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Overview of Micro Cutting

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1.1 Background and Scope

1.1.1 Micro Manufacturing

The increasing demands on micro and miniature parts, components and systems have led to the development of micro and nanotechnology. It is well-recognized that micro manufacturing has been a key enabling technology in industrially producing useful micro products and processes.

Micro Electric Mechanical Systems (MEMS) or micro system technology (MST) as known in Europe has been booming over the last two decades or so. Numerous MEMS products mainly micro sensors and micro actuators using silicon have been fabricated. These MEMS sensors and actuators have been widely used in various applications including medical engineering (e.g. pressure sensors), communications (high frequency resonators), inertial sensing (e.g. accelerometers and gyroscopes), to name a few. The processes employed to fabricate MEMS devices and other microelectronics products can be described as MEMS micro manufacturing or lithography-based micro manufacturing. Common techniques include photolithography, chemical-etching, plating and LIGA, and so on. Lithography-based micro manufacturing has existed and been developed for many years and is regarded as a mature large volume production process, hence the term micro manufacturing is familiar in the semiconductor or microelectronics fields.

In the past 20 years or so, high-accuracy complex shape micro and miniature components made from a range of engineering materials are increasingly in demand for various engineering industries. The geometry and functional requirements have led to the development of another category of micro manufacturing techniques termed as non-MEMS micro manufacturing or non-lithography-based micro manufacturing, which are fundamentally different from MEMS micro manufacturing in many aspects.

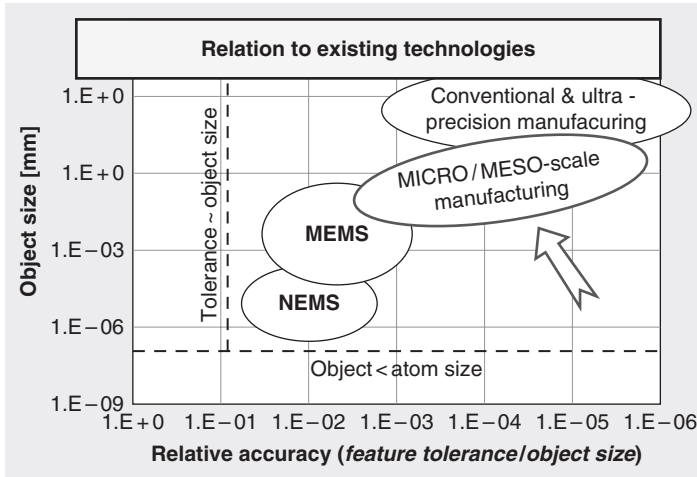


Figure 1.1 Micro manufacturing size/precision domains

Non-lithography-based micro manufacturing is a relatively new area, its concept, theories, processes and applications have been developed and formulated in the past around two decades. A report published by the WTEC panel on micro manufacturing describes non-lithography-based micro manufacturing as the creation of high-precision three dimensional products using a variety of materials and possessing features with sizes ranging from tens of micrometers to a few millimeters (WETC report). Figure 1.1 illustrates micro manufacturing size/precision domains. Micro manufacturing is normally used to produce part or feature size ranging from tens or hundreds of microns. Although micro manufacturing may not be capable of producing the smallest feature size as would be the case using MEMS and NEMS (Nano Electric Mechanical Systems) processes, it is a critical technology in bridging the gap between macro and nano domain [1]. It has many advantages over lithography-based micro manufacturing processes in terms of material choices, relative accuracy and the complexity of part geometry.

Typically non-lithography-based micro manufacturing includes micro EDM, micro mechanical-cutting, laser-cutting/patterning/drilling, micro-extrusion, micro-embossing, micro stamping, micro-injection moulding, and so on. These processes are based on different working principles and have their own respective characteristics in terms of production rate, attainable accuracy and surface finishes, and so on. But they are capable of producing 3D shape geometry micro parts over a wider range of engineering materials. This book will only focus on the micro mechanical-cutting process. Table 1.1 highlights the difference between MEMS micro manufacturing and non-MEMS micro manufacturing techniques (using mechanical micro machining as an example) to compare the fundamental differences between the two category micro manufacturing processes.

From Table 1.1 it can be found that micro mechanical machining has many advantages over MEMS-based process, such as wider materials choices, higher accuracy and capability of producing complex 3D geometry micro parts.

Recently, significant research efforts have been made on non-lithography-based micro manufacturing techniques. Europe has invested heavily in the research and development in

Table 1.1 Comparisons between MEMS-based process and micro machining

	MEMS-based process	Micro mechanical machining
Workpiece materials	Silicon, some metals	Metals, alloys, polymers, composite, technical ceramics
Component geometry	Planer or 2.5D	Complex 3D
Assembly methods	None or bonding	Fastening, welding, bonding
Relative accuracy	10^{-1} – 10^{-3}	10^{-3} – 10^{-5}
Process control	Feedforward	Feedback
Machine size	Macro	Macro to micro
Production volume	High	High or low
Production rate	High	Low
Initial investment	High	Intermediate or low
Applications	MEMS, microelectronics, some planner micro parts	Various applications requiring 3D micro components

micro manufacturing. In the past decade, dozens of EU large Framework projects have been initiated, such as MASMICRO, 4M, Launch-Micro, Production4i, EUPASS, Hydro-mel, HYTI, NANOSAFE2, Manudirect, Napolyde, PRONANO, NaPa, CHARPAN, NANOIMPRINT, and so on. These projects cover all areas in micro and nano manufacturing, precision manufacturing and metrology [2]. In a study conducted by the UK Technology Strategy Board (TSB) on high value manufacturing in the UK, micro and nano manufacturing processes are identified as one of the most significant emerging manufacturing processes which would address challenges for the UK high value manufacturing industry [3].

1.1.2 History and Development Process of Micro Cutting

Micro cutting as an emerging subject area in its own right has attracted growing attention from both researchers and industry in the last two decades. Because mechanical cutting is a well-established area much knowledge from macro cutting has thus been adapted to study micro cutting processes. Some researchers from the conventional mechanical cutting research community shifted their research interests to micro-domain. Basically there are two research approaches being taken to study micro cutting. One approach is miniaturization of the conventional cutting process, tooling and equipment with an emphasis on their scaling down effect. The other approach can find its origin in ultra-precision machining, especially single point diamond turning (SPDT) with the emphasis on cutting mechanics, although the two approaches overlap in some areas and attempt to address similar issues, such as cutting tool edge size effect, minimum chip thickness, and so on.

The approach of miniaturization of the conventional cutting process tends to be process parameters centric. Macro-phenomena such as machining dynamics, chatters, cutting forces, and so on are directly translated into the micro-domain and the machine-tool interaction effect is well considered and modelled. Macro analytical, mechanistic and numerical cutting process models are adapted to micro cutting with consideration of the so called size effect.

The other approach utilizes research output from ultra-precision diamond cutting and tends to be cutting mechanics centric in nature. This approach is similar to diamond cutting research,

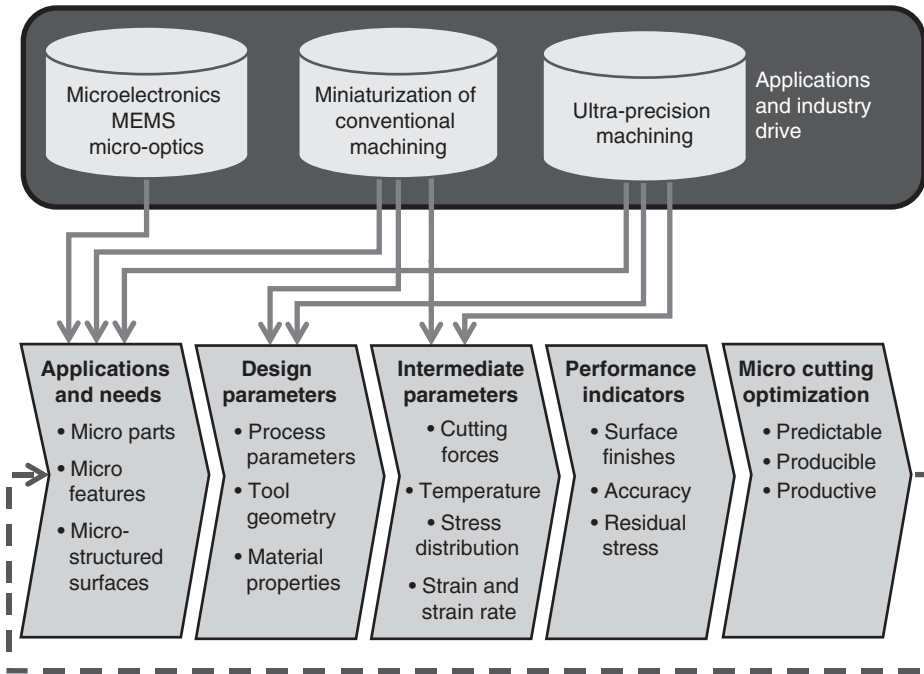


Figure 1.2 A typical micro cutting development process

but studies micro cutting, with more emphasis on tool geometries, material crystalline orientation and micro structures. Machine dynamics are often neglected as cutting forces are given very little consideration so that ultra-precision machines are treated as rigid and their effects do not appear in the models. Atomic scale simulation or other numerical modelling considering micro structure and grain size effects are used for this approach and study.

As discussed above, traditionally MEMS and microelectronics use silicon materials-based micro manufacturing processes which are fundamentally different from mechanical micro cutting. With the increasing requirement on 3D complex shape MEMS devices, mechanical micro cutting will have great potential to fabricate micro parts for MEMS and microelectronics applications. On the other hand, hybrid micro manufacturing approaches, for example, a combination of micro cutting and etching processes to fabricate high precision 3D micro parts, is likely to be a promising method.

Figure 1.2 highlights a typical micro cutting development process, starting from applications and needs which come from microelectronics and MEMS, miniaturization of conventional machining and ultra-precision machining; a micro cutting development flow has a number of key stages. Design parameters including process parameters (e.g. cutting speed, uncut chip thickness, feedrate), tool geometry, material properties, and so on will be developed with the help of existing knowledge from both miniaturization of conventional machining and ultra-precision machining. Intermediate parameters such as cutting forces, temperature, stress distribution, and strain and strain rate are measured and analyzed during the micro cutting process. Depending on the applications, a number of performance indicators such as surface finishes, accuracy and residual stress can be chosen to evaluate the micro cutting performance towards the predictable, producible and highly productive manufacture of micro products.

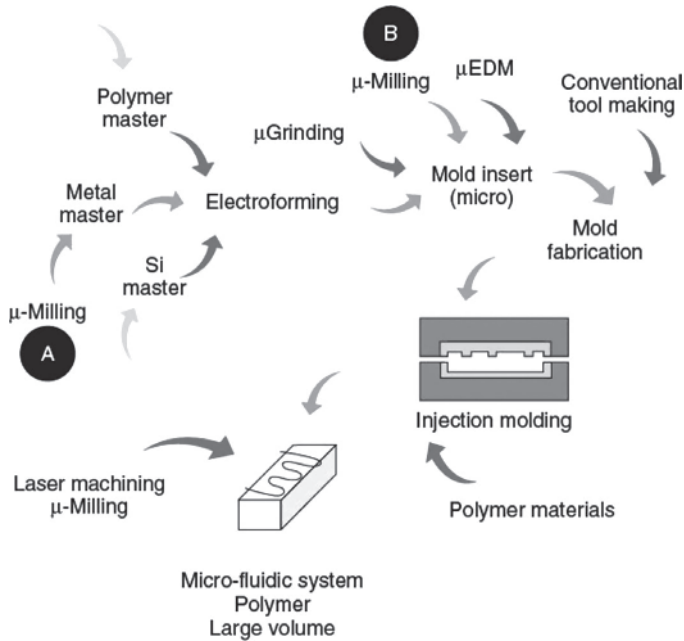


Figure 1.3 Micro cutting processes for micro-injection moulding. Reproduced with premission from [4]

Precision micro-structured surfaces or micro components are commonly directly machined by micro cutting, or through micro injection moulding or micro embossing with micro-cut micro moulds. Figure 1.3 shows that micro cutting, for example, micro milling, is used to fabricate micro moulds.

1.1.3 Definition and Scope of Micro Cutting

Micro cutting is kinematically similar to conventional cutting, but fundamentally different from conventional cutting in many aspects. It is important to define the scope and context of micro cutting, as the term may have different meanings for different people.

Micro cutting refers to mechanical micromachining (direct removal of materials) using geometrically defined cutter edge(s) carried out on conventional precision machines or micro machines. Micro cutting is normally used for machine high accuracy 3D components in a variety of engineering materials. A number of features can be used to characterize and define the scope of micro cutting as follows:

- **Uncut chip thickness.** Uncut chip thickness is the material layer being removed during the cutting process. Uncut chip thickness in micro cutting is different from that in conventional macro cutting. Masuzawa and Tonshoff [5] defined the micro-macro border as around 200 µm, while this border obviously changes according to the contemporary levels of conventional technologies. This borderline of uncut chip thickness decreases with advances in machining technologies. In the current state-of-the-art an uncut chip thickness less than tens of microns has been widely accepted by the micro machining community.

- **Dimensions and accuracy of micro parts or features.** Micro cutting is used to fabricate micro parts, micro features on normal-sized parts, and micro-structured surfaces. In terms of the dimensions of parts/features in micro cutting, micro parts or micro features must have dimensions ranging from 1–1000 μm and at least two dimensions fall into this range. For miniaturized parts such as micro pins, micro gears, that means micro cutting is a three dimensional machining process for a high aspect ratio part. Micro cutting normally achieves form and dimensional absolute accuracy of better than a few microns or a relative accuracy in the order of 10^{-3} – 10^{-5} and surface roughness (Ra) less than 100 nm, although micro cutting has the capability in particular of using diamond tooling to achieve sub-micron accuracy (relative accuracy in the order of 10^{-6}) and nanometric surface roughness for micro components and micro structures.
- **Cutting tool geometry.** The size and geometry of micro cutting tools determine the limit of the size and accuracy of micro features. For micro milling and micro drilling tools, tool diameters are typically in a range from 1000 μm down to 25 μm , although tools of a few microns in diameter are also used in the research laboratories. For micro peripheral turning there is no requirement on tool size, but micro turning tools must be employed for micro-hole boring and face grooving of micro components with the high aspect ratio.
- **Underlying cutting mechanics.** Micro cutting is not a simple down scaling of conventional macro cutting. In micro cutting, when uncut chip thickness becomes comparable to the cutting edge radius of tools or grain size of workpiece materials, a number of critical issues, such as cutting edge radius effect, negative rake angle, tool-workpiece contact at the flank face, minimum chip thickness and micro structure effect, become prominent. These behaviours are known as size effects, which can influence underlying cutting mechanics in terms of micro cutting forces and specific cutting energy, chip formation process, surface generation, burr formation and tool wear mechanism. On the other hand, size scaling down of machine tools and cutting tools results in size effect on machining dynamics which in turn interacts with and affects cutting mechanics fundamentally.
- **Application area.** Micro cutting is capable of machining a broad range of engineering materials including metals, polymers, technical ceramics and composites, and also with achievable accuracy and surface roughness. Micro cutting has found applications in many areas requiring micro components.

Figure 1.4 shows some examples of high-accuracy micro components and micro structures manufactured by micro cutting. These examples illustrate that micro components having complex 3D geometries need to be made from a variety of materials and not just from silicon. Mechanical micro machining is an ideal method for producing complex 3D micro components with high accuracy.

1.1.4 Micro Cutting and Nanometric Cutting

There is no general agreement on the definition of nanometric cutting. But if the uncut chip thickness of mechanical cutting falls to the nanometric level, that is, less than tens of nanometers, the cutting process can be regarded as nanometric cutting. Some researchers have

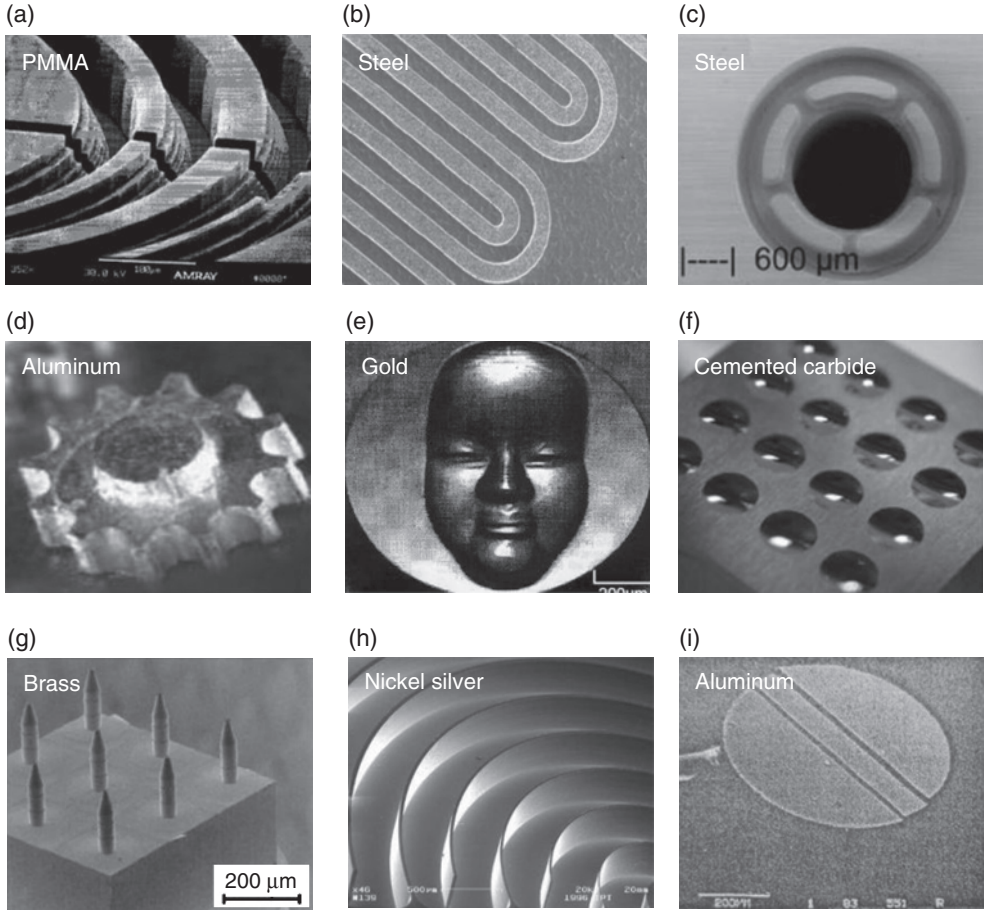


Figure 1.4 Examples of high accuracy micro components and micro structures by micro cutting. Reproduced from [6]: (a) Micro trenches. Reproduced with permissions from [7]; (b) Micro reactor [8]; (c) Micro mould. Reprinted from [9]. Copyright 2001 Elsevier; (d) Micro-gear. Reproduced with permission from [10]. Copyright 2004 ASME; (e) 3D micromachined part – Noh-mark (Fanuc). Images courtesy of FANUC; (f) Micro projection array (Fanuc). Images courtesy of FANUC; (g) Micro needles array. Reprinted from [11]. Copyright 2006 Elsevier; (h) Micro wall. Reproduced with permission from [12]; (i) Target foil for nuclear fusion. Reproduced with permission from [13]. Copyright 2001 EUSPEN

conducted ultra-precision machining experiments under extreme small uncut chip thickness, for example, less than 10nm. This can also be regarded as nanometric cutting. One of the promising applications using nanometric cutting is ductile mode cutting with nanometric level surface roughness and being free from cracks in brittle materials, such as semiconductor materials. But it should be noted that most nanometric cutting experiments were carried out under well controlled conditions in a laboratory environment and not many applications on an industrial scale have been found.

Nanometric cutting experiments are difficult to conduct, numerical simulations are therefore carried out as a powerful tool to study nanometric cutting processes. Among various numerical simulation techniques, molecular dynamics (MD) simulation has played a significant role in investigating nanometric cutting mechanics. MD simulation is an extremely accurate simulation method on the atomic scale and has the ability to fully describe the micro-structural evolution of the material being processed. However, the simulation scale of MD is limited by computational power and so far even at the largest scale it can only reach a few μm^3 . Therefore, MD simulation has been mainly applied to nanometric cutting where depth of cut is at the nanometric level. The application of MD simulations in machining was pioneered by LLNL in the late 1980s [15]. Since then several meaningful studies were carried out in different aspects of nanometric machining, including crystallographic orientation effects on plastic deformation [16], tool edge radius and minimum depth of cut effects on the chip formation mechanism [17], effects of defect structure in the workpiece material, diamond tool wear [18]; [1], subsurface deformed layer property [19], and so on.

Although the simulation scale of MD cannot directly cover micro cutting processes (typically, a few to a few hundreds of microns), these studies provide valuable base-line data and results for micro cutting simulations. The length scale of micro cutting in nature falls between nanometric cutting and macro cutting, therefore the micro cutting inherently has the characteristics of both. Studying the micro cutting process is very important in order to bridge the gap between the conventional macro cutting and nanometric cutting process.

1.2 Materials in Micro Cutting

One of the advantages of micro cutting over MEMS micro manufacturing is that micro cutting has fewer constraints on material choices. Almost all the material families – metals, polymers, glasses, ceramics and composites have been reported to be processed by micro cutting. As shown in Figure 1.4, materials for micro components are application and function dependent: optical components being made from glass, polymer or aluminium; medical engineering components from polymer or glass; mechanical components from ferrous or non-ferrous metals; and dies/moulds from copper alloys, aluminium or high-hardness steels. Some of the micro components and micro structures require sub-micron accuracy and nanometric surface finishes so diamond machinable materials are used to achieve the accuracy and surface requirement.

Although micro cutting uses the same range of materials as macro cutting, there are a number of material issues in micro cutting which is fundamentally different from macro cutting. These material issues affect micro cutting performance and hence research efforts have been broadened to investigate material behaviours at the micro scale.

Most engineering materials used are polycrystalline materials with typical grain size varying from between approximately 100 nm to 100 μm . When a micro part or feature decreases in relation to this size range, grains are actually equivalent to being either removed or refined. For most metals, mechanical properties are dominated by the presence and mobility of structural dislocations. As equivalent grain size is reduced the maximum spacing between a dislocation and a grain boundary is reduced, the ease of dislocation movement is influenced by any number of obstacles such as grain boundaries, defects and micro part/feature surfaces, and so on material strength is therefore increased. The changed material properties will in turn affect machinability of micro cutting.

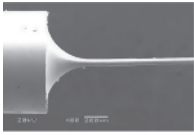
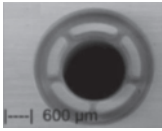
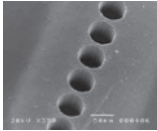
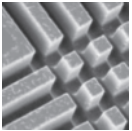
On the other hand, the uncut chip thickness in micro cutting is usually in the same order as the material grain size, hence the workpiece material cannot be assumed as homogeneous and isotropic. Experiments on micro cutting of multiphase materials have shown significant varying cutting mechanisms and the associated process response [20], [21], [22].

Various material constitutive models have been employed to model material behaviours in micro cutting. Most of these material models address material behaviours such as strain hardening, strain rate sensitivity and thermal softening. Multiphase FE simulation models for micro cutting were also proposed to address the material size effect mentioned above [20], [22].

1.3 Micro Cutting Processes

Kinematically similar to conventional cutting, typical micro cutting processes include micro turning, micro milling, micro drilling and micro grinding (with shafts particularly). These four micro cutting processes vary in workpiece geometry, machining efficiency and achievable accuracy, although these cutting process mechanics share lots of common characteristics. Table 1.2 summarizes the geometric characteristics of the four micro cutting processes. Chapters 7–10 will discuss these micro cutting processes in detail.

Table 1.2 Geometric characteristics of typical micro cutting operations

	Micro turning	Micro milling	Micro drilling	Micro grinding
Workpiece Shape	Rotational convex shape with large aspect ratio, such as micro shafts, micro pins, etc.	3D shape both convex and concave with high aspect ratios and high geometric complexity	Round holes through or blind	Hard and brittle materials; 3D convex and concave shape using micro grinding tips
				
Typical size	Down to $\phi 5 \mu\text{m}$, though $100 \mu\text{m}$ above more applicable	$50 \mu\text{m}$ slots are practical applicable	$\phi 50 \mu\text{m}$ holes are practical applicable	Micro structures down to $20 \mu\text{m}$
Achievable surface roughness	$0.1 \mu\text{m Ra}$	Optical surface ($<10 \text{ nm Ra}$) via diamond milling for non-ferrous materials	$0.1 \mu\text{m Ra}$	advantageous for brittle materials with optical surface finish ($<10 \text{ nm Ra}$)
References	[25] [26]	[9]	[27]	[28] [13]

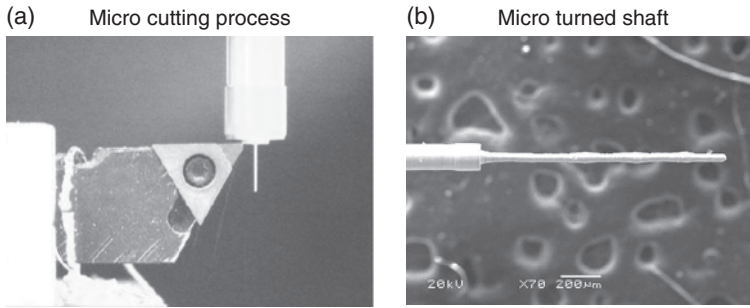


Figure 1.5 An example of micro-turned shaft (Reproduced from [23]). Reproduced with permission from [2]. Copyright 2007 Elsevier

1.3.1 Micro Turning

Micro turning is an effective way to produce micro cylindrical or rotational symmetry components. Figure 1.5 shows examples of a simple micro pin with the diameter of $33\mu\text{m}$. A micro part with the high aspect ratio can be achieved using the micro turning [23]. The most serious problem encountered during micro turning is the cutting force which tends to bend the workpiece, and the machining force influences machining accuracy and the limit of machinable size [24]. A detailed analysis on how size effect influences micro part rigidity and deflection is provided in Chapter 7. Micro turning is performed on either a conventional precision machine or a micro turning system.

Diamond turning of the micro structured surface can be regarded as another group of micro cutting. With the aid of fast tool servos (FTS), complex micro structured surfaces can be generated by diamond turning.

1.3.2 Micro Milling

Micro milling is an emerging technology and is the most flexible and versatile micro cutting process. It is able to generate a wide variety of complex micro components and micro structures. In the past decade significant research has been carried out in micro milling modelling and experiments. Most of the micro components shown in Figure 1.3 were machined using micro milling technology.

Micro tooling is crucial to micro milling as it determines the feature size and also the surface roughness. Commercially available micro milling tools have the tool diameter ranging from $25\text{--}1,000\mu\text{m}$. Due to the limited rigidity of small diameter tools and difficulty in fabricating a micro tool, most of the micro milling tools have only two flutes, and some very small diameter tools ($<100\mu\text{m}$), especially made from natural diamond or CVD, have only single flute or spade type tools. In terms of types of milling operations, micro end milling using either flat end or ball-nosed end mills dominates micro milling applications, and peripheral milling in macro milling is uncommon for micro milling. One of the challenges in micro milling is premature tool chipping and breakage. There are limited choices for micro tool fabrication. Coated micro grain tungsten carbide tools are widely employed, and natural

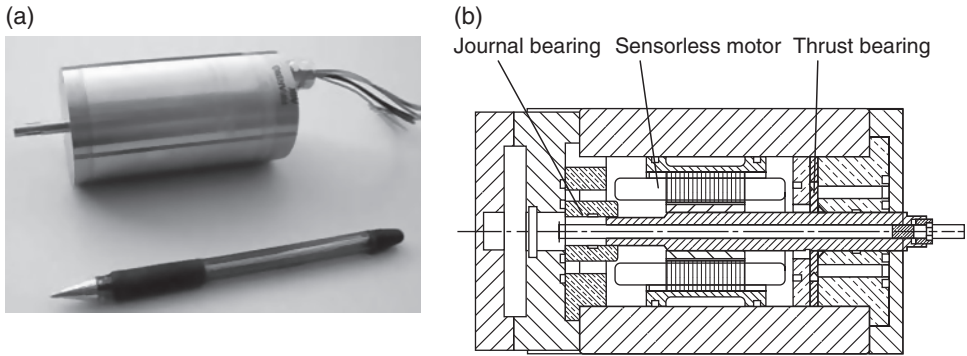


Figure 1.6 The ultrahigh speed aerostatic bearing spindle driven by a sensorless DC motor (a) photograph of the developed miniature spindle; (b) a schematic of the spindle

diamond or CVD micro milling tools are used in some applications requiring very tight tolerance and good surface finishes.

Although micro milling can be performed in a conventional CNC machining centre by retrofitting a high speed spindle, ideally micro milling should be performed in a precision milling machine or micro machine specially designed for micro milling purposes. Chapter 2 presents some industrial precision machine tools and miniature machine tools with micro milling capability. Small diameter micro milling tools require extremely high rotational speeds to achieve even modest machining rates and also a high stiffness spindle to maintain high accuracy in the presence of cutting forces. High machining accuracy also requires low spindle running temperatures to minimize thermal distortion while a fine surface finishing capability can only be achieved with a spindle having low motion errors. So precision high speed spindles with operating speeds of more than 100,000 rpm are commonly used. Figure 1.6 shows an ultra high speed aerostatic bearing spindle with an operating speed range of 20 000 to 200 000 rpm.

1.3.3 Micro Drilling

Drilling is a popular machining method to create a round hole in a part made from many materials. Although it shares many cutting mechanics with other cutting operations, micro drilling has not been researched to the same extent as micro turning and micro milling. This is because micro drilling tools have more complex geometry compared to milling and turning tools. Holes of $50\mu\text{m}$ can be practically machined with commercial twist drills. Micro drills of less than $50\mu\text{m}$ diameter are also available and normally of the spade type. One of the main applications of high speed micro drilling is printed circuit boards (PCBs) drilling. Micro drills of $50\text{--}300\mu\text{m}$ in diameter are commonly used in PCB drilling production lines and a hole depth/diameter ratio up to 15 has been achieved [29].

Compared with micro milling, micro drilling is more efficient in creating holes and capable of machining deep holes, although micro drilling cannot machine flat-bottom holes because of the drilling point. Since a micro drill can easily be broken, sensitive torque feedback control

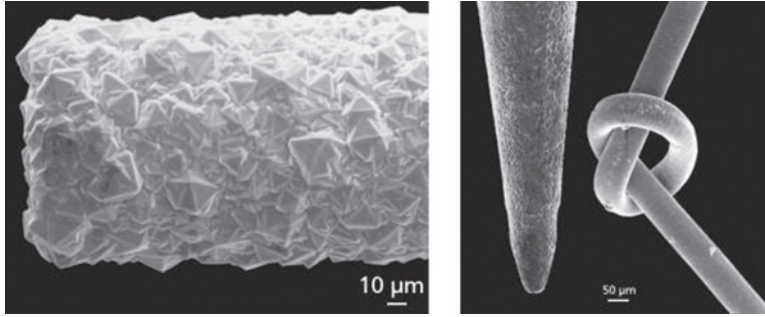


Figure 1.7 Micro CVD diamond-coated grinding tools. Reproduced with permission from [30]

is necessary. But usually a thrust force feedback is employed because of the difficulty in the direct measurement of the torque [5].

Micro drilling has a similar requirement on high speed spindles as micro milling, but speed control is not desirable as with a micro milling spindle. Aerostatic bearing or air turbine spindles with maximum speed more than 100000 rpm are typically used to improve productivity.

1.3.4 Micro Grinding

Micro grinding has been an effective method to produce high dimensionally accurate parts with superior surface finishes. Due to its low material removal rate, micro grinding is normally used as the final production procedure. Unlike other micro cutting processes, such as micro turning and micro milling where ductile or less hard materials are usually used, micro grinding is capable of machining brittle and hard materials.

Similar to the micro turning operation, micro grinding can be performed using relatively large grinding wheels when the micro features do not require micro grinding tools. But the size and geometry of micro grinding tools determine the limit of the size and geometry of micro parts and micro features. Standard diamond abrasive tools are made by bonding diamond monocrystals, PCD or CVD onto a base body. Micro grinding tools have been fabricated by coating CVD diamond layers onto cemented carbides. Figure 1.7 shows a small CVD diamond abrasive pencil with the diameter of 50 to 100 µm.

1.4 Micro Cutting Framework

This section presents a framework for micro cutting with the aim of highlighting various micro cutting aspects in an integrated environment and how these aspects interact and related to each other. Figure 1.8 shows a representation of the micro cutting framework. Challenges and needs of miniaturization are always the main driving force to push micro cutting science and engineering forward. Existing challenges such as size effects and micro-machinability have raised research issues which are being addressed by the micro machining community. The market need for miniaturized and micro products or components with smaller dimensions/

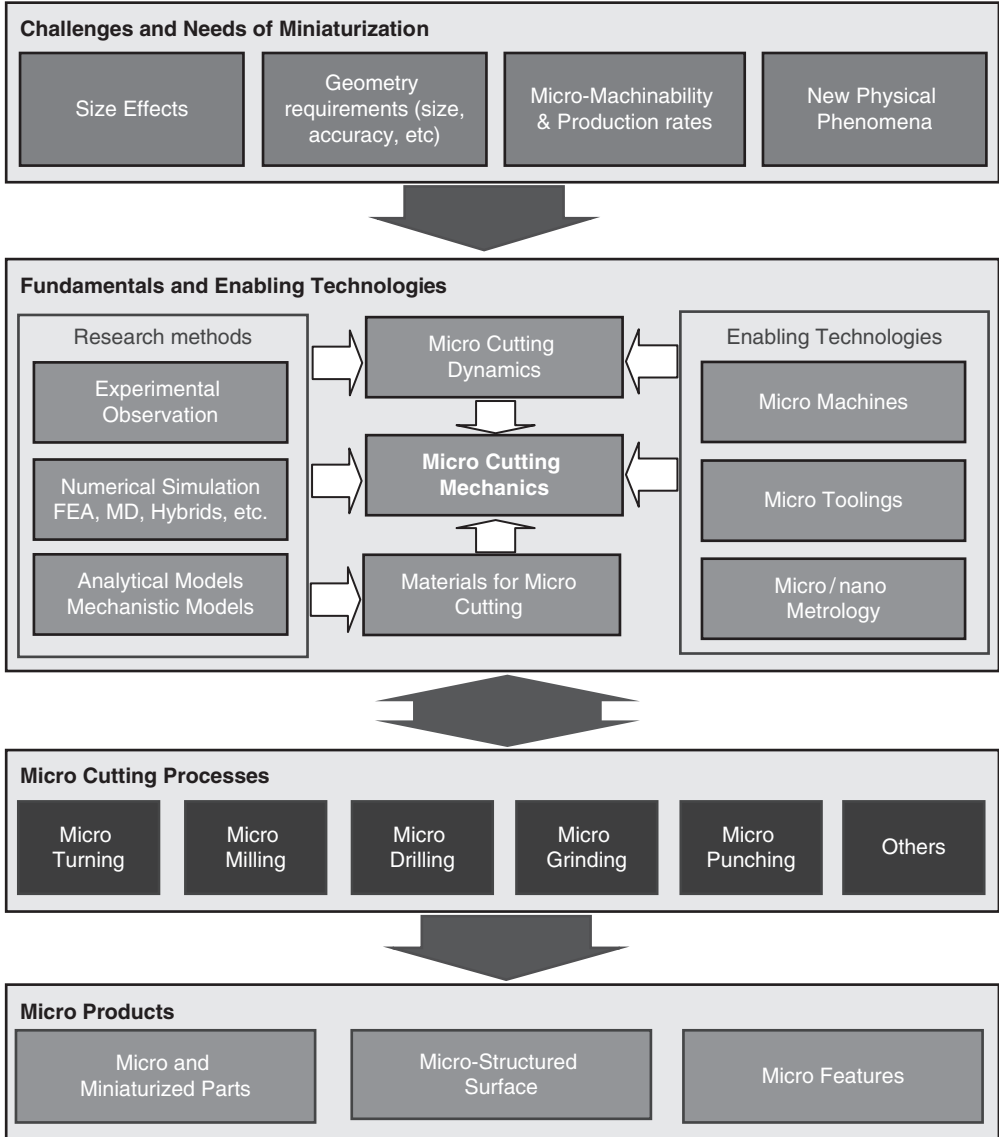


Figure 1.8 A framework for micro cutting

features and tighter tolerance sets the scope of micro cutting and drives the progress of this subject area. Micro-machinability and production rate of micro cutting determine if micro cutting is a feasible and favourable industrial method for a certain micro product.

Micro cutting mechanics are central to the micro cutting fundamentals. Similar to conventional macro cutting mechanics, issues like chip formation, cutting force, cutting temperature, tool wear, burr formation, surface generation, are being investigated, but in the micro domain. Micro cutting dynamics, including tool run-out, tool deflection, micro machining chatter and

vibration, influence the cutting performance and should be linked with micro cutting mechanics. Engineering materials for micro cutting are also important aspects which should be taken into account in micro cutting mechanics. The available research methods in macro cutting, especially the analytical and numerical methods, become increasingly attractive for studies of micro cutting. On the other hand, developments on enabling technologies – machine tools, micro tooling and micro metrology have enhanced the understanding and improvement of research and development in micro cutting processes. The resultant scientific understanding of the micro cutting fundamentals and enabling technologies of micro cutting are being applied to various micro cutting processes and to produce micro parts, micro-structured surface, and micro features in an efficient and effective way, although many new applications and challenges are emerging on an almost daily basis, as indeed micro cutting is a fast moving and timely subject area as well. The subsequent chapters will attempt to discuss these aforementioned scientific/technological challenges, fundamentals, engineering issues and applications in a comprehensive and systematic manner.

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