Title

A Study of Surface Roughness in the Micro-End-Milling Process

Authors

Lee, Kiha
Dornfeld, David A

Publication Date

2004-05-31

A STUDY OF SURFACE ROUGHNESS IN THE MICRO-END-MILLING PROCESS

Kiha Lee and David A. Dornfeld

Laboratory for Manufacturing Automation
Department of Mechanical Engineering
University of California at Berkeley
Berkeley, CA 94720, USA
dornfeld@me.berkeley.edu

ABSTRACT

Micro-end-milling is emerging as an important fabrication process. Its benefits include the ability to fabricate micro and meso-scale parts out of a greater range of materials and with more varied geometry than is possible with lithography and etching. It also enables the creation of micro and meso-scale molds for injection molding.

Factors affecting surface roughness have not been studied in depth for this process. A series of experiments has been conducted in order to begin to characterize the factors affecting surface roughness and determine the range of attainable surface roughness values for the micro-end-milling process. A 229 μm diameter end mill was used to cut slots into aluminum (6061) samples. The machining factors studied were chip load (feed per tooth), cutting speed, and depth of cut. A two level factorial experiment was run, and it was determined that while chip load was the dominating factor, the interaction between chip load and cutting speed was also significant. Further experiments allowed the generation of a second order relationship between chip load and surface roughness. The model, which includes the effect of chip load, cutting speed, and the interaction between the two, predicted the surface roughness values with an accuracy of about +/- 10%. The surface roughness values ranged from 600 Å all the way to 3800 Å over the span of the studied parameters.

It has previously been shown that run-out creates a greater problem for the dimensional accuracy of parts created by a micro-end-milling process as compared to parts created by a traditional end-milling process (Lee, *et al* 2001). It appears that run-out also has a more significant effect on the surface quality of micro-end milled parts. The surface roughness traces reveal large peak to valley variations with a period of twice the chip load. This means that one of the two cutting edges on the tool creates a deeper cut than the other. Cutting marks from the non-dominant cutting edge are also visible on the surface roughness traces as small steps between the much larger marks from the dominant cutting edge. It is postulated that the effect is due to run-out, and that improving machine tool run-out will have a very significant effect on the surface quality of micro-end-milled features.

INTRODUCTION

The end-milling process is one of the most widely used material removal processes in industry. Recently the micro-end-milling process has received increased attention (Damazo, *et al*

1999; Friedrich and Vasile 1996; Schaller, *et al* 1999). Micro-end-milling refers to a basic end milling process using tools down to 10 μm in diameter. Because the geometries that can be produced by micro-end-milling are more flexible than those produced by lithography, this process is potentially useful as a companion to lithography based MEMS processing techniques. Furthermore, a larger range of materials can be processed using this process. This process is also important for the production of meso-scale parts (parts on the order of 1mm to 1cm) which are too large for lithography techniques, but too small for many other traditional processing techniques.

Micro-end-milling is essentially the same process as end-milling on the macro scale. However, there are a few important differences. As the tool diameter becomes smaller, the rotational speed theoretically required to achieve the recommended cutting speed is far above the technical limit of the available spindles. For instance, v_c = 6m/min calculated from n=40,000rpm for a 50 μm diameter tool, as compared to the recommended v_c = 100 m/min for cutting aluminium in a conventional machining process. Another concern with micro-milling is that run-out can become comparable to the diameter of tools. The run-out to tool diameter ratio becomes much larger for micro-end-milling than for traditional milling.

Many applications that could benefit from the micro-end-milling process (optical systems for example) demand extremely good surface quality. Macro scale parts that require a very good surface finish often undergo processing after milling to improve the surface roughness. However, it is more difficult to apply such post processing techniques to features on the micro scale. Therefore, the surface roughness generated by the milling tool is perhaps even more vital at very small scales. With this in mind, the following study to characterize the surface quality produced by the micro-end-milling process has been undertaken.

SURFACE ROUGHNESS IN END MILLING

The typical slot-end-milling process is shown in Figure 1. The surface along the bottom of the slot will be scalloped. As the tool passes through the workpiece, each tooth creates a semi-circular scratch along the bottom of the slot. Thus, the bottom surface will be scalloped.

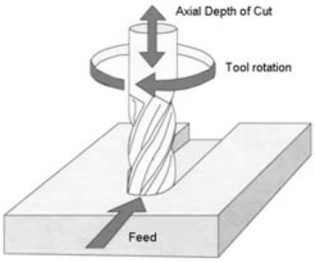


FIGURE 1. SLOT-END-MILLING PROCESS.

The theoretical surface roughness, R_a, can be estimated using the following equation (Montgomery and Altintas 1991):

$$R_a = \frac{f_t^2}{32\left(R \pm f_t n_t / \pi\right)} \qquad \text{Eq. (1)}$$

where R_a is the surface roughness, n_t is the number of teeth on the cutter, R is the radius of the cutter, f_t is the feed per revolution, and the + sign refers to up-milling and the – sign refers to down milling. The above equation does not consider many factors that in reality can affect the surface roughness. For this reason the surface roughness will generally be higher than that predicted by Eq. 1. Statistical models that include such factors as depth of cut and cutting speed in addition to feed per revolution (chip load) have been developed (Alauddin *et al* 1995). Although empirical models do not provide as much insight into the physics of a particular phenomenon, they are useful to determine the effect of factors that are difficult to physically model. Therefore, experiments to provide a statistical model, similar to that developed by Alauddin, *et al*, and to provide qualitative insight have been performed.

EXPERIMENTAL SETUP

The Mori Seiki CNC drilling center shown in Figure 2 was used for the experiments. The drilling center has a maximum spindle speed of 8000 RPM; however an attachment (shown below in Figure 3) allows operation at 40000 RPM.

A 229 μm diameter tool from Robbjack Corporation was used for the experiments. The end-mills are made of 92% WC and 8% Co. Cobalt increases the toughness of tool. The tool used has a very strong inner adhesion and high edge stability. The tool is shown in Figure 4. As can be seen in the figure, the tool is a two fluted end-mill with more or less standard geometry. Slots in aluminum (6061) samples were cut with this tool to determine the affect of machining parameters on surface roughness.

FIGURE 2. MORI SEIKI CNC DRILLING CENTER TV-30, MAXIMUM 8,000RPM.

FIGURE 3. AIR TURBINE TOOL, MODEL 250, (SPEED = 40,000RPM).

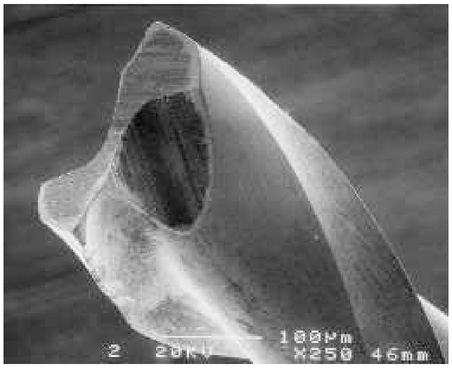


FIGURE 4. ROBBJACK MICRO-END-MILL, 92%WC AND 8% CO.

Surface roughness measurements were taken with a diamond stylus (Tencor P-10), traveling along a straight line over the surface. It features the ability to measure micro-roughness with up to 0.5 Å (0.002 µin.) resolution over short distances as well as waviness over a full, 60 mm (2 inch) maximum scan length.

A three factor full factorial experiment was performed. The factors included in the experiment were chip load (or feed per tooth) f_t, cutting speed v_t, and depth of cut a_c. The machine tool used can only operate at two spindle speeds. Since it was desired to keep the tool radius constant, only two levels for the cutting speed parameter were used. Since it was considered that the chip load would probably be the most dominant factor, the experiments covered four different chip loads. Furthermore, it has been shown that for macro scale end-milling the surface roughness response to chip load is nonlinear (Alauddin *et al* 1995). Two levels and a center point were used for depth of cut. Taking a subset of the data collected, a two level factorial analysis was performed, and a linear model was developed. Then, a more detailed analysis was performed on the chip load factor using all four levels. A final model was developed with a quadratic relationship for chip load, and linear relationship for the other two factors.

RESULTS AND ANALYSIS

Results of 2 Level Factorial Analysis

A two level factorial analysis was performed on a subset of the data. The high and low values for depth of cut correspond to 1/2 and 1/4 the tool diameter respectively. The cutting speed values correspond to 7500 RPM and 40000 RPM with a 229 μm diameter tool.

The chip load is by far the most dominant factor affecting the surface roughness. However, both cutting speed and the cutting speed X chip load interaction appear to be significant as shown on the normal probability plot in Figure 5. Any points that lie off a straight line in this plot can be considered a real effect and not due to random variation in the process. The effects of the other factors (those points not labeled in Figure 5) are within the noise of the process and so have been left out of the models developed.

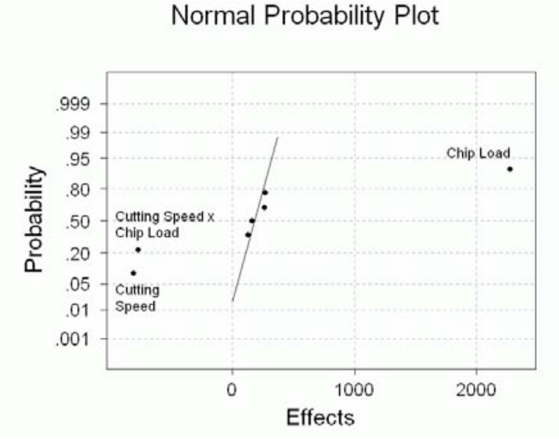


FIGURE 5. NORMAL PROBABILITY PLOT OF MAIN EFFECTS AND INTERACTIONS. POINTS THAT LIE OFF A STRAIGHT LINE ARE THE SIGNIFICANT EFFECTS AND ARE LABELED.

Although cutting speed and the cutting speed X chip load interaction are significant, their affect is far smaller than the effect of chip load. A linear model, shown in Eq. 2, was developed using the data from the 2 level factorial analysis.

$$R_a = 96.5 + 697 f_t + 589 v_c - 818 f_t v_c \qquad \text{Eq. (2)}$$

The model predicts the surface roughness within about plus or minus 10% of the measured value.

Tipnis, *et al.* (1976) developed a multiplicative model, given by Eq. 3, to model surface roughness.

$$R_a = c v_c^k f_t^l a_a^m \qquad \text{Eq. (3)}$$

c, k, l, and m are experimentally determined constants. Alauddin, *et al* (1995) used a logarithmic transformation to convert the data from a factorial experiment into this form. They found good correlation between this model and their experimental data. A similar logarithmic transformation was used in this analysis to determine the constants for Eq. 3 based on measured data. However, it was found that the deviations between the predicted values and the measured values were about twice as high using the multiplicative model compared to the linear polynomial model. Therefore, it was thought more appropriate to use the simple linear polynomial model.

Higher Order Factorial Analysis

Four different chip load levels were tested in order to generate a quadratic model for this factor. The extra two levels were added in between the high and low level used for the two level factorial. Surface roughness results for two different depths of cut are shown in Figure 6.

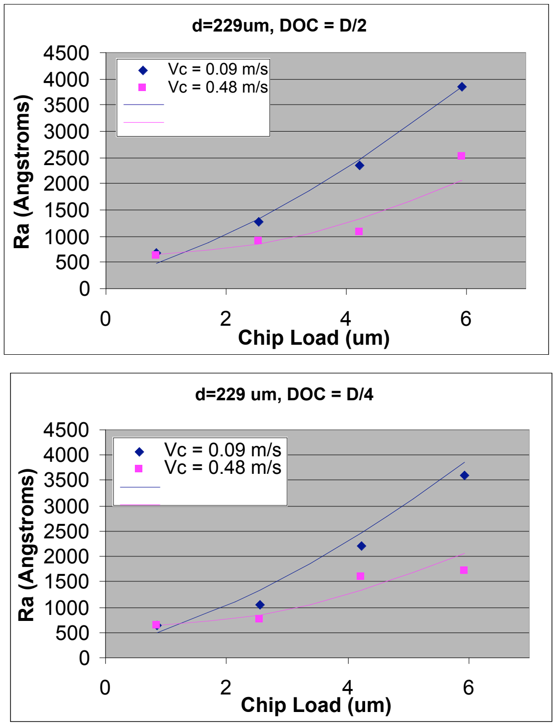


FIGURE 6. SURFACE ROUGHNESS AS A FUNCTION OF CHIP LOAD FOR 2 DIFFERENT DEPTHS OF CUT AND CUTTING SPEEDS. THE TREND LINE IS THE VALUE PREDICTED BY A QUADRATIC POLYNOMIAL MODEL.

The relationship between chip load and surface roughness appears slightly non-linear, particularly at high cutting speed. A polynomial model was developed incorporating a second order term for chip load. The model is given by Eq. 4.

$$R_a = 43.6 + 439 f_t + 46.3 f_t^2 + 1256 v_c - 990 f_t v_c$$

Eq. (4)

As shown in Figure 6, the model fits the measured data very well at low cutting speeds. The model does not fit the data quite as well at high cutting speeds probably due to the increased variation in the measured values at higher cutting speeds. The figure also demonstrates the chip load X cutting speed interaction effect. At high chip loads, the effect of cutting speed is much more pronounced.

These results are similar to those of Alauddin, *et al.* (1995). They found that chip load is the most important factor. They also found a nonlinear relationship between chip load and surface roughness, and a negative relationship between cutting speed and chip load (higher cutting speed results in lower roughness). However, the results of these experiments differ in that the interaction between chip load and cutting velocity is important. Alauddin, *et al* found none of the interactions to be significant. While they found that cutting speed had the same effect on surface roughness regardless of chip load, the experiments show that for the micro-end milling process, the effect of cutting speed on surface roughness is more pronounced at higher chip loads.

Additional runs were done with a tool of smaller diameter for comparison. The results of those tests are shown in Figure 7. Note that because the tool diameter is smaller, the cutting speeds are lower. The surface roughness values compare fairly well with those using a larger tool for comparable chip loads. An interesting feature of these extra runs is that surface roughness appears to be linear with chip load. Notice also that the model does not predict the surface roughness well for a cutting velocity of 0.05 m/s. This is expected since the model was generated using data only in the range of about 0.1 m/s to 0.5 m/s. It is possible that one of the reasons that the surface roughness seems to be more linear at lower cutting velocities is that temperature effects are less noticeable. Whatever the reason, the relationship between surface roughness and chip load seems to be linear at lower cutting speeds and lower chip loads.

Effect of Runout on Surface Roughness

Figures 8 and 9 show surface roughness traces for several slots machined with different combinations of chip load. Large marks from the cutting tooth (a deep valley followed by a high peak) are easily visible on the surface roughness traces. Interestingly, the period from large peak to large peak is twice the chip load, which means that the large marks are created once per revolution rather than once for each tooth. In many of the surface roughness traces, a step is clearly visible midway between larger peaks. This affect is most likely the result of run-out.

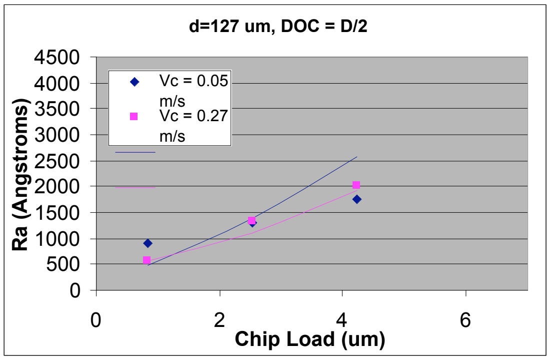
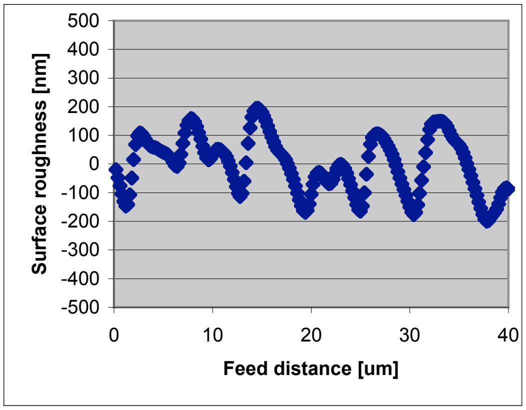
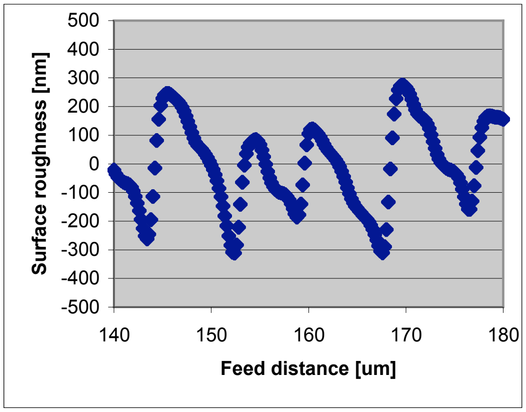


FIGURE 7. SURFACE ROUGHNESS AS A FUNCTION OF CHIP LOAD & CUTTING VELOCITY FOR A SMALLER TOOL DIAMETER.

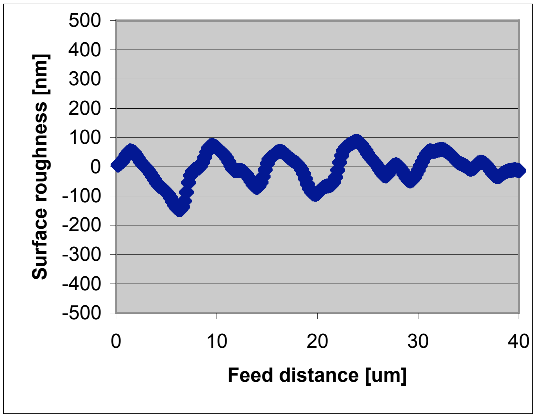


1/2d DOC; 7500RPM; 0.847 μμ/tooth

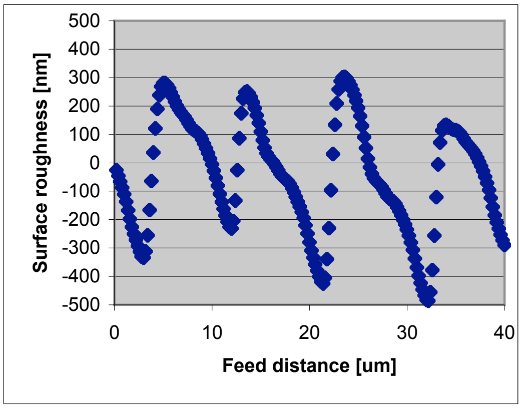


1/2d DOC, 7500RPM; 4.233 µµ/tooth

FIGURE 8. SURFACE ROUGHNESS TRACES AND SEM MICROGRAPHS AT 7500 RPM FOR LOW AND HIGH CHIP LOADS.



40,000RPM; 0.826 µm/tooth



1/2d DOC; 40,000RPM; 4.128 µm/tooth

FIGURE 9. SURFACE ROUGHNESS TRACES AND SEM MICROGRAPHS AT 40000 RPM FOR LOW AND HIGH CHIP LOADS.

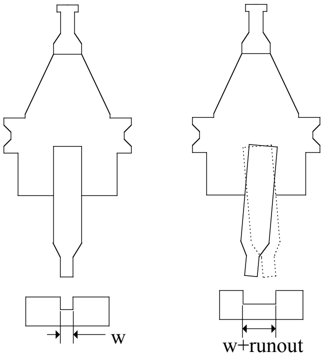


FIGURE 10. COMPARISON OF THE IDEAL CHANNEL AND THE CHANNEL MACHINED WITH RUN-OUT.

Run-out of a machine tool results in a machined feature that is larger than the diameter of the tool. This is caused by imperfect tool alignment, asymmetric tool geometry, mismatch between tool and machine tool, and vibration of tools during machining (Stephenson, and Agapiou 1997). Figure 10 shows how run-out affects the size a machined slot. In addition, radial cutting forces deflect cutting tools like a cantilever beam. The deflection can be reduced through minimizing the length of the tool and toolholder, the use of a stiffer toolholder and clamping unit for the cutter, and the use of a toolholder and tool materials with higher moduli of elasticity. For a conventional macro-scale machining process, the run-out, typically on the order of micrometers, has a small (often negligible) effect on the dimensional accuracy of the machined feature. For micro machining, however, the tool run-out to tool diameter ratio becomes much larger. According to the test results by Bao and Tansel (2000), run-outs of the holder with a collet were 0% to 65% and run-outs of the conventional holder were between 40% and 87%.

In addition to producing features with inaccurate dimensions, run-out also negatively impacts surface roughness. Because the tool is not perfectly orthogonal to the surface being cut, the one side of the tool will cut deeper than the other side. This can be clearly seen in many of the surface roughness traces of Figures 8 and 9. Reducing runout would most likely have a beneficial effect on surface roughness. Values for surface roughness range from about 600 Å to 3800 Å for this experiment. It is reasonable to assume that with improved run-out, micro features with an optical quality surface roughness below 500 Å could be produced. Unfortunately, run-out is primarily a function of machine tool design, and cannot be improved much by changing machining parameters.

CONCLUSION

A set of experiments designed to begin the characterization of surface quality for the micro-end-milling process have been performed. The effect of chip load, cutting speed, and depth of cut on surface roughness of aluminum (6061) samples was studied. An initial 2 level factorial experiment shows that chip load (or feed per tooth) is by far the most dominant factor of those studied. Cutting speed and the chip load X cutting speed interaction were also significant effects. Further experiments were performed allowing the generation of a second order relationship between surface roughness and chip load. The second order model generated, which includes the effect of chip load, cutting speed, and the interaction between the two, predicts surface roughness reasonably well. The deviation between predicted and measured surface roughness values was within an error band of about plus or minus 10%. The surface roughness values varied from about 600 Å to about 3800 Å over the experimental range.

Run-out appears to play a significant role in the surface quality of micro-milled parts. The dominant cutting marks (as seen on the surface roughness profiles) have a period of twice the chip load, meaning that one cutting edge is making a deeper cut than the other cutting edge. The cutting marks of the non-dominant edge are also visible as small steps on the surface roughness profiles. This effect is most likely due to run-out. Improving run-out could easily lead to optical quality surfaces having a roughness of less than 500 Å. Unfortunately, run-out is primarily a function of machine tool design, and not cannot be improved much by changing machining parameters. However, by using the optimal optimal machining parameters determined by these experiments along with improved run-out, features with very good surface quality can be produced with the micro-end-milling process.

ACKNOWLEDGMENTS

This work was supported by the Consortium on Deburring and Edge Finishing (CODEF). The authors also thank Air Turbine Technology and Robbjack Corp. for their support.

REFERENCES

Alauddin, M., Baradie, M., Hashmi, M.S.J., (1995), “Computer-aided analysis of a surface-roughness model for end milling,” *Journal of Materials Processing Technology*, 55, 123-127.

Bao, W.Y., Tansel, I.N., (2000), “Modelling micro-end-milling operations. Part II: Tool run-out,” *International Journal of Machine Tools & Manufacture*, Vol. 40, pp. 2175-2192.

Damazo, B. N., Davies, M.A., Dutterer, B.S., Kennedy, M. D., (1999), “A summary of micro-milling studies,” *1st international conference and general meeting of the European society for precision engineering and nanotechnology*, Bremen, Germany, 31 May – 4 June, 1999. p.322-324.

Friedrich, C. R., Vasile, M.J., (1996), “Development of the micromilling process for high –aspect-ratio microstructures,” *Journal of Microelectromechanical Systems*, Vol. 5, no. 1, March, 1996.

Lee, K., Ahn, S.-H., Dornfeld, D., Wright, P.K., (2001), “The effect of run-out on design for manufacturing in micro-machining process,” *Proc. ASME IMECE 2001*, MED-Vol. 12, ASME, New York, pp.11-17.

Montgomery, D., Altintas, Y., (1991), “Mechanism of cutting forces and surface generation in dynamic milling,” *ASME J. Eng. Ind.*, 113, 160-168.

Schaller, Th., Bohn, L., Mayer, J., Schubert, K., (1999), “Microstructure grooves with a width of less than 50 μm cut with ground hard metal micro end mills,” *Precision Engineering*, Vol. 23, pp. 229-235.

Stephenson, D. A., Agapiou, J.S., (1997), Metal cutting theory and practice, Marcel Dekker, Inc.

Tipnis, V.A., Buescher, S.C., Garrison, R.C., (1976), “Mathematically modelled machining data for adaptive control of end milling operations,” Proc. *NAMRC-iv*, pp. 279-286.