

The profiles of the generated micro-steps in the y–z plane (perpendicular to the feed and parallel to the tool axis) showed big form errors, Fig. 4. The profiles of the vertical side walls exhibited complex shapes depending on the cutting conditions.

In the following analysis, form error size is described as the maximum height difference Δy in the profile of a vertical side wall in the y-direction along the depth of cut (z-direction), Fig. 5. Furthermore, form errors are characterized by means of the

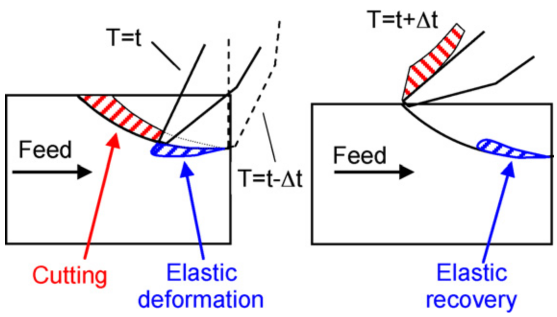

Fig. 3. Schematic illustration of the effect of elastic deformation and recovery in up-milling.

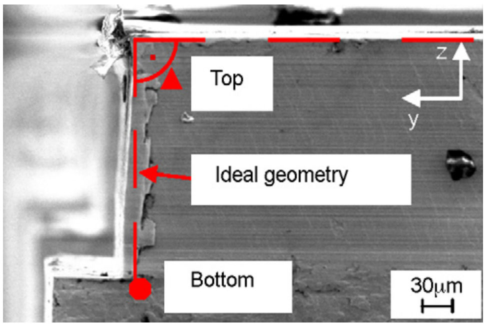

Fig. 4. Form error of a micro-step in the y–z plane (down-milling stainless steel, DOC = 254 μm, WOC = 64 μm, f_t = 3 μm).

gradient angle α of the profile in reference to an ideally vertical side wall.

Fig. 5 shows the vertical surface profile of stainless steel and aluminum. The shape of the surface profiles did not vary with feed rates but with depth of cut. In stainless steel, the form error increases approximately linearly from the top of the vertical wall to the bottom and the profiles show a constant positive gradient except 254 μm depth of cut, where form error increases linearly from the top of the vertical wall to the bottom, but the profile has a kink at approximately 70% of the depth of cut. From this kink, the form error increases with reduced gradient. The form error (Δy) varies between 3 and 11 μm in down-milling and increases significantly with the depth of cut. Furthermore, the increase of form error size with feed rate is more pronounced for larger depths of cut.

Aluminum showed the same trend as stainless steel in terms of form error. The kink appeared at a depth of cut of 127 and 191 μm but a negative gradient showed from the kink to the bottom which should be avoided for the mold features. The form error (Δy) varies between 1.8 and 4.2 μm in down-milling.

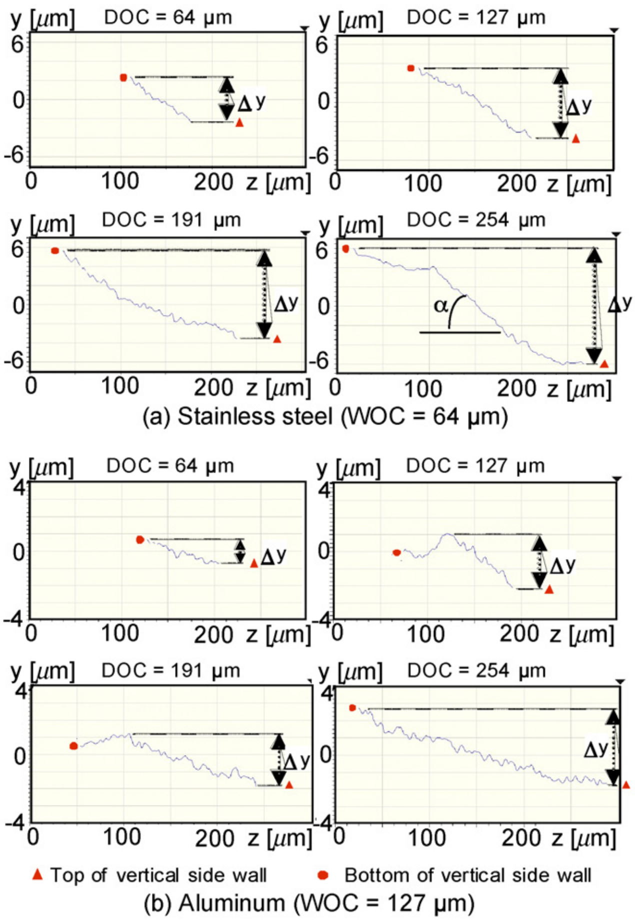

Fig. 5. Vertical wall profiles for down-milling.

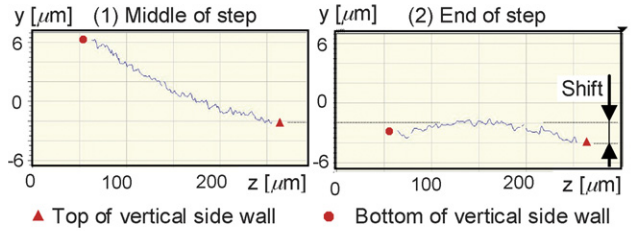

Fig. 6. Comparison of side wall profiles (y–z plane) at different x-positions within one vertical wall (down-milling stainless steel, DOC = 191 μm, WOC = 64 μm).

Since the stiffness of micro-end-mills decreases with smaller tool diameters, the deflection of the cutting tool as a result of bending is usually the most important cause of form error, especially with milling steps.

Fig. 6 shows two surface profiles of stainless steel (down-milling); one from the middle of the step and the other from the end of the step (in feed direction). The form error almost disappeared at the end of the step. The same trend was observed for all the different micro-steps milled under various cutting conditions and indicates that the form error of side walls was caused by deflection of the cutting tool.

When cutting in the middle of the step, the y-component of the cutting and feed force tend to separate tool and workpiece. Thus, the end-mill cuts in a bent state and the actual tool path are slightly shifted from the nominal one. When the surface at the end of the wall is generated, the cutting and feed force decrease in the direction of the step, where there is less material left resulting in a smaller tool engagement length. Hence, the tool springs back to its original position and cuts the last revolutions on its nominal path.

3. Initial contact detection

During the fabrication of the mold, various tool diameters have to be used. The integrity of the X and Y origin may not be affected by a tool change because the machine generally stores the coordinates and the center of all applied tools can be reasonably assumed to be the same with a precision tooling set. But whenever a tool is changed, the integrity in Z direction is lost and resetting relative z-coordinates takes tedious efforts and time. Commercial touch probes currently available are not capable of handling less than 1 μm resolution. Therefore, it is critical to find a reliable and easy method to find reference points at the required accuracy and furthermore automate the process for micromachining application.

In order to develop a solution to these problems, the following requirements should be considered:

- *Easy to setup*: A tool should stay during detection. Sensor mounting and other setup procedure should not hinder machining setup.
- *High sensitivity*: The system should detect contact without damaging the workpiece more than specified accuracy.
- *Automation*: The whole procedure should be automated to reduce setup time and prevent any other possible error sources.

The purpose of this study is to demonstrate the potential of the acoustic emission sensor for the first two requirements. An automatic detection system using the AE sensor was built and preliminary tests showed promising results.

3.1. Experimental setup

A block of the workpiece material is directly mounted on the AE sensor (PZT-type). Three sizes (127, 254, and 508 μm diameter) of micro-end-mills were used. The tools were rotated at 8000, 10,000, and 15,000 rpm for stainless steel and 15,000, 20,000, and 24,000 rpm for aluminum. Approaching feed in z-direction was

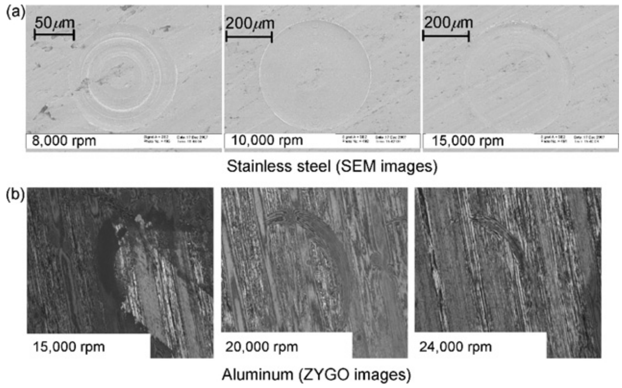

Fig. 7. SEM and ZYGO images of the contact damage (508 μm diameter tool).

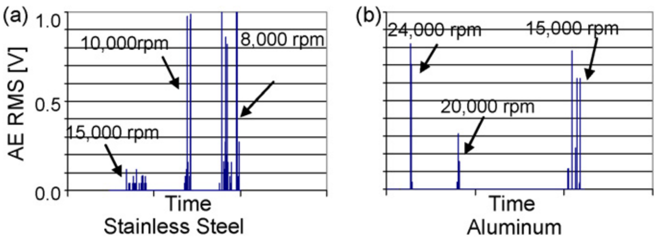

Fig. 8. AE RMS (508 μm diameter tool).

manually applied at 0.1 μm increments in order to check if the AE detects the contact within 0.1 μm damage to the workpiece.

3.2. Results

The AE sensor detected the initial contact on various combinations of tool size and rotational speed with average damage of less than 0.1 μm on stainless steel workpiece. Fig. 7 shows tool marks at the contact by 508 μm diameter endmill and Fig. 8 shows RMS value of AE signals. In stainless steel, the maximum peak-to-valley (PV) value of the contact damage was 0.730 μm while the surface roughness (R_a) was 0.828 μm for 10,000 rpm and 508 μm diameter tool. All other experimental results also showed the maximum PV by contact damage was less than surface roughness.

However, for the aluminum, the AE sensor was not able to detect the contact with smaller diameter tools. The damage (PV = 1.262 μm) made by the contact was much bigger than surface roughness (R_a = 0.475 μm) at 24,000 rpm and similar tendency showed up at other spindle speeds. The strength of the AE signals depends on the media where elastic energy releases and turns into elastic wave which propagates through and to the surface. The modulus of elasticity of aluminum is much less than stainless steel and thus, creates less elastic energy for the same amount of impact. Therefore, to detect the contact more precisely in aluminum, instantaneous impact has to be increased while maintaining damages at minimum level by increasing feed. In this experiment, the approaching feed was almost zero because one click of manual move was made at the table movement resolution (0.1 μm) of the CNC machine. Further experiments are required to calibrate sensor for various combinations of workpiece material and tool sizes.

4. Conclusion

For micro-mold manufacturing, dimensional accuracy and surface quality are of great importance. Therefore, the effects of process parameters on the surface roughness and the form error of vertical side walls created in a step-milling was studied.

Down-milling showed better surface quality and dimensional accuracy than up-milling. For down-milling, a significant effect of feed rate on surface roughness was observed. The optimum feed rate bearing the best surface quality existed in most cases, which is closely related to effective rake angle and the minimum chip thickness. The formation of uneven and rough surfaces in up-milling was explained by elastic deformation and recovery.

The profiles of the vertical side walls showed form errors resulting from deflection of the cutting tool. Different profile shapes occurred for various depths of cut and, furthermore, an increase in form error size could be observed with increasing depth of cut and feed rate. However, the effect of feed rate was less pronounced, especially when milling with small depths of cut.

Also, for better dimensional accuracy, reliable and easy setup of micro-tools, an AE sensor was used to find relative position of the tool and the workpiece, and it showed promising results on stainless steel while further calibration and proper application of feed are required on aluminum.

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