Title
Recent Advances in Mechanical Micromachining

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Publication Date
2006

Recent Advances in Mechanical Micromachining

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Abstract

This paper reviews some of the main drivers, developments and future requirements in the field of micromanufacturing as related to the machining process from the perspective of the recent research and development literature. For the purposes of this paper micromachining includes creation of precise two and three dimensional workpieces with dimensions in the range of a few tens of nanometers to some few millimeters by cutting using defined geometry cutting tools. The review includes topics of process physics, including materials and microstructural effects, machine tools, tooling and sensing, workpiece and design issues, software and simulation tools, and other issues, e.g. surface and edge finish, and outlook for future developments.

Keywords:
Micromachining, modelling, machine tools

ACKNOWLEDGEMENT

The bulk of the references in the literature on which this paper was based is the work of CIRP colleagues and is cited. In addition, the authors are grateful to the following persons for their specific contributions to the preparation of this paper:

Dr. G. Bissacco, Technical University of Denmark, Denmark, Professor E. Brinksmeier, University of Bremen, Germany, Dr. F. Fang, Singapore Institute of Advanced Technology, Singapore, Professor J. Fleischer, University of Karlsruhe, Germany, Professor F. Klocke, WZL, Aachen University, Germany and his co-workers, Professor Steven Liang, Georgia Institute of Technology, USA, Professor T. Moriwaki, Kobe University, Japan, Dr. H. Ohmori, RIKEN, Japan, Professor R. Rajurkar, University of Nebraska, USA, Professor K. Weinert, University of Dortmund, Germany, Professor E. Uhlmann, Technical University of Berlin, Professor K. Yamazaki, University of California at Davis, Dr. D. Lee, University of California at San Diego, USA, Mr. J. Hartnett, University of California-Berkeley, USA.

1 INTRODUCTION

The motivation for the fabrication of smaller and smaller workpieces has been essentially the same since manufacturing was first established as an art/science – new applications, better performance, less expensive and higher quality. Machining processes have always played an important role in manufacturing of workpieces 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.

CIRP has had a long history of contributing to the research and development of micromachining technology. More recently, Masuzawa and Tönshoff’s 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, defined micromachining relative to parts that are “too small to be machined easily” and where it fits relative to other microfabrication processes. Alting, et al [5] covers a broad range of fabrication techniques for small scale parts and placed microfabrication processes relative the broader field of “microengineering” and discussed the design of microproducts.

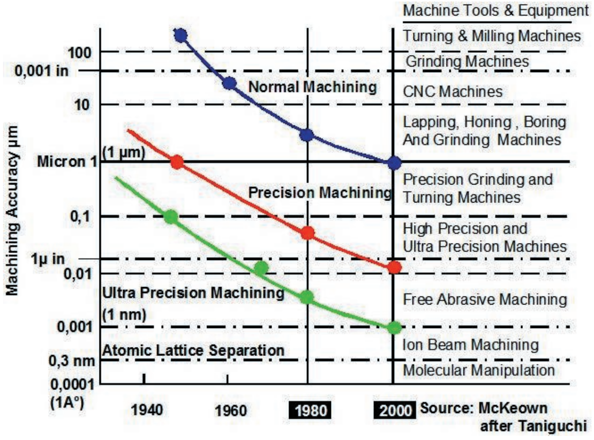


Figure 1: Micromachining capability over time [2].

This paper focuses primarily on material removal by geometrically defined cutting edges for the purpose of creation of precise three dimensional workpieces with dimensions in the range of a few tens of nanometers to some few millimeters. The motivation for increasingly smaller components parallels the improvements in cutting technology as outlined in [2]. 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. The response of the scientific community has been energetic but mixed. That is, while the development of machine tools for micromachining follows more traditional paths of scaling down conventional components, process research and development is less structured. This is apparent from the literature. 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.

The preparation for this keynote benefited from the availability of a number of excellent reports and publications recently in the literature on microscale manufacturing. For example, a special issue of the ASME Trans, J. Manufacturing Sciences and Engineering in 2004 covers a broad range of topics on micromachining and is an excellent reference [6]. Similarly, a recent report published by the WTEC Panel on Micromanufacturing, and edited by Ehmann and DeVor [7] offers a detailed view of the drivers for micromanufacturing and the opportunities and requirements for further development of the technology from a US viewpoint.

This paper aims to put into perspective the earlier work and, specially, emphasize the present state and future requirements for increased understanding of the fundamental process physics, modeling efforts and experimental validation and machine tool development. Research on manufacturing in general and mechanical micromachining in particular must be viewed in the context of a number of different "scales" besides part dimensions including: societal, sensing and process intelligence, reconfigurability, modeling, and machine tools. This review does not cover societal issues, as important as they are, or reconfigurability, but do attempt to include all the others in this discussion. Micromachining can be defined in many different ways depending on the industry, feature size, and focus of interest. The definition of machining typically involves material removal processes such as cutting, polishing, etching, sputtering, thermal removal processes, etc. Many of these processes are used in the semiconductor industry and for MEMS related applications and they tend to be referred to as micromachining or nanomachining. In this review, micromachining is strictly defined as mechanical cutting of features with tool engagement less than 1 mm with geometrically defined cutting edges. With this definition, then, all chemical, thermal, and abrasive processes are excluded. The review begins with process physics as it is fundamental to understanding micromachining.

2 PROCESS PHYSICS

Micromachining incorporates many characteristics of conventional machining. At the same time, micromachining raises a great number of issues mainly due to size or scale. Downsizing the scale of machining does not change the general characteristics of the process to some reasonable limit. However, when either the ratio of part size to be produced or size of the microstructure of the work material to the tool dimension used (say diameter) becomes small (approaching a single digit), size effects can change the whole aspect of machining.

There are two different aspects of size effects of concern, e.g. when the depth of cut is on the same order as the tool edge radius, and where the microstructure of workpiece material has significant influence on the cutting mechanism.

2.1 Homogeneous and isotropic micromachining

Many materials are considered to be homogeneous and isotropic in machining regardless of the tool edge radius/chip thickness ratio. The main difference between micromachining and macromachining resides in the cutting mechanism. In general, the cutting mechanism in macromachining is mainly shearing of the material in front of the tool tip and forming a chip. Micromachining relies on more complicated mechanisms depending on the degree of the size effect. Thus, in this paper, the size effect is defined as the effect due to the small ratio of the depth of cut to the tool edge radius but for which the material still behaves as homogeneous and isotropic.

Early work by Backer et al [8] showed the amount of imperfections per unit volume that might be due to the size effect. Boothroyd and Knight [9] explained the plowing force with the size effect and Larson-Basse and Oxley [10] explained its contribution to strain rate.

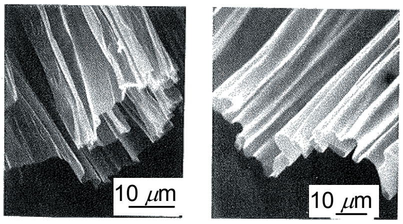
Nakayama and Tamura [11] realized that certain amounts of energy dissipation which had been neglected in macromachining should be accounted for when the depth of cut is very small. When they conducted experiments on brass at low speed (0.1 m/min) with depths of cut ranging from 2 - 40 μm using tools with edge radii of 3 - 4 μm and 17 μm, the subsurface plastic flow related to the shear zone under the machined surface was significant and accounted for energy dissipated in this zone. Another important issue would be energy dissipation by elastic recovery at the flank surface.

Von Turkovich and Black [12] conducted very early orthogonal micromachining at very low cutting speed based on the microscopic observations of chip formation of copper and aluminum crystals with depths of cut ranging from 1 to 100 μm.

Moriwaki and Okuda [13] pioneered research on the practical issues in micromachining in the late 1980s and investigated fundamental aspects of micromachining including chip formation, crystallographic orientation effects and grain boundary effects (to be discussed in a later section), tool edge radius effects, cutting force, etc. and conducted ultra precision diamond cutting on copper material with depths of cut from 3 μm to 2.5 nm. Continuous chip formation was observed at these levels and related to surface integrity, Figure 2 and Figure 3. They also found that as the depth of cut decreases, the ratio of thrust force to the main cutting force increases and thrust force becomes larger than the main cutting force at 0.2 μm depth of cut, indicating a transition of material removal mechanism from cutting to plowing.

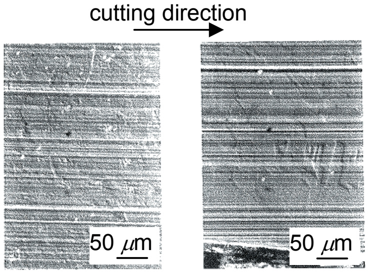
Most of early efforts on micromachining came from optical device fabrication. Many researchers investigated ultraprecision machining on optical materials to achieve fine surface and precise shapes for large size lenses. Most of them used diamond turning and thus the investigation was limited only to glass and some non-ferrous materials. But Moriwaki et al's investigation on copper material [13, 14] further expanded to steel materials [15].

Weule et al. [16] concluded that the roundness of a cutting edge is very important in micromilling due to the size effect. Since the tool edge is relatively large compared to other tool dimensions and the tool is relatively weak due to micro-tool fabrication methods, it is important to choose proper cutting parameters.

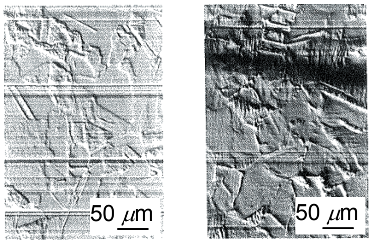


(a) Depth of cut: 5 nm (b) Depth of cut: 57 nm

Figure 2: SEM photographs of typical chips formed by orthogonal fly cutting (cutting speed 754 m/min) [13].



(a) Depth of cut: 5 nm (b) Depth of cut: 82 nm



(c) Depth of cut: 0.41 μm (d) Depth of cut: 1.62 μm

Figure 3: Surfaces obtained by orthogonal fly cutting (cutting speed: 754 m/min) [13].

2.2 Anisotropic machining

In additional to the size effects discussed in the previous section, workpiece material microstructure effects play a significant role in micromachining. When the tool dimension or a feature to be generated is of the same order as the grain size, or where material cannot be treated as isotropic and homogeneous, the cutting mechanism differs substantially from conventional machining. This can also be observed in conventional machining of single crystal or anisotropic materials however there is still a significant difference due to size effects.

Typically, the cutting edge radius of a sharpened single crystal diamond tool is on the order of 10 nm and, then, the depth of cut with such a tool can be realized in the submicron range. Most polycrystalline materials are thus treated as a collection of grains with random orientation and anisotropic properties [14].

Sumomogi et al. [17] conducted a series of microturning experiments on single crystal silicon in order to see the effect of the crystallographic orientation on surface and subsurface crack generation. A micro-Vickers hardness indenter was used as a tool for turning with decreasing depths of cut. Machining was considered to be ductile mode when surface cracks disappeared. The depths of cut where no subsurface crack was observed were smaller than ductile depths of cut and depended on the crystallographic orientation of silicon.

Vogler et al. [18, 19] investigated the microstructure effects of single and multi phase materials on surface generation and cutting force in a micro-end milling process. They confirmed that the edge radius effect contributes significantly to surface generation due to a minimum chip thickness, specially for single phase materials. They also reported interrupted chip formation leading to poor surface finish when the tool passed through different phases.

Schmidt et al. [20] investigated the influence of material structure on the surface quality in micromilling. In the case of mold fabrication, where highly wear resistant materials are often used, the material has to be heat treated before microcutting to achieve reasonable surface finish.

Furukawa and Moronuki's [21] micromachining experiments on various materials proved that the cutting mechanisms are very different for polycrystalline, single crystal or amorphous materials and for brittle or ductile materials. They found that the specific cutting force depends highly on the aspect ratio of the undeformed chip thickness (feed per tooth) to tool engagement length and increases exponentially as depth of cut decreases below 3 μm for all materials tested (pure copper, aluminum alloy, PMMA, CaF_2, and germanium). Cutting force varied as the tool passed grain boundaries, Figure 4. Cutting of single crystal fluorite and amorphous acrylic resin gave more consistent cutting forces with rather regular and homogeneous surface properties. They suggested the use of about ten times larger depth of cut than the grain size for a specific material to avoid the crystallographic effects of grains.

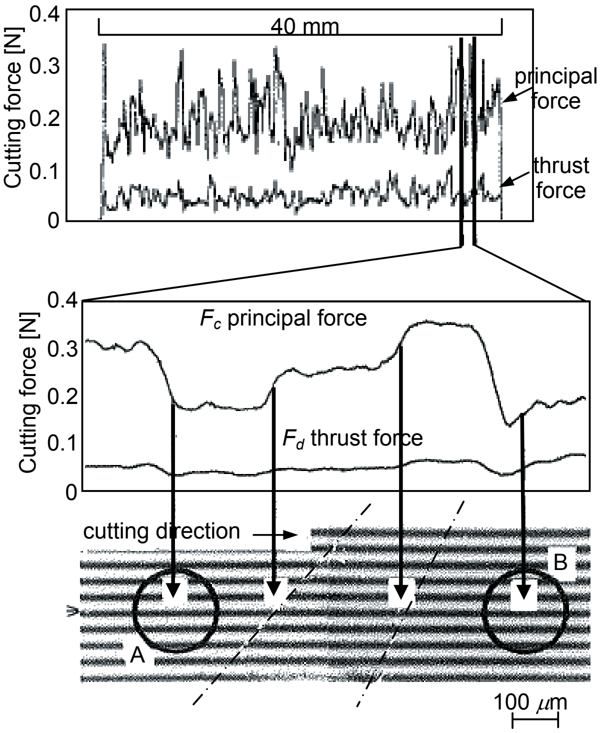
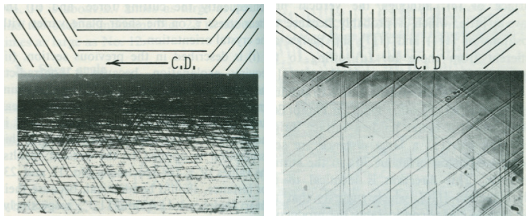


Figure 4: Cutting force variation corresponding with the grain boundary of Al alloy (grain boundaries can be seen in magnified image in A and B) [21].

Many researchers have observed changes in various parameters, such as cutting force, chip formation, and surface roughness over multi phases or multi grains in micromachining. Sato et al. [22] investigated the effects of crystal orientation on the flow mechanism in orthogonal cutting of single crystal aluminum and found that variation of cutting performance with cutting direction can be explained by the crystallographic slip system Figure 5.



(a) (b)

Figure 5: Calculated slip lines (above) and those observed on the side surface of (001) [110] (a), (110) [001] (b) orientation [22].

Yuan et al. [23] also confirmed the crystallographic orientation effects on surface roughness and cutting force for single crystal copper and aluminum in ultra precision diamond cutting. They employed a micro-plasticity model to explain the variations in cutting force and surface roughness as a function of crystallographic orientation. They calculated the shear strength of a specific crystal orientation using an effective Taylor M factor and compared this with experimental data. Variation in shear strength caused cutting force variation over different cutting directions and the resulting material induced vibration, in addition to machine induced vibration, degraded surface quality. They proposed the use of fine grain material or cutting isotropically to avoid such problems.

Lee and Zhou [24] further improved the micro-plasticity model to analyze the orientation of the shear zone in single crystal cutting. According to their investigation, shear planes are not exactly slip planes but a result of co-operative slip processes in the crystal. These observations were verified with micro-orthogonal cutting of single crystal copper [25].

2.3 Minimum chip thickness and specific cutting energy

Both isotropic and anisotropic cutting are greatly influenced by the ratio of the depth of cut to the effective cutting edge radius of the tool. In micromachining, the edge radius of the tool tends to be the same order-of-magnitude as the chip thickness. Thus, a small change in the depth of cut significantly influences the cutting process. This ratio predominantly defines the active material removal mechanism such as cutting, plowing, or slipping and thus the resulting quality, surface roughness for example. The concept of a minimum chip thickness, below which no chip will form, or a minimum depth of cut below which no material removal will occur, has been investigated by a few researchers. This is an attempt to understand the necessary minimum chip thickness to ensure proper cutting and avoid plowing and sliding of the tool [26, 27].

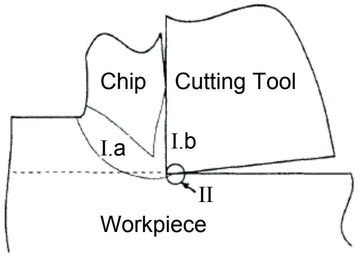
Weule et al. [16] explained the achievable surface roughness in terms of minimum depth of cut. They found that minimum chip thickness (or minimum cutting depth) depends primarily on sharpness of the tool and secondarily on material properties. The surface roughness achievable can be predicted based on spring back of elastically deformed material once the cutting depth reaches an upper bound of a minimum chip thickness where material is removed by a shearing mechanism.

Kim et al. [28] observed plowing under a certain depth of cut indicating that there exists a minimum chip thickness for chip formation. Shimada et al. [29] conducted a similar study by using molecular dynamics simulations to determine the achievable ultimate accuracy and found that the minimum chip thickness is around 5 % of the cutting edge radius for copper and aluminum. However, Yuan et al. [30] found in their diamond turning experiments on aluminum alloys that the minimum chip thickness was estimated to be between 20 to 40 % of the cutting edge radius. Hence, the value of minimum chip thickness varies with cutting edge radius, workpiece material, and cutting processes as reported. In modeling efforts, Vogler et al. [19] suggested that two separate force models should be developed to properly handle the minimum chip thickness effect. Further efforts should be made to accumulate enough knowledge on this issue because this is the key to achieve good surface quality in micromachining.

Lucca and Seo [31] experimentally investigated the effect of single crystal diamond tool edge geometry on the specific energy in the ultraprecision orthogonal flycutting of Te-Cu material. The nominal rake angle has a great influence on the specific energy when the depth of cut is smaller than the tool edge profile as does the effective rake angle when the depth of cut approaches the size of edge contour. Moriwaki and Okuda [13] and Furukawa and Moronuki [21] observed a large increase of specific energy during their diamond turning experiments in the submicron depth of cut range. Some portion of the increased energy at the small depth cut is due to the fact that elastic recovery of the workpiece material under the flank face results in sliding and this increases at small depths of cut.

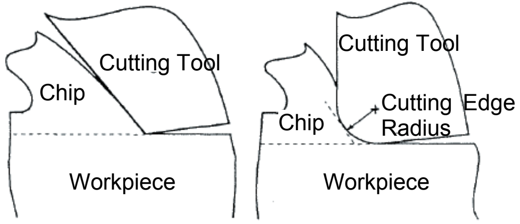
Additionally, at this level, the effective rake angle becomes negative and results in plowing which contributes substantially to the specific energy,

Figure 6. Lucca et al. [32] also found that the total specific energy is seen to significantly increase at small depths of cut in micromachining of OFHC copper. Hence, the specific energy is closely related to the minimum chip thickness and can be another indicator for cutting mechanism changes and process control.



I. Chip Formation:
  a. Shear throughout the shear zone
  b. Sliding of chip along the rake face of the tool

II. Sliding: Tool/Workpiece interaction caused by either flank wear or elastic recovery of workpiece material



III. Plowing: Resultant from negative rake angle or "effective" negative rake angle when edge radius is of the order of the depth of cut

Figure 6: Chip formation, sliding, and plowing in orthogonal metal cutting [32].

2.4 Ductile mode machining

A potential thrust area for micromachining is the fabrication of microscale structures in brittle materials. The machining of normally brittle materials (such as many optical glasses, ceramics, etc.) is desirable over conventional processing techniques (such as traditional polishing) due to increased flexibility in geometries produced, and higher material removal rate, translating to higher production throughput. However, machining brittle materials at the high depths-of-cut (DOC) found in conventional machining tends to cause excessive surface and subsurface cracking. To overcome this, machining in a ductile mode at a low enough DOC has been proposed by many researchers, including Bifano [33]. When cutting below a critical DOC, brittle materials can be machined in a ductile fashion with good surface finish and no surface pitting or cracking. Since the chip thickness in micromachining can be on the order of the critical DOC, micromachining can serve as a novel means of fabricating unique features in brittle materials not achievable by polishing or other techniques.

Ueda et al. [34] found that some ceramic materials can be machined in a ductile mode by decreasing the depth of cut and/or increasing cutting speed. ZrO_2 and WC-Co were easily machined in a ductile mode due to their high fracture toughness. But Al_2O_3 and SiC exhibited only brittle mode cutting with the smallest possible depth of cut at that time, 2 μm. The machining mode of Si_3N_4 changed from brittle to ductile as cutting speed increased.

Blake and Scattergood [35] investigated ductile regime diamond turning of brittle optical components (silicon and germanium) and suggested optimal cutting parameters such as critical depth of cut, tool geometry, and cutting speed based on an analytical model and experiments, Figure 7.

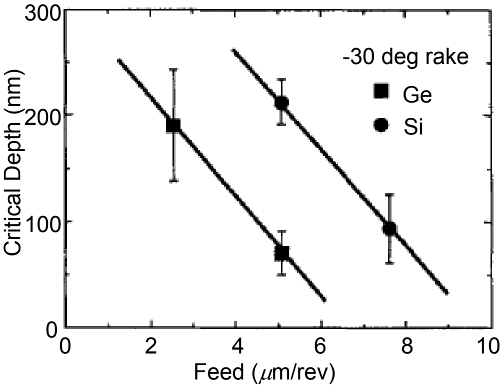


Figure 7: Apparent critical depth of cut versus feed: (100) germanium and silicon with -30° rake and 6° clearance angles [35].

Nakasuji et al. [36] did similar tests with a focus on critical depth of cut for ductile mode cutting and surface finish in machining of Ge and Si depending on crystallographic orientation, Egashira and Mizutani [37] studied critical depth of cut (feed direction) for ductile mode microdrilling of single crystal silicon.

Fang et al. [38] studied brittle-ductile transition of glass materials using indentation and reported that unlike metals, glass viscously deforms only in a very small region under hydrostatic compressive stresses at temperatures below the softening point. They also conducted ultra-precision turning operations on glass materials and found that a negative rake face angle generates the necessary hydrostatic compressive stress and enables ductile regime cutting but resulted in rapid tool wear.

Shimada et al. [39] claimed that any material regardless of its ductility can be machined in a ductile mode by adjusting the depth of cut to a sufficiently small value. Their experimental and MD analysis found that the critical tensile strength, which is sensitive to pre-existing defects, showed a significant size effect and thus, by changing the depth of cut, the mode of material removal can be switched either into ductile or brittle mode regardless of the material.

Although, theoretically, any brittle material can be machined in a ductile mode, the practical application of this is very difficult due to the extremely small critical depth of cut necessary to achieve a ductile mode for certain materials and for typical machine accuracy. Takeuchi et al. [40] built an ultraprecision lathe to overcome these difficulties and proved Shimada's claim by micro-ball end milling a glass material.

2.5 Chip formation and built-up-edge

Focusing now on chip formation, Donaldson et al. [41, 42] conducted early investigations on micro-chip formation and Nishiguchi et al. [43] established various chip formation mechanisms based on cutting edge radius. Jackson [44] considered that chip formation was closely related to the machined surface roughness and correlated the curl shape of the chips to mechanisms associated with the primary or secondary shear zone. His model predicted that the primary chip curl was due to deposited material on the rake face of the tool which varied the rake angle and, thus, changed the shear plane, Figure 8.

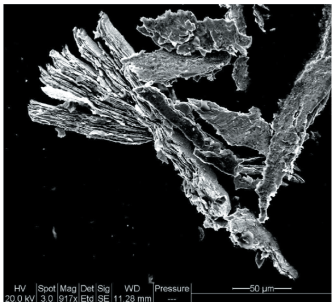


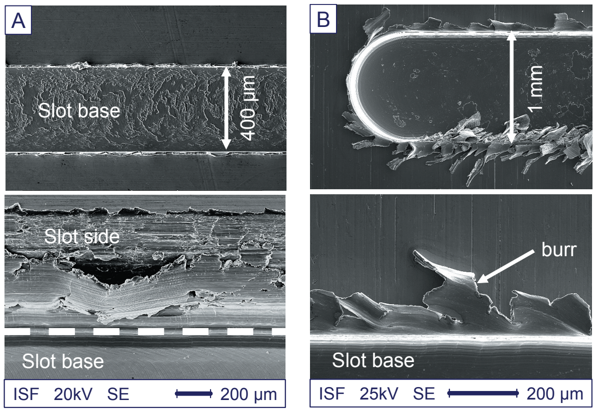
Figure 8: Micromachined chips of aluminum showing folded sections in the form of a curl [44].

In conventional machining, the built-up-edge is usually associated with a sudden change of surface roughness. Weule et al. [16] found that this can be also true in micromachining in micro-fly cutting experiments on SAE 1045 steel. Waldorf et al. [45] observed that a stable built-up-edge forms on the cutting edge and significantly increases the plowing force when the feed rate is smaller than the cutting edge radius.

Kountanya and Endres [46] also investigated material deformation mechanism in the vicinity of the cutting edge using blunt-edge tools. They observed a stable built-up edge formed near the edge radius in cartridge brass in real time and related it to the variations in cutting force measured simultaneously.

2.6 Surface and edge finish

Various problems such as surface defects, poor edge finish, and burrs in conventional machining have plagued conventional manufacturing for some time. Some of these problems have been avoided by post processing and process optimization. These problems are also significant in micromachining and require much more attention because, in many cases, inherent material characteristics or limitations in part geometry do not allow some of the solutions used in macromachining. Figure 9 shows some typical defects in micromilling.



(a) Adhesion (b) Burr formation

Figure 9: Typical surface defects in micromilling (work material: NiTi shape memory alloy) [47].

In ultra precision diamond machining for optical devices, non-ferrous metals exhibited poorer surface roughness than geometrically predicted due to the steady, small amplitude vibration of the tool which is usually larger for round edge tools than for straight edge tools [48, 49]. This small vibration was investigated by Zhang and Kapoor [50, 51] using a model which can handle deterministic and stochastic excitation and construct a 3-D texture of a machined surface. At the micro level, material properties become non-homogeneous and thus variation in material hardness causes the cutting tool vibration. This effect is significant at low feed and cutting speed and leads to irregular surface roughness.

Vogler et al. [18] studied the relationship between surface roughness and microstructure of the ferrous materials and developed a model to predict surface generation in micro-end milling. This is described in the modeling section of this review.

The work material NiTi is used for many medical applications, such as surgical implants, and micromilling is commonly used to fabricate these products. This material is very ductile and easily work hardens during machining causing adhesion and high burr formation. Additionally, high ductility causes adverse chip formation, long and continuously snarled chips. At the micro level, these chips interfere with tool engagement and burrs and contribute to poor surface quality of finished parts [47].

Lee and Dornfeld [52] conducted micro-slot milling experiments on aluminum and copper and found various standard burr types depending on location and work geometry. Interestingly, these burr shapes were similar to those found in macromachining in terms of formation mechanisms and influence of cutting parameters. One major difference found was that the influence of tool run-out on burr formation was significant in micro-slot milling.

Min et al. [53] conducted micro-fly cutting and microdrilling experiments on single crystal and polycrystalline OFHC copper in order to understand the effects of crystal orientation, cutting speed, and grain boundaries on surface roughness, chip formation, and burr formation. Certain crystallographic orientations were found to yield rougher surface finish, as well as significant burrs and breakout at the tool exit edge. The <100> and <110> direction of machining on the workpieces exhibited the greatest amount of variation in formation of burrs and breakout at the exit edge and in chip topology as a function of the angular orientation of the workpiece. This corresponded to a variation in the interaction between the tool and the activate slip systems.

They also conducted slot milling experiments on the same material and found a strong dependency of top burr formation on slip systems of each crystal orientation except (100) workpiece [54]. The (100) workpiece did not show a clear correlation due possibly to less anisotropy of the slip systems. Sato et al. [22] proposed that the (100) orientation has a relatively smaller anisotropy than the (110) and (111) orientations because it has a greater degree of symmetry, resulting in more equally distributed slip systems than the other orientations.

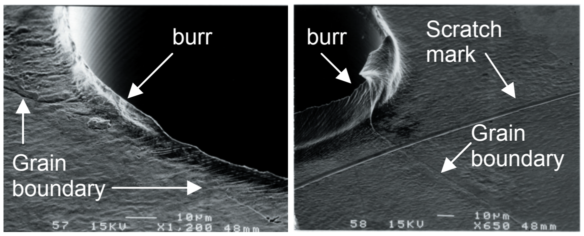
Bissacco et al. [55] found that top burrs are relatively large in micromilling due to the size effect. When the ratio of the depth of cut to the cutting edge radius is small, high biaxial compressive stress pushes material toward the free surface and generates large top burrs.

Ahn and Lim [56, 57] proposed a burr formation model in a microgrooving operation based on a side shear plane and an extended deformation area which is caused by the tool edge radius effect. The material near the cutting edge experiences the side shear deformation due to hydrostatic pressure. Aluminum and OFHC generated larger burrs than brass, and thus it was concluded that the thickness of the burr is proportional to the ductility of the material.

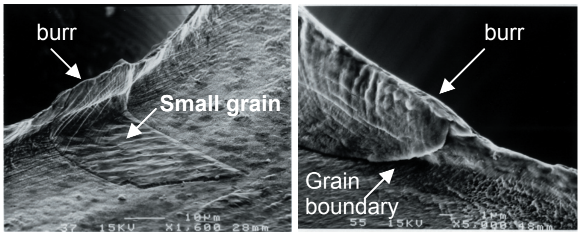
Further work by Schaller et al. [58] showed that when fabricating microgrooves in brass, burr formation can be drastically reduced by coating the surface with cyanacrylate.

Sugawara and Inagaki [59] investigated the effect of drill diameter and crystal structure on burr formation in microdrilling. They utilized both single crystal and polycrystalline iron with a thickness between 0.06 mm and 2.5 mm and high speed twist drills with diameters from 0.06 mm to 2.5 mm. In general they confirmed that burr size is reduced and cutting ability increased as drill size decreases.

Min et al. [53] found that grain orientation affected burr formation in drilling of polycrystalline copper, Figure 10. A single material may produce a ductile-like cutting mode in one grain and brittle-like cutting in another, indicating that favorable and non-favorable cutting orientations for good surface and edge condition exist as a function of crystallographic orientation. These observations demonstrate the importance of further research in this field.



(a) 10 mm/min, 7000 rpm (b) 5 mm/min, 6000 rpm



(c) 5 mm/min, 7000 rpm (d) 10 mm/min, 8000 rpm

Figure 10: Microdrilling burr formation (250 μm diameter); (a) burr within grain boundary, (b) burr across grain boundary, (c) burr over small grain, (d) grain boundary follows burr topology [53].

3 MODELING

One of difficulties in micromachining is the microscopic level of the phenomena. Hence, it is difficult to conduct experiments, and make in-process observations and measure results after the experiment. Moreover, the cutting process itself is very complicated involving elastic/plastic deformation and fracture with high strain rates and temperature and for which material properties vary during the process. Thus, analytical modeling is considered extremely difficult at the current level of understanding of material behavior. Most analytical modeling efforts are based on kinematics from empirical observation combined with classical cutting models at the macro level. The applicability and accuracy of these models are subject to many limitations.

Modeling based on numerical relationships, often accompanied by computer simulation, has become the tool of choice for many researchers. It is a good compliment to experimental approaches as it can overcome some of the limitations, if correctly done. It is not a perfect solution because it also involves many of the same assumptions as in analytical modeling. However, computer based models can offer a reasonable insight into certain verifiable trends or guidance on empirical research to assist further understanding of the process. Finite element modeling (FEM) has been a popular simulation technique but it has one critical limitation for micromachining. FEM is based on principles of continuum mechanics. Hence, material properties are defined as bulk material properties whereas, in reality, the material behaves discontinuously in many cases of micromachining. In most cases of isotropic micromachining, FEM can still be an attractive modeling method because the process can be reasonably treated in continuum space.

Since the molecular dynamic (MD) simulation technique is based on interatomic force calculations, it can accommodate micro-material characteristics as well as dislocations, crack propagations, specific cutting energy, etc. Hence, many researchers have turned to MD for micromachining studies. However, there are three major obstacles in MD modeling. The core part of MD requires good representation of interatomic forces among various combinations of atoms involved in cutting, referred to as a potential. Formulating a potential requires the equivalent of one good Ph.D. level study and thus very few potentials are available. Second, since MD calculates interatomic forces among all atoms within a certain boundary, intensive computational power is required. Therefore, many MD studies are limited to a very small space, such as at a nanometer or angstrom level. Third, MD analysis lacks a good representation of continuum behavior of material. Therefore, most MD simulations clearly state the boundary of application.

More recently, multi-scale modeling techniques combining FEM and MD have been proposed to overcome the disadvantages of each method and allow the coverage of a wider range of behavior.

Details on these approaches and examples of recent research are given below.

3.1 FEM

In the early stages of computer simulation of metal cutting, a FEM approach was not directly used to develop a model. Rather, it was used for intermediate steps to obtain certain values using semi-mechanistic or empirical models. Ueda et al. [34] proposed such an approach in order to analyze the material removal mechanisms in micromachining of ceramics. FEM was used only to calculate the J-integral around a crack in front of the cutting edge. The obtained value was then used to determine likelihood of fracture in micromachining. Using this approach, they were able to model ductile and brittle cutting modes and the results were used to maintain the process in the ductile mode.

Ueda and Manabe [60] modeled chip formation in micromachining of amorphous material using rigid-plastic FEM (RPFEM). Again, they used FEM only for further understanding of localized adiabatic deformation. The model was able to produce a lamellar structure of the chip formation, which was also observed during experimental machining using a SEM. The formation of lamellar structured chip was due to the periodical occurrence of a localized shear band and smooth chip formation, the frequency of which was proportional to the depth of cut.

Moriwaki et al. [61] developed a similar model using RPFEM for micro-orthogonal cutting of copper. They used a two-step FEM approach; first, the model obtains the deformed status of cutting and, second, then obtains specific values such as stress and strain which were used as input values to the thermal FE analysis combined with semi analytical formulations. The roundness of the tool edge was also taken into consideration in the model. The analysis showed that cutting ratio is decreased with an increase in the ratio of the tool edge radius to the depth of cut. It was also found that the temperature gradient in the workpiece increases in front of the cutting edge due to the material flow relative to the cutting tool. Similarly, Fleischer et al. [62] used experimental values to improve a FE model to predict cutting forces in micromachining.

The aforementioned FE modeling is primarily for isotropic micromachining where no crystallographic effects were considered. Chuzhoy et al. [63, 64] developed a FE model for micromachining of heterogeneous material, Figure 11. Their model was capable of describing the microstructure of multi phase materials and thus captured the microcutting mechanism in cast iron. Microcutting of multi phase materials exerts larger variations in the resulting chip shape and the cutting force than seen in cutting of a single phase material.

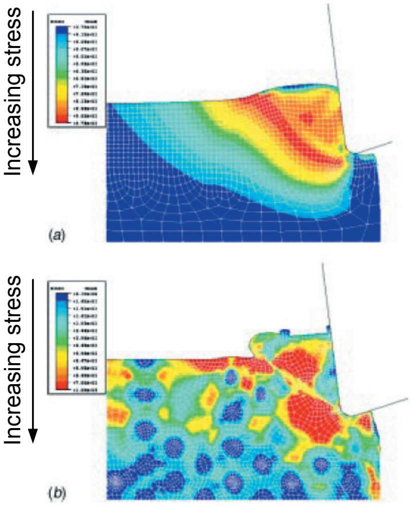
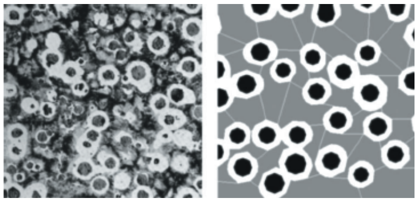
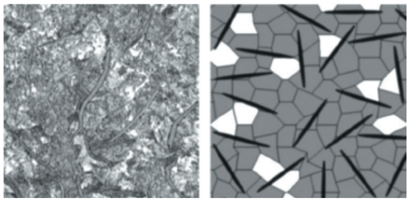


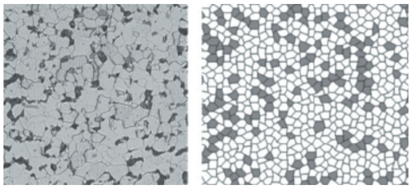
Figure 11: Computed equivalent stress for 125 μm depth of cut and 25 μm edge radius at t=0.00012 s with (a) ferritic workpiece, (b) ductile iron workpiece [63].



(a) ASTM A536 grade 80-55-06 .70% pearlite



(b) Gray iron



(c) AISI 1018 steel

Figure 12: Actual (left column) and simulated (right column) microstructures of different ferrous materials [65].

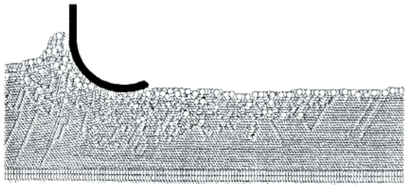
Park et al. [65] tried to calibrate the mechanistic cutting force through FEM simulation for ferrous materials including ductile and gray irons and carbon steels. Their model is primarily based on analysis of the microstructure of the work materials in their various phases, such as the graphite, ferrite, and pearlite grains seen in ductile iron, gray iron, and carbon steel microstructures. Their model was mainly used to calibrate a cutting force model, Figure 12.

3.2 MD

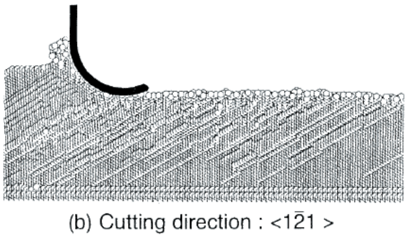
Research work on molecular dynamic simulation of cutting can be traced back to early 1990s. Most of the early researchers used copper as a work material because of its well established structure and potential function. A diamond was used as a cutting tool since it can be reasonably assumed to have a very sharp edge, needed at the MD level [27, 66-69].

The work of Inamura et al. [67, 70, 71] focused on a trial of molecular dynamics at an atomic level cutting simulation with a couple of potential functions. This computational study showed that MD is a possible modeling tool for the microcutting process. The simulation was able to correlate the intermittent drop of potential energy accumulated in the workpiece during cutting with the heat generation associated with plastic deformation of the workpiece and impulsive temperature rise on the tool rake face. In a simulation of cutting of polycrystalline copper, the plastic deformation first initiated at the grain boundaries and then propagated into neighboring grains in the direction of dislocation development. They also reported that the rate of energy dissipation in plastic deformation at this scale is larger than in conventional cutting and that a concentrated shear zone did not appear, contrary to what is normally observed in conventional cutting.

Shimada et al. [72] developed a MD model for understanding the chip removal mechanism in micromachining of copper with depths of cut down to 1nm. The model was able to continuously generate dislocations in front of the tool tip and produced chip morphology showing very good agreement with experimental results. In another work [73], they also investigated crystallographic orientation effects on plastic deformation on single crystal copper using MD simulation. Additionally, they found that the ultimate possible surface roughness was about 1 nm for both single crystal and polycrystalline copper materials assuming perfect cutting condition, Figure 13.



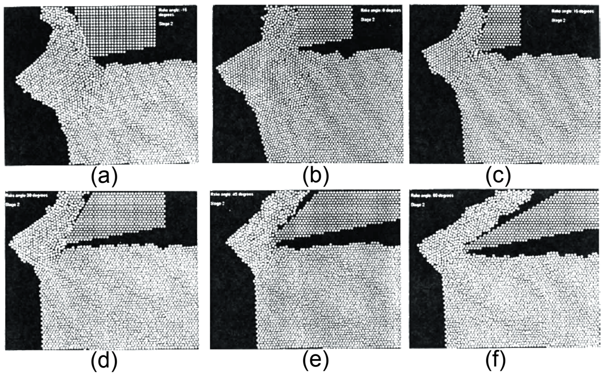
(a) Cutting direction : < $1\bar{1}0$ >



(b) Cutting direction : <$1\bar{2}1$ >

Figure 13: Deformation around the cutting edge in microcutting of single crystal copper [73].

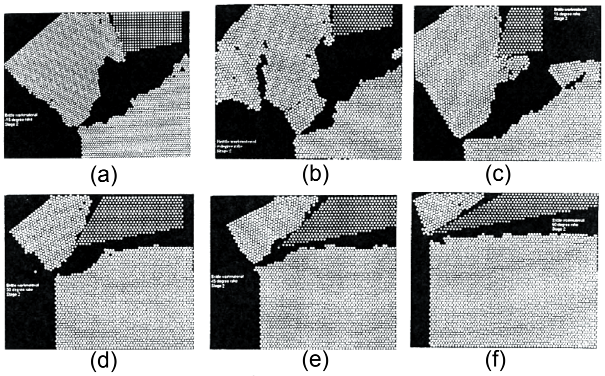
In general, MD simulation requires impressive computational power in order to model a cutting process. Hence, many MD models have been applied to two dimensional orthogonal cutting with a very small model size, or unrealistically high cutting speed. Komanduri et al. [74] proposed a new method called a length-restricted molecular dynamics (LRMD) simulation by fixing the length of the work material and shifting atoms along the cutting direction and applied it to nanometric cutting with realistic cutting speeds. They also studied the effect of tool geometry using several ratios of tool edge radius to the depth of cut with various parameters such as cutting force, specific energy, and subsurface damage [75] and further investigated the effect of crystal orientation and direction of cutting on single crystal aluminum and silicon [76-78]. They also applied MD simulation to exit failure and burr formation in ductile and brittle materials with a face centered cubic (FCC) structure. They successfully simulated burr formation on a ductile material and crack propagation in brittle material, Figure 14 and Figure 15 [79].



(a) (b) (c)

(d) (e) (f)

Figure 14: MD plots of the nanometric cutting process performed on a ductile work material with no elastic constraint at the exit for various tool rake angles (a) −15° (b) 0° (c) 15° (d) 30° (e) 45° and (f) 60° [79].



(a) (b) (c)

(d) (e) (f)

Figure 15: MD plots of the nanometric cutting process performed on a somewhat brittle work material with no elastic constraint at the exit for various tool rake angles (a) −15° (b) 0° (c) 15° (d) 30° (e) 45° and (f) 60° [79].

Komanduri et al. [80] also tried Monte Carlo simulation of nanometric cutting of a single crystal material. This method is only applicable to systems that are neither canonical nor microcanonical. Their model provided a reasonable estimation of the local temperature at the cutting zone. This model was based upon several other models previously developed.

Another typical assumption used in most MD simulations of nano or micro level cutting is that the tool is a rigid body and, thus, dynamic change of tool geometry due to wear during cutting can be ignored. Cheng et al. [81, 82] used MD simulation to model the diamond tool as a deformable body. Their model includes heat generation due to cutting and provided analysis of the relationship between the temperature and sublimation energy of the diamond atoms and silicon atoms. The simulation results were compared with experiments using the diamond tip of an atomic force microscope (AFM) on a single crystal silicon plate. The model was able to produce thermo-chemical wear of the diamond tip.

Rentsch and Inasaki [83] and Fang et al. [84] investigated surface integrity of nanomachining and nanoindentation on brittle materials using a conventional MD technique.

3.3 Multiscale modeling

Inamura et al. [70] used multiscale modeling techniques to cover both atomic and continuum levels of simulation. Using MD, they calculated displacements of interacting atoms in cutting and then transferred into a point in the continuum by weighted mean values of the surrounding atoms to obtain continuum property values such as stress and strain.

In other research [85], they found that a very complicated stress state in the workpiece material including a concentrated compressive and shear strain in the primary shear zone, tensile strain along the rake face, and no shear stress inside the workpiece as part of the primary shear zone, exists. They attributed this partially to buckling deformation but left a detailed explanation for future work.

3.4 Mechanistic modeling

Most of the mechanistic modeling of cutting is based on Merchant's assumption that the tool edge is sharp [86-89]. Kim and Kim [90] proposed an orthogonal cutting model of micromachining with a round edged tool to study sliding along the clearance face of the tool due to elastic recovery and plowing caused by the relatively large edge radius of the tool. They found that the effect of the tool clearance face contributes significantly to the overall cutting force, Figure 16.

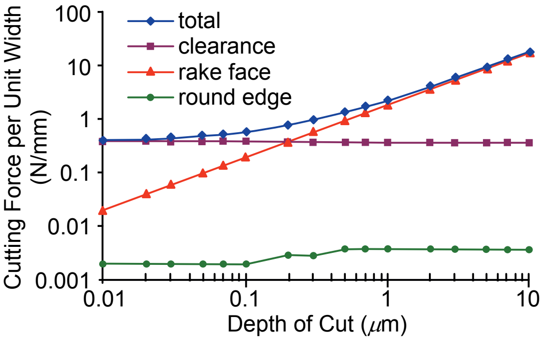


Figure 16: Components of cutting force per unit width in round edge cutting model (friction coefficient: 0.3, rake angle: 0°, workpiece: copper (CDA110), edge radius of the tool: 0.01 μm) [90].

In an effort to better understand cutting forces in micro-end milling applications, Bao and Tansel [91-93] developed an analytical model to predict cutting forces. The model is based on geometrical calculation of the chip load by considering the trajectory of the micro-tool tip. The cutting force was calculated by Tlusty and MacNeil's model [94] with previously calculated chip thickness. The model considers many parameters including process conditions, tool geometry, and workpiece material. Their model predicted cutting force within 10% of comparable experimental values and accounted for tool run-out and wear.

Vogler et al. [18, 19, 95] developed a micro-end milling model for various microstructures of workpiece material. The model used tool and surface profile computation and finite element simulation for determination of the minimum chip thickness. With this model, they were able to predict interrupted chip formation over the phase boundaries consistent with experimental results for ductile iron. A slip-line cutting force model for depths of cut larger than minimum chip thickness and an elastic deformation force model for smaller depths of cut were employed assisted by FEM analysis. This model predicted the cutting force for the primary metallurgical phases, ferrite and pearlite, of multiphase ductile iron workpieces and showed good agreement with experimental values.

Kim et al. [96] proposed modeling chip formation and cutting force in a microscale milling process accounting for the coupled minimum chip thickness and edge radius effects. Interestingly, the model predicts that the micromilling tool may rotate without cutting when the feed per tooth is smaller than the minimum chip thickness and that the periodicity of cutting forces is a function of the minimum chip thickness, feed per tooth, and position angle. The model can provide an upper limit of feed per tooth for a given tool diameter, which can be used as a basis for process parameter selection.

Finally, Joshi and Melkote [97] developed a model focused on the material removal mechanism at the micro level. Their model was based on a strain gradient theory whereby the material strength is a function of the strain gradient. The primary deformation zone (PDZ) was modeled and material strength was evaluated as a function of material length scale governing the size effect. The model was able to predict a lower bound value of specific shear energy.

4 WORKPIECE AND DESIGN ISSUES

4.1 Micromolding

The microturning operation, specially single point diamond turning [98], is commonly used for generating small parts with 3D convex shapes. For 3D concave shapes, microdrilling and micromilling are commonly used. For mass production of microparts, micromachining is not suitable due to low productivity. However, micromachining is key to provide proper tooling for other micro-mass production technology such as micromolding, microforming, and micro-die casting. The quality of products and reliability of these processes is highly dependant on tooling manufactured primarily by micromachining.

As in conventional molding, the precision of the mold is one of the most important factors in micromolding. Mold precision represents the quality of the molded products. As a result, diamond machining is an excellent candidate for micro-mold fabrication. Mold life is another important factor in micromolding since that influences manufacturing costs and part quality. The affinity of diamond to ferrous material causes serious problems in machining the tool steels or hard ferrous materials that are generally preferred for the mold. Hence, various efforts have been made to avoid such problems, for example:

- cutting in a carbon saturated atmosphere [99]
- cooling the cutting process [100]
- modifying the chemical composition of the work material [101]
- superimposing the tool motion with ultrasonic vibration during the cutting process [102, 103].

These approaches have been partially successful in minimizing wear of the diamond tool but, with the exception of the ultrasonic vibration assisted cutting, the applicability to industry is questionable [16].

Schaller et al. [104, 105] have successfully fabricated a micromold of martensitic steel by micromachining with tungsten carbide tools to create features of 200 μm to 330 μm in depth and 220 μm to 420 μm in width. The machining was completed prior to hardening the steel, and then electrochemically polished to remove any remaining burrs. Completion of this type of mold is important because it will allow for long term production of a wide range of plastic as well as metal and ceramic filled polymers.

Freidrich and Vasile [106] were able to produce trench features 8 μm wide and 62 μm deep for an aspect ratio of nearly 8, over a length of 8 mm, Figure 17. This aspect ratio is good enough for most micromolding applications including X-ray masks.

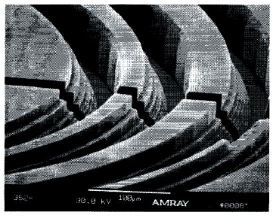


Figure 17: Portion of micromilled trenches with stepped and straight walls (scale bar = 100 μm) [106].

Micromachining has been successfully employed to fabricate multi-level mold inserts for micromolding of a micro-valve system by Fahrenberg et al. [107]. They combined micromachining with deep etch X-ray lithography to create the micromold with features 60 μm in height and 50 μm wide. This study showed the possibility of stacking several molds for high aspect ratio parts.

Another effort in micro-mold fabrication combines the use of other manufacturing processes with micromachining. Fleischer et al. [108, 109] surveyed potential fabrication processes and listed their characteristics and potential for combining. They found that a combination of micromilling, micro-EDM, and laser processes compensates for inherent individual weaknesses and benefits from the strengths of each process.

Bissacco et al. [110] investigated a wide range of processing methods for mold fabrication. Figure 18 illustrates the process chain for micro-injection molding for micro-fluidic systems. MEMS technology provides high precision processing capabilities but is very limited in achievable shapes allowing only molds in 2.5-D and those with a number of stackable layers.

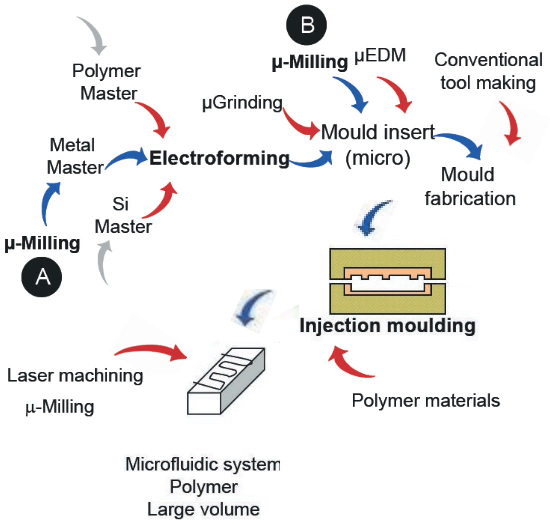


Figure 18: Process chain of micro-injection molding [110].

4.2 Creation of micropattern and microstructure

One of the more interesting applications of micromachining is in micropattern generation either on flat or curved surfaces. These patterns can work as reflectors, abrasives, and other functions. Traffic signs, Fresnel lenses, and possible CMP (chemical mechanical planarization) pad surfaces are typical examples. Various microgrooves can be created by feeding a rotating cutting tool along one direction relative to the workpiece, as illustrated in Figure 19 [111].

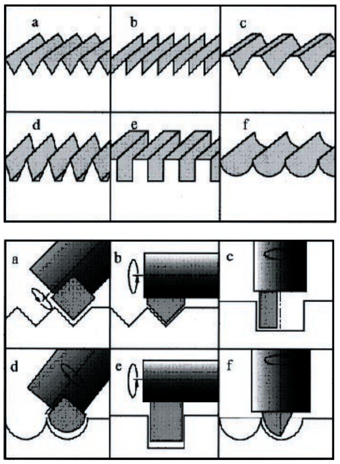


Figure 19: Various microgrooves and their fabrication by rotational cutting tools [111].

Changing the angle and depth of groove, six different trapezoid microgrooves were created on a brass surface, as shown in Figure 20. The grooving was done with cutting conditions of 50 mm/min feed rate, 13 m/sec cutting speed, and 1 μm depth of cut for finishing and 5 µm for rough cutting. A diamond tool was used to create the trapezoidal microgrooves. With respect to these grooves, it was found that the machined surfaces are very smooth with sharp edges similar to more conventional V-shaped microgrooves. Trapezoidal microgrooves were successfully applied to bond two small parts without adhesives.

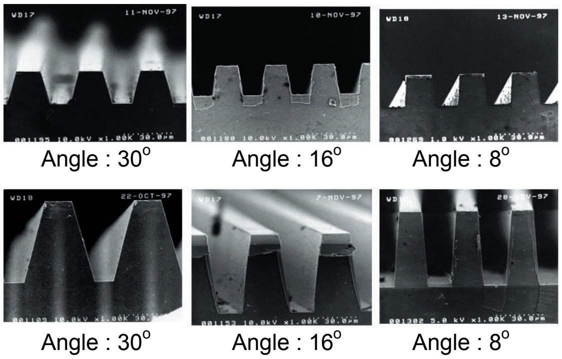

Angle : 30° Angle : 16° Angle : 8°
Angle : 30° Angle : 16° Angle : 8°

Figure 20: Various kinds of trapezoid microgrooves (first row: 20 μm, second row: 50 μm depth) [unpublished data from Y. Takeuchi].

Figure 21 shows micro-lenses on a silicon plate fabricated by rotating a circular arc diamond cutting edge and feeding the tool along an axis perpendicular to the silicon plate. The machining method corresponds to plunge cutting by a rotational tool. A suitable choice of cutting conditions allows for cutting of brittle materials [112].

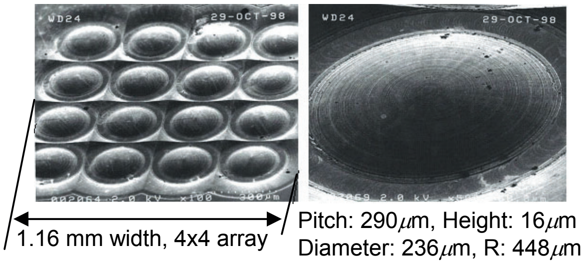


Figure 21: Micro-lens array of silicon [112].

As for multiple-focus micro-Fresnel lenses, it is difficult to produce those using conventional ultraprecision lathes since the configuration is not rotationally symmetric. The circular grooves are cut at each lens area, and a number of cutting start and end points exist on the same lens plate. Rotational cutting tools are not able to machine these kinds of microgrooves since the rotational tool, due to the rotational radius of the tool, yields long slopes at the cutting start and end points. Thus, two- and three-focus micro-Fresnel lenses have been manufactured utilizing 5-axis ultraprecision machining centers and non-rotational diamond tools. In non-rotational cutting tools, the cutting speed is equal to the feed rate. Although cutting speed is too low compared to rotational tools, a suitable choice of cutting condition allows parts to be cut in this manner.

Figure 22 shows an example of a three-focus micro-Fresnel lens, whose diameter is designed to be 2 mm machined using this technique. From the experimental results, it was found that this method, using a non-rotational cutting tool, is effective for producing optical devices with microgrooves on the order of about 0.1 μm deep [113].

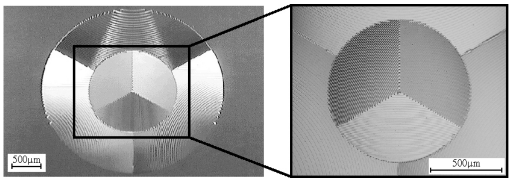


Figure 22: Machined 3-focus micro-Fresnel lens [113].

Maeda et al. [114, 115] created ultraprecision microgrooves for optical devices such as holographic optical elements using non-rotational cutting tools. V-shaped diamond tools were used to determine an optimal cutting speed by observing burr formation and chip shape. They proposed two cutting methods to create flat end microgrooves, seen in Figure 23 and Figure 24.

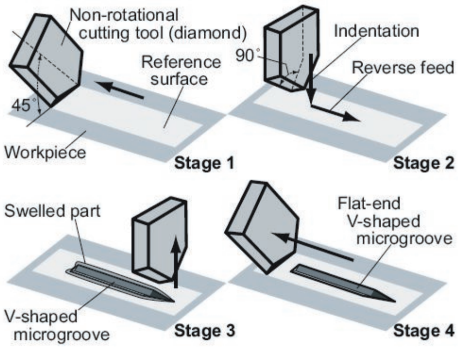
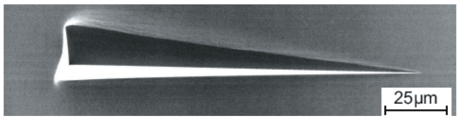
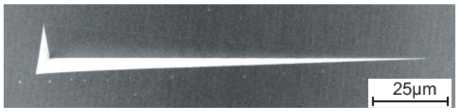


Figure 23: Flat-end microgroove machining with reverse feed method [115].



(a) After indentation



(b) After removal of swelled part

Figure 24: Machined flat-end microgroove using reverse feed method [115].

4.3 Creation of 3-Dimensional Shape

One of the advantages of mechanical machining is full 3-D fabrication capability. A number of researchers have tried to create very complicated shapes to test the capabilities of their machine tools and control algorithms at the micro level. Most found that the capabilities of 'conventional' machines are generally applicable with minor modifications. However, the biggest challenge lies in the fabrication of the proper tool geometry for creating various 3-D features.

Takeuchi et al. [116] designed a pseudo diamond ball-end mill. The tool is composed of a half-cut single crystal diamond offset from the rotational axis by a specific amount so that the tool can avoid zero cutting speed at any location on the tool and to enhance chip removal. They were able to create a very complicated small shape from gold using 36 hours of 5-axis control machining, Figure 25 [117].

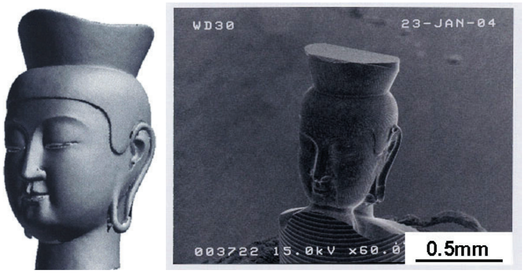


Figure 25: Creation of a small statue (Mirokubosatsu) by 5-axis control machining [117].

4.4 Ultrasonic vibration assisted micromachining

At the micromachining level, inherent material property characteristics make it difficult to achieve the desired part quality. Hard and brittle materials such as silicon, glass, quartz crystal and ceramic are increasingly used in MEMS devices and reliable methods to process these materials are necessary. One of the efforts directed towards machining these difficult to cut materials is using an ultrasonic vibration cutting method at a frequency range of 20-100 kHz with an amplitude of 25 μm or less. Yu et al. [118] tried microcutting with ultrasonic vibration on some of these materials and they found that tool wear was a significant problem. They applied a uniform wear method developed for micro-electrical discharge machining and experimented with various tool path planning strategies.

In precision or micromachining, diamond tools are usually the preferred cutting tools. However, diamond's affinity for ferrous metals causes severe tool wear. In order to overcome this problem, Kumabe [119] applied an ultrasonic vibration cutting method in diamond micromachining of ferrous material. This method reduced tool wear but sacrificed some degree of surface quality. Later, Moriwaki and Shamoto [102, 103] developed an ultrasonic elliptical vibration cutting method which showed improved cutting performance, Figure 26.

Although not vibration based, another approach to reducing wear of the diamond tool on ferrous materials is cryogenic machining. Evans [100] built a special machining setup with constrained liquid nitrogen flows and achieved surface roughness better than 25 nm Ra on 400 series stainless steel work material.

Ohnishi and Onikura [120, 121] applied ordinary ultrasonic vibration to microdrilling on an inclined work surface. The slippage of the drill tip at engagement on an inclined workpiece surface and large partial burrs on the hole exit surface have been difficult problems in industry where inclined surface drilling is commonly required in many applications. In microdrilling, these problems are more serious since tool stiffness is generally much lower and run-out more significant than in conventional drilling. The researchers added a 40 kHz ultrasonic vibration with a 3.5 μm amplitude to the drill during microdrilling of a duralumin workpiece and observed reduced cutting forces and improved cutting accuracy in terms of hole diameter, roundness, and the center location. Also, thinner chips generated by ultrasonic vibration enhanced chip removal during cutting leading to reduced tendency of tool breakage.

Egashira and Mizutani [122] tried ultrasonic vibration drilling (40 kHz and 0.8 μm amplitude) to make a 10 μm diameter hole in glass materials. To avoid either fracture or crack formation around the rim of hole, drilling was conducted in the ductile regime using a depth of cut 0.05 μm.

Egashira and Masuzawa [123] conducted similar microdrilling tests using ultrasonic vibration but the vibration was applied to the workpiece instead of the tool. Quartz glass work material and a sintered diamond tool were used for the tests and they succeeded in drilling holes as small as 5 μm diameter.

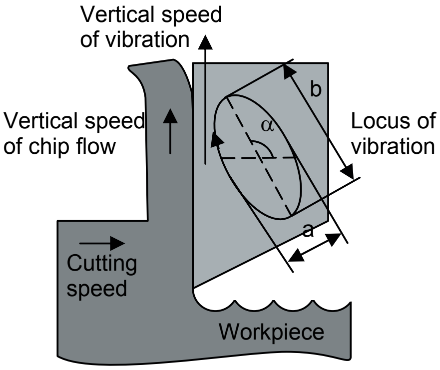


Figure 26: Principle of elliptical vibration cutting [103].

5 MACHINES, TOOLS, AND SYSTEMS FOR MICROMACHINING

Most of the experimental research for micromachining has been conducted on either conventional precision machine tools or specialized machine tools built by researchers. Conventional precision machine tools have been greatly improved with respect to motion accuracy, stiffness, and capability. These machines are specially useful for micromachining of large size parts such as optical lenses. In-house machine tools are generally very small in size and have functions limited to specific designed experiments. These special built machines often offer advantages over conventional machine tools in terms of energy and space savings, simplicity of operation, and ease of reconfiguration. Over the last two decades, knowledge has been accumulated for design of ultraprecision machine tools for micromachining, resulting in stringent requirements as follows:

- Thermal stability -> compact size, enclosure for temperature controlled air circulation
- Precise spindle bearings and linear guides: hydrostatic air bearing/guide or hydrostatic oil bearing /guide: air flow from turbulent to lamellar so that forced vibration of the machine parts induced by the turbulent air flow is eliminated.
- High resolution of linear and rotary motions: special motors and encoders, typically 64 M pulses/revolution for encoder, 1nm for linear motion, 1/100,000 deg for rotary motion.

Masuzawa and Tönshoff [3] summarized various system configurations for micromachines considering translation of coordinate systems for small size tools, Figure 27. Conventional machine tools use configuration B but that is generally not suitable for small tools due to tool offset and tilting. Configuration A is for on-the-machine tool making. Micro-tools are fabricated on the same machine for micromachining and the highest accuracy can be achieved. But this is not suitable for mass manufacturing where productivity is the key issue. Fujino et al. [124] pointed out that setting tools in the right position on the machine and correct location/orientation relative to the workpiece is very critical in achieving the desired machining accuracy and part quality. Langen et al. [125] further explored this configuration to an on-the-machine assembly concept. Configuration C treats the tool and the spindle as a set and thus increases the productivity. But this configuration requires extra spindles for various tool sets and has potential for positioning error.

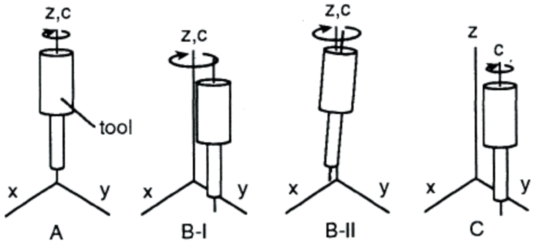


Figure 27: Coordinate relationship in tool making and machining [3].

5.1 State of the art of ultra precision machine tools

Early development of ultra precision machine tools was largely geared towards the machining of large-scale optical devices [126, 127]. Precision diamond turning machines are a typical example.

In recent years, multi-axis control ultraprecision machining centers with varying degrees of freedom are commercially available. They are used to produce small workpieces with complex geometries and microscale patterns and texture such as molds and dies for CD pickup lenses, contact lenses, Fresnel lenses, etc. driven by increasing market trends in consumer products. The efficient fabrication of these components is a matter of concern and interest for miniaturization and integration of consumer products along with the rapid development of micro and optical electronics [128, 129].

Currently available multi-axis controlled ultraprecision machining centers are in fact a progressive developmental form of traditional machine tools. These ultraprecision machine tools can be classified into several types, based on the type of positioning mechanism used. Mechanisms include a screw-based system driven by a rotary motor, linear motor drives, and a ball screw or aero-/hydrostatic screw-based system. With respect to the table slide mechanism, two common configurations include the roller slide system or aero-/hydrostatic slides in order to feed the table with low friction and high straightness. Bearings for rotational elements are similar to those found in the table slide mechanism.

Furukawa et al. [130] built a machine using alumina-based ceramics for the structural members because of their high rigidity and thermal reliability and surface-restricted type aerostatic slideways to avoid friction. Takeuchi et al. [131] developed a 5-axis ultraprecision milling machine using non-friction servomechanisms for the creation of 3D microparts with translational resolution of 1 nm, rotational resolution of 0.00001 degree, and slideway straightness of about 10 nm/200mm. Figure 28 shows a commercial 5-axis ultraprecision machining center employing aerostatic guideways and coreless linear motors to provide non-contact, high resolution drive mechanisms achieving 1nm motion accuracy. To ensure thermal stability, alumina ceramics were used for structural components [132].

Figure 28: Commercial 5-axis control ultraprecision machining center [132].

Currently, the machining lead time is considerable for micromachining (particularly for complex features) and fabrication of individual components may not be economically viable. However, the micromachining process is viable for fabrication of tooling (molds, dies, etc.) and as a parallel process with other microfabrication technologies, thus making a contribution to the effective fabrication of products and components of increasing miniaturization and integration.

An elliptical vibration milling algorithm and machine was developed by Moriwaki and Shamoto [102, 103, 133-137] in order to achieve additional machining precision over that of other ultraprecision machines. The elliptical vibration milling machine used a double spindle mechanism to generate circular vibratory motion of the cutting tool, which resulted in improved surface finish, even with a diamond tool on ferrous materials.

Hara et al. [138] developed a high stiffness microcutting machine with dynamic response up to 2 kHz, stiffness of 80 N/μm, and in-feed resolution of 5 nm. The contact between the tool and the workpiece was detected through a piezoelectric contact sensor with an accuracy of ±0.1 μm.

Various concepts have been tried in pursuit of micromachine tool development. Subrahmanian and Ehmann [139] developed a multi-axis meso-scale machine tool using an air-turbine-based dental drill spindle (320,000 rpm), a piezoelectric actuator positioning system, and a two-axis micro-pulse system controller. Werkmeister and Slocum [140] developed a mesoscale mill using wire capstan drives, ball-screw splines, and an air bearing spindle with an integral Z-axis.

5.2 Micro-tools

Commercially-available micro-drills are typically on the order of 50 μm in diameter, and have a similar twist geometry to that of conventional drills. Flat drills with simplified geometries are more common for diameters smaller than 50 μm.

Fabrication of micro-tools is another challenge in micromachining. Imprecise geometry and the irregularity of tools often negate the advantages of ultra precision process control, state of the art machine tools, and ultra fine tuning of process parameters. Figure 29 a-c shows the tool geometry deviation with respect to the size of the tool; as the tool size decreases from 2 mm to 0.2 mm, the deviation of the given tool geometry from the tool design increases. Also, scaling effects can play a significant role in process physics, which are closely related to the cutting mechanism, caused by a change in tool geometry during cutting. Figure 29 d-f demonstrate tool wear occurring during the micromilling of hardened steel as a function of the engagement length and tool diameter [47].

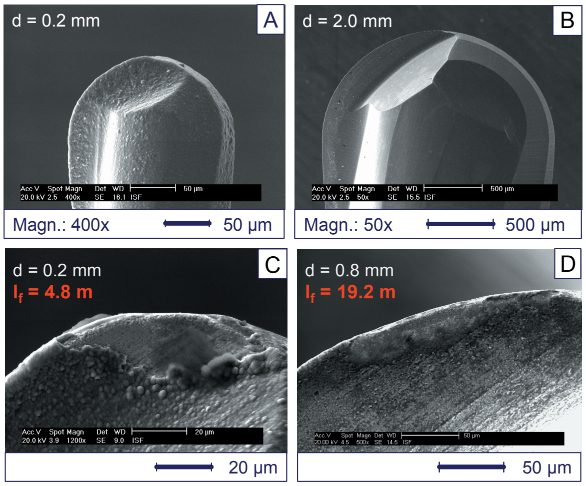


Figure 29: Scaling effect on tool geometry and wear (work material: 40CrMnMo7, 50 HRC, cutting speed: V_c = 200/100 m/min, depth / width of cut: $a_p = a_e = 0.04 \times d$, feed: $f_z = 0.01 \times d$, number of teeth: 2, down milling, tool material: cemented carbide with TiAlN coating) [47].

Due to its hardness, single crystal diamond is the preferred tool material for microcutting. Diamond cutting tools were used in most of the early micromachining research due to their outstanding hardness (for wear resistance) and ease by which a sharp cutting edge could be generated through grinding. However, as diamond has a very high affinity to iron, microcutting is mostly limited to the machining of non-ferrous materials such as brass, aluminum, copper, and nickel. Hence, micromachining tests have been limited to non-ferrous materials [141, 142] except as noted earlier in the paper and in [16, 143-146].

The focused ion beam process has been used to fabricate micro-tools. Using this method, Vasile et al. [106, 147] fabricated 25 μm diameter steel milling tools and Adams et al. [148] fabricated 13 μm diameter microgrooving and microthreading cutting tools of high speed steel and tungsten carbide. Adams et al. [149] also fabricated micro-end mills having less than 25 μm diameter by sputtering the same materials. They used a focused gallium ion beam to generate a number of cutting edges and tool end clearance and machined trenches with widths nearly the same as the diameter of the tool. They were able to achieve surface finishes of 250 nm (Ra).

Aoki and Takahashi [150] developed a 25 μm diameter thin-wire cut tool of tungsten carbide by cutting an oblique face into the shank. Egashira and Mizutani [151] fabricated micro-ball end mills with a radius of 10 μm using electrical discharge machining (EDM). They also used a wire electrodischarge grinding process (WEDG) to make a micro-drill with a D-shaped cross section and cutting edge radius of 0.5 μm. They used this to study ductile regime drilling and optimal tool geometry for holes with aspect ratios of 4 or higher [37].

Grinding is also used for fabricating micro-tools by many researchers [58, 106, 152, 153]. However, the grinding process has a limitation on tool geometry and is usable only to 65 μm diameter [58]. Onikura et al. [154] proposed ultrasonic vibration grinding to overcome this limitation in fabricating micro-cylindrical tools and flat micro-drills of ultra fine grain cemented carbides. By adding ultrasonic vibration to the grinding process, they were able to produce high aspect ratio tools such as a 11 μm diameter with a length of 160 μm. Ohmori et al. [155] not only focused on fabricating micro-tools, but also investigated the surface quality of the tools since the surface quality is closely related to machining performance, part quality, and tool rupture strength. They developed a machine tool fabrication process utilizing ELID grinding technology to fabricate various cross sectional shapes of the tool with high surface quality, Figure 30.

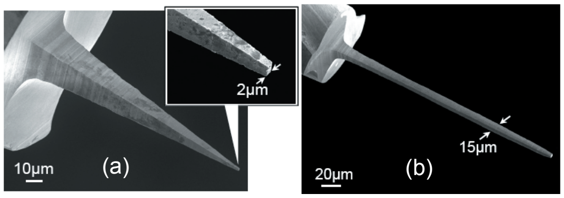


Figure 30: Overviews of produced micro-tools under optimum machining conditions: (a) Ultra precise tool (b) Extremely large aspect ratio micro-tool [155].

Uhlmann and Schauer [156] proposed a new parametric tool design for micro-end mills by dynamic load and strain analysis using FEM analysis. Under micromachining, micro-tools experience a different loading situation from that seen in conventional machining. The optimized tool has a tapered shape with a reduced diameter at the tool shank to avoid any contact with workpiece during cutting.

Tool life in micromachining is difficult to characterize, especially when feed-per-tooth values are large. Tansel, et al. [157, 158] attempted to study the relationship between wear and stress on the tool shank. They hypothesized that the cutting forces on micro-end mills are similar to those of conventional machining, but that the wear mechanisms are different. The first mechanism proposed is chip clogging. When clogging occurs, cutting forces and stresses increase rapidly, and can cause tool breakage in only a few rotations. This mechanism is very unpredictable and happens extremely rapidly. After the tool begins to wear, fatigue related breakage becomes an issue due to increased cutting force and stress on the tool shaft. The last mechanism identified is excessive stress breakage. The concept is that the cutting edge loses its sharpness and becomes dull. The tool is now unable to remove enough material to create satisfactory space for the central section of the shaft of the tool, and the tool begins to deflect. This deflection paired with a constant feed creates an excessive stress that leads to tool failure. Cutting force variations in micromachining increased constantly during machining due to increasing tool wear and can be used as a tool wear indicator.

Chen and Ehmann [159] did wear studies on microdrilling of copper-epoxy stacks typically found in printed circuit board applications. A drill life model was developed based on the independent parameters: feed, spindle speed, aspect ratio, and copper-to-epoxy ratio. It was found that increases in any of these parameters produce a reduction in tool life. The least-dependent factor is the copper-to-epoxy ratio (board density).

Sugano et al. [160] studied wear of single crystal diamond tools and their effects on the microroughness and the residual stress of surface layers under various machining conditions. They found that wear of the diamond tool has less influence on microroughness. Fang et al. [161] investigated relationships between tool geometry and tool life (focusing on tool breakage) in micromilling using FEM analysis and concluded that tapered tool design is optimal for longer tool life and performance as did Uhlmann and Schauer's study [156].

Godlinski et al [162] tried to minimize the tool wear by optimizing tool material and its microstructure. They used a two-step sintering process on a very fine alumina powder to avoid inter-granular fracture. This tool exhibited stronger wear resistance. Gaebler et al. [163] tried coating spiral micro-drills, two flute end mills and abrasive pencils with CVD diamond to improve tool wear and performance.

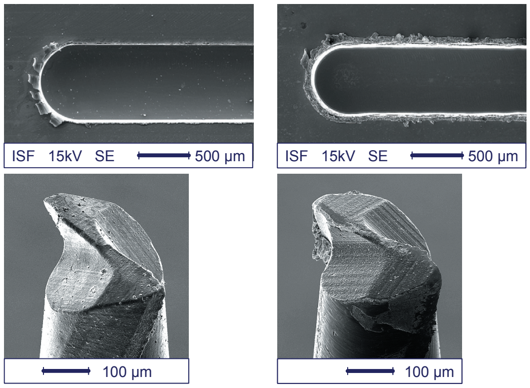
In general, micro-tools are used with high rotational speed, which may cause vibration problems. Huang [164] investigated the dynamic characteristics of the microdrilling process and found that the natural frequency of a micro-drill decreases as the thrust force increases. Also, stiffness of the micro-tool is important when fabricating high precision parts. Some studies [164-169] conducted tests on bending stiffness of micro-drills and proposed multi-step shaped drills as a result.

Run-out is another issue which has a larger impact in micromachining. Due to the low strength of micro-tools, machining must be performed on a machine with air bearing stages and spindle and closed loop position and speed control. Furthermore vibration must be minimized and feed rate must be controlled in a smooth and continuous manner. Tool run-out needs to be minimized. Even with a precision tool shank and collets, this interface can lead to undesirable radial run-out. Friedrich et al. [152, 170] were able to minimize this by utilizing a 4-point V-block bearing. Additional run-out was removed by making manual adjustments to the tool in the collet using a video microscope. Adjustments continue until radial run-out can no longer be seen. They found the remaining run-out to be on the order of 3-5 μm.

5.3 Cutting fluid

A typical flood supply of lubrication is generally not suitable for micromachining. First, the flow pressure of lubricants may influence cutting tool behavior. Second, even with negligible flow rate or proper control of flow rate, removal of excess working fluid after micromachining is challenging. Hence, special care is needed in lubricating, cooling, and transporting chips and debris during micromachining.

Figure 31 shows surface and edge quality under two different lubrication conditions: (a) minimum quantity lubrication (MQL) and (b) dry. Burrs form only at the end of the trench under MQL while a burr is present along the entire trench length under dry conditions. The surface quality of the side walls (the second row in the figure) is much better and chip adhesion on the tool surface is much lower under MQL conditions. Obviously, MQL performs much better in micro-end milling on NiTi materials [47].



(a) MQL (b) Dry

Figure 31: Micro-end milling experiments under MQL and dry (work material: NiTi shape memory alloy, cutting speed: V_c = 33 m/min, depth of cut: a_p = 10 µm, width of cut: a_e = 40 µm, feed: f_z = 12 µm, micro-end mill: cemented carbide with TiAlN coating, d=400 µm) [47].

Recently, several unconventional cutting fluids have been tried in micromachining. Dry ice (CO_2) shows some promise on micromachining of NiTi materials, Figure 32. The proper combination of nozzle distance, supply pressure and supply method (continuous and intermittent) is under investigation for optimal process results.

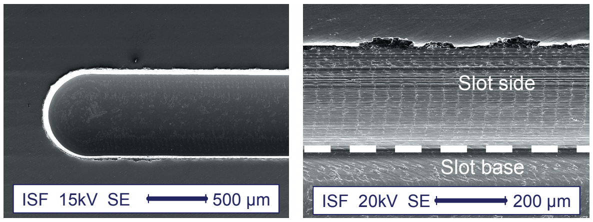


Figure 32: Micro-end milling under dry ice supply (work material: NiTi shape memory alloy, cutting speed: V_c = 19 m/min, depth of cut: a_p = 10 µm, width of cut: a_e = 10 µm, feed: f_z = 20 µm, micro-end mill: cemented carbide with TiAlN coating, d=400 µm, nozzle distance: 80 mm, intermittent supply of dry ice) [47].

Bissacco et al. [55] investigated the effect of working fluid on the accuracy of micromachining. Commercially available ultraprecision machine tools have a position resolution up to 1 nm with high speed spindles up to 100,000 rpm, but their practical accuracy decreases when thermal deformation is considered. At these levels, a small offset caused by thermal deformation may contribute to significant errors. Axial depth of cut can be significantly offset by thermal expansion of a high speed spindle and/or machine tool column. The temperature difference between the cutting fluid and spindle is also a source of error.

5.4 Microfactories

In general, micromachining is performed on precision machine tools with conventional dimensions. However, the work size and the required power for processing are relatively much smaller for micromachining. Downsizing the machine tool itself has been pursued by several machine tool builders and researchers in order to achieve economic benefits such as structural cost savings, shop floor space savings, energy reduction and performance benefits including reduction of thermal deformation, enhancement of static rigidity and dynamic stability as well [171, 172].

One unique effort is to build a microfactory system where one or several machine tools are small enough to be placed on the desktop. In late 1980s, Japanese researchers started fabricating microfactory prototypes, and the first realization of the concept was a microlathe smaller than a human palm with 1.5W spindle motor [173], followed by more powerful and precise desktop and portable machines [5, 174-177].

Gaugel et al. [178, 179] built flexible micromachines utilizing a modular concept. The machine configuration can be easily changed depending on the process required for microparts production. It adopted the “plug-in” concept (as found in the computer industry) to reconfigure machine modules and their corresponding control algorithm. The overall system is referred to as the ‘Advanced Modular Microproduction System (AMMS)’.

Codourey et al. built a desktop clean room for a microfactory which requires a clean working environment [180] and a centralized control system for the microfactory which consists of several modules [181]. Other researchers have also tried microfactories [182-184].

5.5 Machine components and controls

In order to achieve high precision and quality, development of machine tool components with suitable control algorithms as well as an understanding of process physics is needed. Precision positioning systems, a high speed spindle, and fixturing and handling devices are most important for the successful micromachine. A number of researchers have focused on this.

Otsuka et al. [185, 186] developed an ultra precision positioning system using a stepper motor and ball screw with 1 nm positional resolution with piezoelectric actuators. Holmes et al [187] developed a magnetic-bearing motion control stage with 0.1 nm positional resolution. Kempf and Kobayashi [188] employed a discrete-time tracking controller for a precision positioning table actuated by direct drive motors. And Mizumoto et al. [189] developed a tri-mode ultraprecision positioning system using twist-roller drive and aerostatic guideway with active inherent restrictor. This device achieved 25 pm positioning resolution. Yagyu et al. [190] designed an adaptive control system architecture for multiple micromachines.

Micromachining requires very high speed spindle speeds due to small tool diameters and thus the dynamic characteristics of the spindle dominate machining quality. Small deviations in the spindle may result in large run-out given the poor stiffness of micro-tools. Noguchi et al. [191] developed a measurement technique to monitor high speed spindle error and Ohishi and Matsuzaki [192] investigated thermal deformation of spindle units with aerostatic bearings and found that axial thermal deformation is proportional to the spindle speed. Yokoyama [193] measured the deformation of precision air-spindles in diametrical expansion and axial contraction due to the centrifugal force during spindle rotation.

Hargrove and Kusiak [194] surveyed available fixture design methodology and projected the future direction of fixture developments. They concluded that integration of a CAE system to fixture design should be the key issue because of its effectiveness in improving parts handling and precision positioning. Qiao and Bu [195] proposed vacuum chucks to fix small parts with control of suction force which may damage microparts.

Zesch et al. [196] designed a micropart handling system. The specially designed vacuum gripping tool consists of a glass pipette and a computer controlled vacuum supply and is capable of picking and placing 50-300 micron sized metallic and nonmetallic particles. Codourey et al. [197] also developed similar tool integrated into microfactory under clean room environment. Bellouard et al. [198] developed an SMA based microgripper. Sato et al. [199] developed a micro-object handling system composed of a right-left handed robot, stereo microscope and force sensor. Another system they developed utilized adhesive force through a needlelike tool. The adhesive force was mainly due to the electrostatic force between the tool and microparts [200]. This is still an area of active research.

5.6 Metrology in Micromachining

A major advantage of micromachining is its ability to fabricate increasingly smaller features reliably at very high tolerances. In-situ monitoring systems that can be used to characterize, control, and improve the fabrication of these smaller features are therefore needed to meet increasing demands in precision and quality. Sensor-based monitoring yields valuable information about the micromachining process that can serve the dual purpose of process control and quality monitoring, and will ultimately be the part of any fully-automated manufacturing environment. However, a high degree of confidence and reliability in characterizing the manufacturing process is required for any sensor to be utilized as a monitoring tool.

In material removal processes at the microscale, the undeformed chip thickness can be on the order of a few microns or less, and can approach the nanoscale in some cases. At these length scales, the surface, subsurface, and edge condition of machined features and the fundamental mechanism for chip formation are much more intimately affected by the material properties and microstructure of the workpiece material, such as ductile/brittle behavior, crystallographic orientation of the material at the tool/chip interface, and microtopographical features such as voids, secondary phases, and interstitial particulates [201, 202]. Characterizing the surface, subsurface, and edge condition of machined features at this fine scale, as well as tracking relevant process parameters such as material removal rate (MRR), tool contact/cycle time, and state of tool condition (wheel loading in grinding, tool wear in machining, for instance) are of increasing importance for monitoring, evaluating, and controlling the manufacturing process.

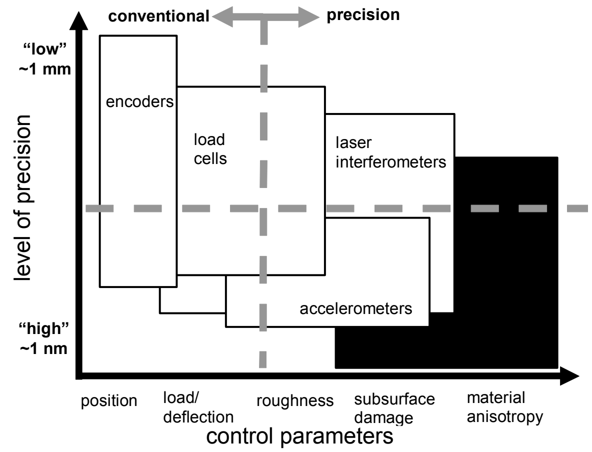


Figure 33: Sensor application vs. level of precision and control parameters [203].

A variety of sensors (each having a degree of applicability depending on the level of precision required or type of phenomena or control parameter that needs to be measured) are used to capture necessary information about the manufacturing process. Figure 33, which serves as an update to a similar diagram from [204], illustrates several different classes of sensors and their applicability to both level of precision (starting at the conventional scale and moving down the ordinate to ultraprecision material removal levels) and type of control parameter. It is important to note however that the boundaries for each sensor type are not necessarily "hard" boundaries, and that continually improving sensor technology will allow sensors to cover a wider range of control parameters with increasing sensitivity (the recent introduction of microcutting load cells is a good example).

Conventional measuring techniques such as load cells are suitable for measuring conventional-scale control parameters such as cutting and thrust forces at ranges from several to hundreds of Newtons. However, conventional sensors may not have the necessary signal-to-noise (S/N) ratio and sensitivity required to adequately and reliably characterize surface finish, subsurface damage, and cutting forces at the ultraprecision scale due to the extremely low cutting forces (~0.1 N and lower) and low power consumption present in ultraprecision machining.

Umeda [205] conducted surveys on measurement technology related to micromachining and found that measurements of material properties, force and displacement dynamics and shape in fabrication at the micro level were the most interesting. As the scale of features and machined parts decreases, the resolution of techniques used to measure and quantify these parts must increase of course. Demands on efficiency and accuracy of measurements are increasing for applications ranging from simple geometry and surface profiles to micro-spheres and micro-holes. Generally, measurement devices can be separated into two categories. The first includes those that measure the distance between edges of a feature, electron microscopes and optical profilometer, for example. These include a sensor (mechanical, magnetic, optical or capacitive), a workpiece holding table, and a transducer to displace the workpiece. The second category of measurement devices record either height or changes in height. This category includes mechanical stylus instruments, optical profile followers, atomic force microscopes, and interference measurement devices such as laser interferometer [206].

However, none of those instruments can really satisfy all the various measurement requirements on micro-devices. Hence, many researchers seek new devices by modifying or combining existing measurement techniques. Howard and Smith [207] modified conventional AFM technology to cover long ranges of surface metrology. They used a precision carriage and slideway mechanism to cover about 20 mm of travel and the AFM force probe, which utilizes the repulsive atomic force, to generate the surface contour.

In many cases, microparts include inside features such as pockets, holes, and channels. No technology exists to measure such features. Hence, Masuzawa et al. [208] developed a vibroscanning method to measure the inside dimensions of micro-holes. This method is limited only to conductive materials because it uses a sensitive electrical switch by contacting a vibrating micro-probe onto the workpiece. They added another probe utilizing contact by bending of the probe [209].

Miyoshi et al. [210] developed a profile measurement system using inverse scattering phase retrieval method. The system was able to conduct in-situ measurement of a surface profile with submicron accuracy. The tests on symmetric and non-symmetric fine triangular grooves showed promising results in reconstructing measured profiles.

Many researchers developed a precision CMM (Coordinate Measuring Machine) device with micron or submicron level resolution [211-213] but they were not sufficient for present levels of micromachining capability. Further development [214-216] improved the resolution up to few tens of nanometer and finally Jäger et al. [217] developed a 3D-CMM with a resolution of 1.3 nm using a probe and laser interferometers with angle sensors for guiding deviation.

Cao et al. [218, 219] developed a three dimensional micro-CMM for precise three dimensional micro-shape measurements. For this, they also developed a 3D opto-tactile sensor for the probe using a silicon boss-membrane with piezo resistive transducers which can simultaneously measure deflections of the probe and force in three dimensions. The system consists of two stage measurements; coarse and fine measurements with a resolution up to 1.22 nm and uncertainty less than 100 nm.

Grigg et al. [220] surveyed the applicability of white light interference microscopy on measurement of micro-systems. They investigated surface profilometry, integrated profilometry, and lateral metrology for full 3D characterization, defect detection, etc.

Finally, Okuda et al. [221] demonstrated that ductile and brittle cutting modes could be detected by use of an AE sensor and tool force measurements, and ductile-mode cutting for brittle materials were achieved.

6 CONCLUSION AND OUTLOOK

This paper has attempted to review a field which has been actively researched by precision engineers and manufacturing engineers for some time. The literature, specially that related to modeling and process physics, is impressive. One sees the results of creative researchers responding to natural curiosity and industry demands in ways seldom experienced in the past in manufacturing. And the capability of industrial practice resulting from this is substantial.

But, “grand challenges” still exist in mechanical micromachining. First and foremost is the trade-off between “big” conventional machines doing micromachining and “small” microfactories. Both have their advantages. But a factory you can carry in your pocket may not be able to create microfeatures on a conventionally sized workpiece, for example. Otherwise, machine tool development seems to be progressing nicely, often scaling from conventional machines or conventional instruments with capabilities at these scales.

The other challenges push us to continue our research and development and include the following:

- design and fabrication of cutting tools (which still suffer from inadequate geometry control and edge definition, poor stiffness and excessive tool wear; and coatings have hardly been fully evaluated)
- processing difficult to machine materials (carbon steels are still a challenge for diamond tools, brittle materials frustrate high MRR with reasonable surface quality, and very ductile materials, as often seen in medical devices, are difficult)
- limited productivity (serious challenges remain with respect to fixturing and handling of microparts, increasing material removal rates, and efficient tool path planning; this is specially true as mechanical micromachining is paired up with other microfabrication techniques, MEMS, for example.)
- dry versus wet (what role, and what composition, will lubricants play in helping these challenges?)
- understanding and modeling of process mechanics (this is specially important because of the “non-continuous” nature of the materials at this scale and difficulty of validating model predictions), and
- metrology (although approaches exist, the productive application of the methods is limited)

These are not insurmountable challenges. But they will drive the continued development of mechanical micromachining for some time.

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