Micromachining and Burr Formation for Precision Component

Jeffrey Hartnett, Sangkee Min, David Dornfeld
Laboratory for Manufacturing and Sustainability, Department of Mechanical Engineering
University of California at Berkeley
Berkeley, California USA

Abstract

An understanding of the fundamentals of surface and edge formation (e.g. burrs) leads to procedures for insuring efficient production of machined features in precision components. This depends on analytical models of burr formation and edge effects, studies of tool/workpiece interaction for understanding the creation of features and, specially, the material influence, data bases describing cutting conditions for optimal edge quality, and design rules for burr and edge defect prevention. Ultimately, engineering software tools must be available so that design and manufacturing engineers can use this knowledge interactively in their tasks to yield a mechanical part whose design and production is optimized for production of all critical specifications. This paper reviews recent research work done using a Mori Seiki NV1500 DCG Vertical Milling Machine as part of the MTTRF machine loan program at the University of California at Berkeley relative to burr formation in precision micro-machined components. Specific applications of micromachining in a number of micro-scale components are indicated.

Keywords: Micromachining, microfeature production, experimental data bases

1 INTRODUCTION AND BACKGROUND

The motivation for the fabrication of smaller and smaller work pieces has been essentially the same since manufacturing was first established as an art/science – new applications, better performance, less expensive or higher quality. Machining processes have always played an important role in manufacturing or work pieces and have seen their capability for precision machining steadily improve. Taniguchi's paper in 1983 /1/ "defined the terms" by which we have discussed micromachining in the ensuing two decades. Figure 1, from Taniguchi as modified in [2] shows micromachining capability in terms of Taniguchi"s unit removal, the amount of workpiece removed during one cycle of process- one engagement of the tool, for example.

A number of organizations, including CIRP, have had a long history of contributing to the research and development of micromachining technology. More recently, Masuzawa and Tonshöff's CIRP keynote on 3-D micromachining /3/ and Masuzawa's review of the state of the art in 2000 /4/ discussed micromachining capabilities and, in the case of Masuzawa, defining micromachining relative to parts that are "too small to be machined easily." A keynote to be presented at the 2006 CIRP General Assembly in Kobe Japan will elaborate a review of the work in mechanical micromachining from several aspects /5/.

Demand for reduced weight, reduced dimensions, higher surface quality and part accuracy while at the same time decreasing component costs and reducing batch sizes for components of devices ranging from electro-mechanical instruments to medical devices force us along Taniguchi's curve. These are the forces driving miniaturization. As unit removal size decreases, issues of tool edge geometry, grain size and orientation, etc. – effects considered to have little or no influence at larger scales – become dominant factors with strong influences on resulting accuracy, surface quality and integrity of the machined component.

This paper reviews work done at UC-Berkeley as part of the MTTRF machine loan program since the machine installation in December, 2005.

In our paper at the MTTRF conference in 2005 /6/ a strategy for effectively addressing burr prevention and insuring edge quality was reviewed and required that the entire "process chain" from design to manufacturing be considered to integrate all the elements affecting burrs, from the part design, including material selection, to the machining process.

This was shown to be specially true for precision machined components, for which the fundamentals of machining are often not well understood. Burr formation affects work piece accuracy and quality in several ways; dimensional distortion on part edge, challenges to assembly and handling caused by burrs in sensitive locations on the work piece and damage done to the work subsurface from the deformation associated due to the exit of a cutting edge is seen in Figure 2. A number of things are clear from this image– there is substantial damage and deformation associated with a burr, the shape is quite complex and, hence, the description of a burr can be quite complex, and the presence of a burr can cause problems in manufacturing.

Although the burrs shown in Figure 2 give the appearance of a rather simple phenomena, the range of burrs found in

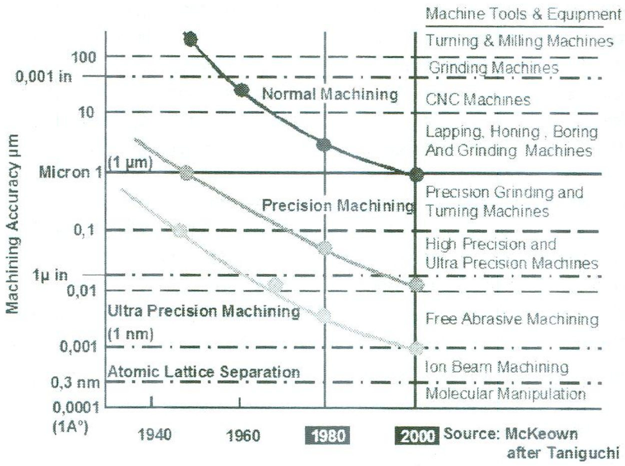

Figure 1 Micromachining capability over time.

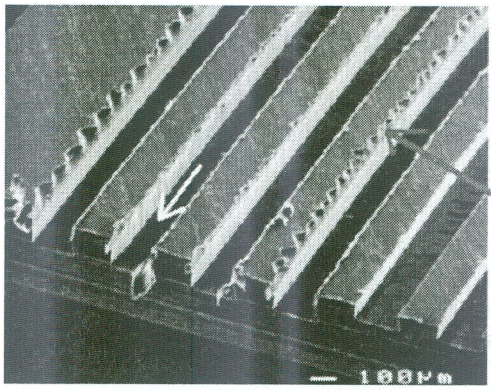

Figure 2 Typical burrs in slot milling of precision components, from /6/.

usual machining practice is quite wide.

A better strategy was proposed – that is to attempt to minimize, or prevent, burrs from occurring in the first place /7/. This gives two immediate benefits in that, first, it eliminates the additional cost of deburring the component and possible damage during the deburring process (a major issue in precision parts) and, second, in the case burrs cannot be eliminated it improves the effectiveness of any deburring strategy due to reduced and more standard burr size and shape.

To minimize or prevent burr formation requires that all stages of manufacturing from the design of the component through process planning and production be integrated so that the potential part features and material constraints, tooling and process sequences and process variables be considered from a perspective of the potential for creation of burrs on the workpiece. That is, the inputs (process, material, tools, workpiece geometry, fixturing, etc.) must be considered along with the part functionality (part performance, fit and assembly requirements) as well as any expected or required deburring processes.

2 RESEARCH OBJECTIVES

Machine tools, such as the one received as part of the MTTRF loan, Figure 3, have the capability to machine very fine features (both drilling and milling). Precision manufacturing (specially at the microscale) requires special considerations of process parameters to insure that the part machined meets all form and tolerance specifications, including edge and surface finish.

Research at Berkeley in the Consortium on Deburring and Edge Finishing (CODEF) of the Laboratory for Manufacturing Automation has been concerned with the fundamental aspects of burr formation and other edge defects for over 15 years. Research is conducted in collaboration with industrial partners to develop strategies for burr prevention, minimization and removal. This research develops a variety of software and hardware tools for assessing the likelihood of burr and edge defect generation and suggests optimized process plans to insure burr-free or minimum burr conditions. An important part of this work is validation of analytical or empirically developed process models — that is, machining tests.

\It is important to determine whether or not algorithms and tools developed for macro scale components (that is, parts of a more conventional size) can be applied to these smaller features and to determine the performance of precision micro machines relative to edge effects and feature characteristics.

Figure 3 Mori Seiki NV1500 DCG Vertical Milling Machine at UC-Berkeley.

This research project continues our work on developing a basic understanding of machining of micro-scale features by milling and drilling. The objective of this research is to extend this work into micro milling using the NV1500 High Precision Vertical Machining Center. We have previously established some guidelines for successfully machining small features based on our work at larger sizes. The machine allows us to concentrate on experiments in micro-milling for basic studies and data base building.

The research reviewed here has addressed the following elements of our research plan:

i. micro milling (with tools on the order of 100 microns or less) for observation of burr formation and associated finishing problems,

ii. machining of aluminum specimens.

iii. burrs formed in all tests were measured and included in burr data bases and expert systems under development at Berkeley.

iv. burrs formed were observed for improved understanding of burr formation mechanisms.

v. for milling, burr formation will be observed and included in software for tool path planning already developed for macro scale milling operations.

Finally, we are beginning to use the machine tool for some acoustic emission micro-sensor development and evaluation, specially for micromachining, based on thin film micro-sensors under development in the lab and wireless sensor technology.

3 RESEARCH RESULTS

The focus of the initial research is the creation of positive features for use, for example, in an injection micro-molding application as a mold feature. Information on fabrication of "micro" protrusions would be useful. It is important to be able to produce these protrusions with the following characteristics:

- Accurate: defined as close replication of design dimensions.

- Clean: burr free with desired surface finish and minimum contamination from chips or other materials.

- Efficient manufacture: produced in a timely manner, and both input (energy) and output (waste) conscious.

The objective of a set of experiments conducted was to create a feature that maximizes aspect ratio while simultaneously minimizing feature size (width & depth) without compromising manufacturing accuracy. We evaluated the impact of three parameters on finished features in aluminum 6061 work material with a two flute, coated HSS 1 mm diameter end mill:

- depth/width ratio (2 and 10)
- tool path (profile- counter-clockwise vs clock-wise)
- cutting velocity (50-60 m/min)

The test specimen geometry used is shown in Figure 4.

Other process conditions include 0.65 μm feed, 250 μm axial depth of cut, 750 μm rough cut and 250 μm final cut radial depth of cut.

The experimental results were classified according to the following measurements:

- feature geometry
- feature location
- burr and edge characteristics

Details are given below.

Feature geometry - Height was replicated within -7.6 μm, with only a modest impact due to process parameters. Closer replication was found when climb milling (by average of 13 μm) and at high aspect ratio (average of 12 μm). Height replication was nearly independent of cutting velocity. Width and length replication had an average design deviation of +27.9 μm. Slightly better replication was found while down milling (average of .9 μm). Higher cutting velocity yielded more accurate parts. A modest improvement in accuracy at lower aspect ratio (average of .55 μm). Excellent repeatability was observed in the test runs.

Height: ± 2 μm

Width: ± 2.95 μm

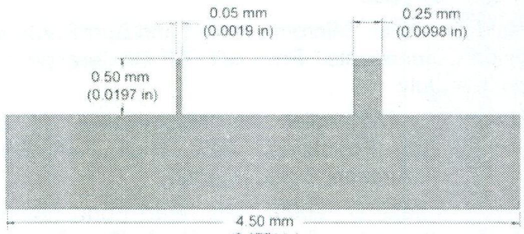

Figure 4 Test specimen cross-section with feature design, length 1 mm.

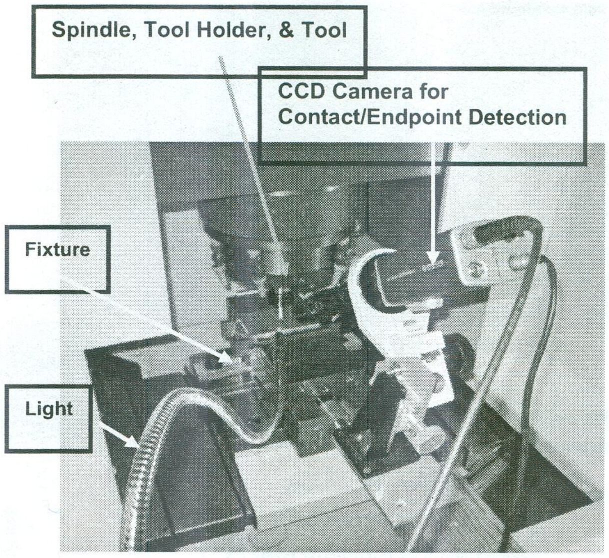

Figure 5 Machining test setup with camera for contact/endpoint detection.

Length: ± 3.95 μm

The bulk of the observed variation was likely attributable to tool diameteral runout which is on the order of ± 50 μm. This is a common issue with smaller diameter tools. A roughing and then finishing pass may improve results.

Feature location – Feature location results were measured on a coordinate measuring machine relative to a series of points on the specimen, Figure 7. Design deviation of the feature location was on same order as width and length deviation, that is, +27.9 μm for X & Y directions. Point 5 (Figure 7) has a higher deviation due to compounding of error in X & Y machining directions. The effects of process parameters at Point 5 are also slightly larger. Higher cutting velocity and down milling yields more precise parts (average 3 & 2.2 μm improvement.) Finally, a higher aspect ratio yields more error (average of 1.6 μm) likely due to work deflection.

Burr and edge results – Evidence of an exit burr at tool exit location on the corner of the feature was seen. A typical burr formed in this type if machining is seen in Figure 8. Evidence of a top burr (combination of a Poisson & tear burr) along entire top edge of feature was also seen. The

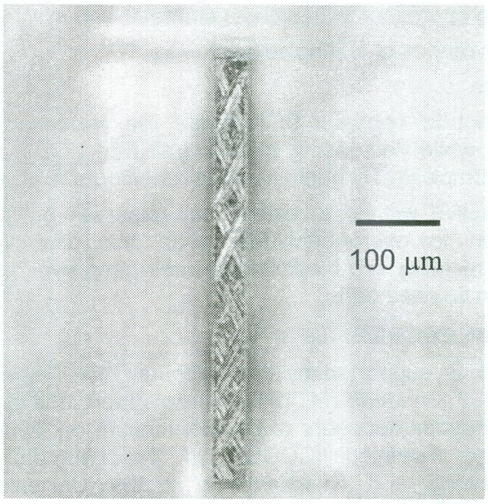

Figure 6 Typical feature (50 micron wide) machined in test.

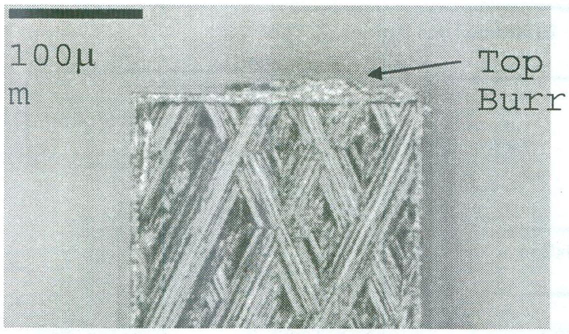

Figure 8 Top burr on a 250 μm wide feature.

exit and top burr were minimized for the following conditions:

- depth/width ratio is low.
- cutting velocity is high.
- tool rotation for climb milling.

These results agree with past research in micromachining on more conventional machine tools /8/.

4 SUMMARY AND CONCLUSIONS

Although edge finishing in machined components is a constant challenge in precision manufacturing of mechanical components, there are a number of strategies, built on competent process models and extensive data bases, that can substantially minimize or eliminate burrs. These strategies can be incorporated in the software relied upon by design and manufacturing engineers to insure that the conditions which can lead to close feature replication and minimized edge defects can be obtained while insuring that production efficiency is maintained. The inclusion of design rules for feature creation and burr minimization will allow the design engineers to reduce the likelihood of work piece defects at the most effective stage — during product design.

Our research work will continue with further investigation of process parameters on feature accuracy and cleanliness, focusing on:

- tool path effects
- tool path variation to support high aspect feature during milling
- finishing operations with smaller diameter end mills
- broader ranges of cutting velocity
- feed rate

We expect to continue to increase the aspect ratio of features, while decreasing their overall size and increase feature complexity by adding curves & contours.

The objective will be to extend our expertise on feature fabrication to micro-mold fabrication (for example for injection molding and bio-fluidic devices), and evaluate the impact on finished parts.

ACKNOWLEDGEMENTS

This work is supported by the Machine Tool Technology Research Foundation (MTTRF). That support, and support of the industrial sponsors of the Consortium on Deburring and Edge Finishing (CODEF) in the Laboratory for Manufacturing and Sustainability at the University of California at Berkeley is gratefully acknowledged. Research on drilling burr formation is also supported by the National Science Foundation under grant DMI-0300549 (the views expressed are those of the author and do not necessarily reflect the view of the National Science Foundation). Additional information on CODEF can be found at lma.berkeley.edu.

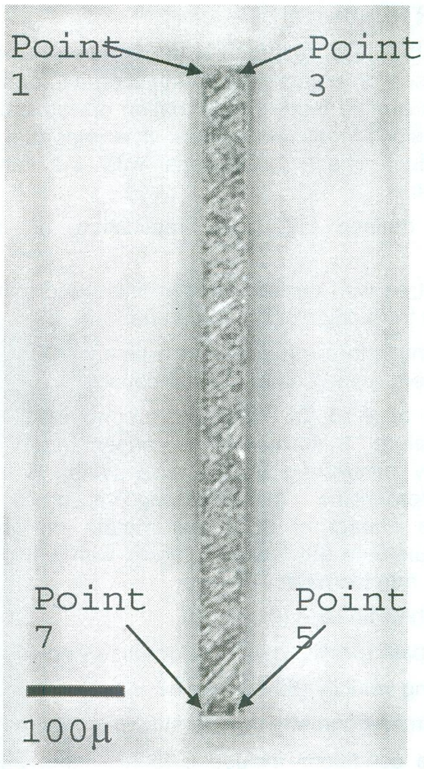

Figure 7 Measurement locations for feature location data.

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