CHAPTER 1

FUNDAMENTALS OF MICRO-MANUFACTURING

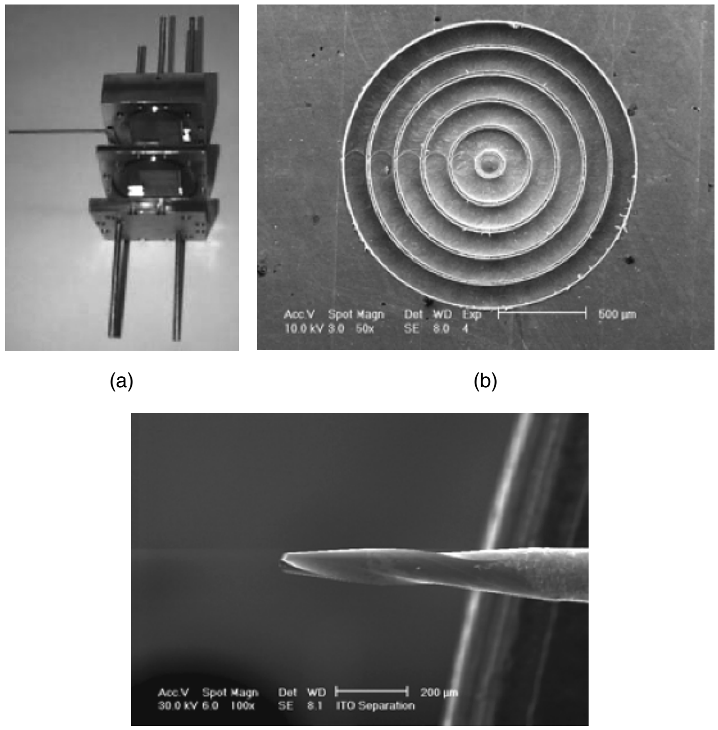
MUAMMER KOÇ
Center for Precision Forming (CPF — National Science Foundation IUCRC), Virginia Commonwealth University, Richmond, VA
Istanbul Sehir University, Turkey

TUĞRUL ÖZEL
Manufacturing Automation Research Laboratory, School of Engineering, Industrial and Systems Engineering, Rutgers University, Piscataway, New Jersey

1.1 INTRODUCTION

During the last decade, there has been a continuing trend of compact, integrated and smaller products such as (i) consumer electronics—cell phones, PDAs (personal digital assistant), etc.; (ii) micro- and distributed power generators, turbines, fuel cells, heat exchangers [1–4]; (iii) micro-components/features for medical screening and diagnostic chips, controlled drug delivery and cell therapy devices, biochemical sensors, Lab-on-chip systems, stents, etc. [5–8]; (iv) micro-aerial vehicles (MAV) and micro-robots [9–12]; and (v) sensor and actuators [13,14] (Fig. 1.1). This trend requires miniaturization of components from meso- to micro-levels. Currently, micro-electromechanical systems (MEMS), mostly limited to silicon, are widely researched and used for miniaturized systems and components using layered manufacturing techniques such as etching, photolithography, and electrochemical deposition [15,16]. Such techniques are heavily dependent on technologies and processes originally developed for micro-electronics manufacturing. However, MEMS have some limitations and drawbacks in terms of (i) material types (limited to silicon in combination with sputtered and etched thin metallic coatings), (ii) component geometries (limited to 2D and 2.5D), (iii) performance requirements (i.e., types of mechanical motions that can be realized, durability, and strength), and

Micro-Manufacturing: Design and Manufacturing of Micro-Products, First Edition.
Edited by Muammer Koç and Tugrul Özel.



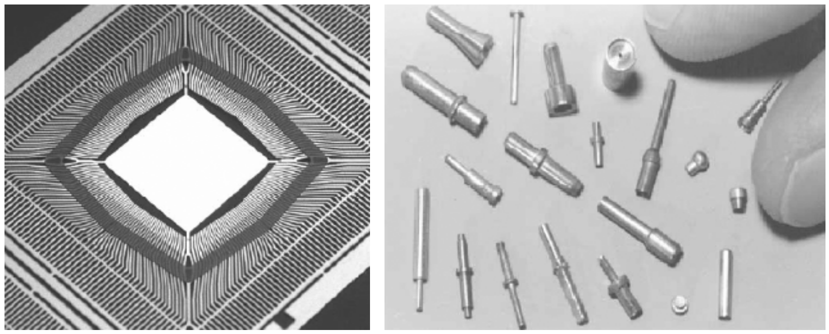
(a) (b) (c)

Figure 1.1 (a) Micro-channel chemical reactor, components are manufactured by laser micro-machining [20]; (b) pattern of concentric 127 μm channels of varying depth up to 125 μm cut into a brass workpiece; (c) SEM photograph of the front view of the 127 μm diameter two-flute end mill [21].

(iv) cost (due to slow and sequential nature of processes that are not amenable to mass production).

These issues lead the way for researchers to seek alternative ways of producing 3D micro-components with desired durability, strength, surface finish, and cost levels using metallic alloys and composites. Micro-machining processes have been widely used and researched for this purpose [15–17]. For instance, the laser micro-machining is used to fabricate micro-structures (channels, holes, patterns) as small as 5 μm in plastics, metals, semiconductors, glasses, and ceramics. Aspect ratios of 10:1 are claimed to be possible with this process. As a result, micro-scale heat exchangers, micro-membranes, micro-chemical-sensors and micro-scale molds can be fabricated with micro-machining. However, these processes are not appropriate for high-volume-low-cost applications [18,19]. Figure 1.2 depicts representative parts and features manufactured using mechanical micro-machining process.

As an alternative, micro-forming (micro-extrusion, micro-embossing, micro-stamping, micro-forging, etc.) processes have been considered and researched



(a) (b)

Figure 1.2 (a) lead frame (pitch 300 μm) blanks stamped for electronic connectors [19]; (b) Sample micro-extruded/forged parts.

as a prominent processing method because of their potential capabilities to produce a large volume of components cost-effectively [19,22–25]. Examples of micro-extruded parts are shown in Fig. 1.2. Micro-forming poses some difficulties because of the size and frictional effects associated with material forming processing. For micro-components in the ranges of interest (0.1–5 mm), the surface area/volume ratio is large, and surface forces play important roles. As the ratio of feature size to grain size becomes smaller, deformation characteristics change abruptly with large variations in the response of material [26]. Thus, new concepts are needed to extend forming processes to micro-levels. Early research attempts indicate that micro-forming is feasible but fundamental understanding of material, deformation, and tribological behavior in micro-/meso-scale is necessary for successful industrialization of micro-forming [24,27].

The development of novel methods and use of alternative instruments for accurate and cost-effective measurement of material properties are needed in micro-forming process and tool and product design. As is well known, both solids and fluids exhibit different properties at the micro-scopic scale. As the size scale is reduced, surface and size effects begin to dominate material response and behavior. Consequently, material properties obtained on regular scale specimens are no longer valid for accurate analysis and further design. Mechanical, tribological, and deformation properties deviate from bulk values as the characteristic size of the micro-components approaches the size scale of a micro-structure, such as the grain size in polycrystalline materials [22,27]. The ultimate challenge and the fundamental underlying barrier in the advancement of micro-forming processes are to be able to characterize these properties at the micro-scale in an accurate and reasonably cost-effective manner.

1.2 MICRO-FORMING (MICRO-SCALE DEFORMATION PROCESSES)

Micro-forming is defined as the production of metallic parts by forming with at least two part dimensions in the submillimeter range [27]. When a forming process is scaled down from the conventional scale to the submillimeter range, some aspects of the workpiece such as the micro-structure and the surface topology, remain unchanged. This causes the ratio between the dimensions of the part and parameters of the micro-structure or surface to change, and is commonly referred to as the *size effects*.

The trend toward further miniaturization—in particular, in the field of electronics, consumer products, energy generation and storage, medical devices, and micro-systems technology (MST)—will persist as long as consumers still seek for compact devices with heavily integrated functions. Metal forming processes are well known for their high production rate, minimized material waste, near-net-shapes, excellent mechanical properties, and close tolerances. These advantages make metal forming suitable for manufacturing of micro-features, especially where a high-volume-low-cost production is desired [19,28]. However, the well-established metal forming technology at the macro-scale cannot be simply applied in the micro-levels due to the so-called "size effects" on the material behavior. At the micro-level, the processes are characterized by only a few grains located in the deformed area; thus, the material can no longer be considered as a homogeneous continuum. Instead, the material flow is controlled by individual grains, that is, by their size and orientation [29]. As a result, conventional material properties are no longer valid for accurate analysis at this level. Furthermore, the deformation mechanism changes abruptly with large variations in the response of material as the ratio of grain size to the feature size decreases. Surface interaction and friction force become more prominent as the ratio of the surface area to volume increases [26,28]. These issues have been investigated to better understand, define, and model the "size effects." Additional size effects concerning the forming process are forming forces, spring-back, friction, and scatter of the results.

A micro-forming system comprises five major elements: material, process, tooling, machine/equipment, and product as illustrated in Fig. 1.3. The size effect is a dominant factor in design, selection, operation, and maintenance of all these elements. For example, a major problem in micro-forming lies in the design and manufacturing of the tools (i.e., dies, inserts, and molds). Small and complex geometries needed for the tools are difficult to achieve, especially when close tolerances and good surface quality are desired. Special tool manufacturing techniques are required to overcome these difficulties. Carefully selected tool material and simple shaped/modular tools can help reduce the cost of tool making and the degree of difficulty regarding the tool manufacturing, and increase tool life.

A vital challenge for micro-machine and equipment is the required precision at a high-speed production. In general, positioning of the micro-parts during the production process requires an accuracy of a few micrometers to submicrometers depending on the part type and ultimate use. In addition, as the part size is extremely small and the part weight is too low, handling and holding of micro-parts becomes very difficult due to adhesive forces (van der Waals, electrostatic, and surface tension). Therefore, special handling and work holding equipment need to be developed to overcome these difficulties in placing, positioning, and assembling the micro-parts. Also, clearance or backlash, between a die and a

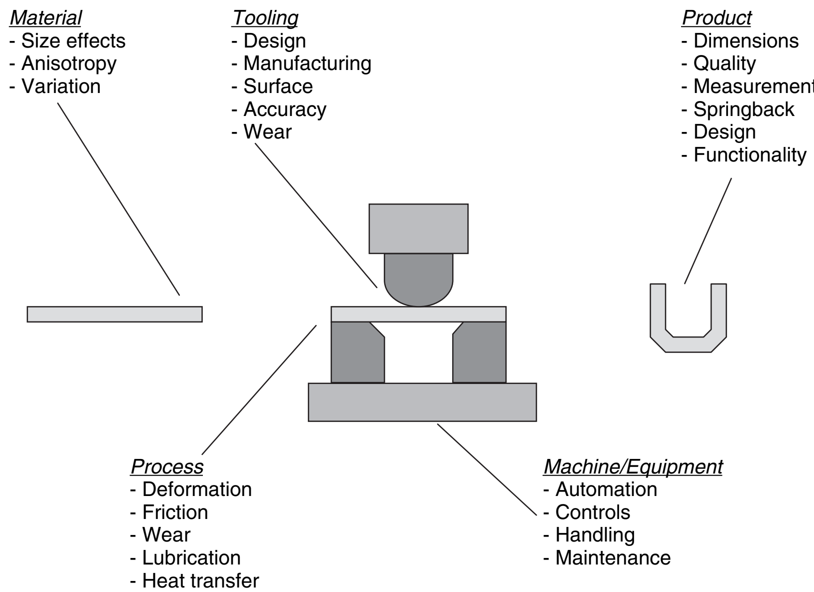


Figure 1.3 Micro-forming system.

punch that could be negligible at the conventional scale, can be a problem when the total required stroke to form the micro-part and clearance lies in the range of a few hundred micrometers [27]. Another challenge concerns the accurate measurement, inspection, and monitoring system of the process and dimensional parameters during and after the forming process. Automation systems for the micro-manufacturing are another issue that will eventually need to be studied and improved for the high-volume-low-cost production process.

1.2.1 Size Effects in Micro-forming Processes

For the accurate analysis and design of micro-forming processes, proper modeling of the material behavior at the micro-/meso-scale is necessary by considering the size effects. Two size effects are known to exist in metallic materials. One is the "grain size" effect and the other is the "feature/specimen size" effect (see Figure 1.4). The former is generally represented by the Hall–Petch law, which states that the material strengthens as the grain size decreases. The latter is observed when the miniaturization of the part occurs resulting in the decrease of the flow stress. Although the first studies on "feature/specimen size" effect were as early as the 1960s, up until now, no models quantitatively describe the phenomena. In order to implement the miniaturization effect into simulation tools, a quantitative description of the phenomena is necessary. In this chapter, an attempt has been made to quantify the size effect on the flow stress by considering the fundamental properties of single and polycrystal plasticity.

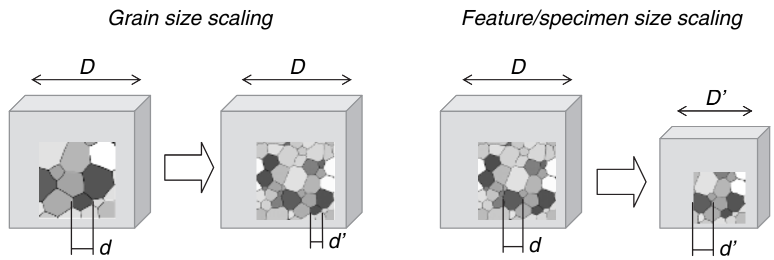


Figure 1.4 Illustration of two types of scaling effects: "grain size effect" and "feature/specimen size effect." (A full color version of this figure appears in the color plate section.)

According to Armstrong [30] and Kim *et al.* [31], the size effects can be investigated under two categories—the "grain size effect" and the "feature/specimen size effect." The "grain size effect" has been known to follow the Hall–Petch equation [32,33]. This effect purely depends on the average size of the material grains and is the dominant effect on the material response at the macro-levels. However, as the feature/specimen size reduces to the micro-scales, the "feature/specimen size effect" has also been reported to have considerable impact on the material response, and thus manufacturability.

Depending on the material testing methods or metal forming processes, the "feature/specimen size effect" could be further divided into two distinctive effects: the "feature size effect" and the "specimen size effect." In general, the "specimen size" can be referred to as the diameter of a billet (rod) or the thickness of a blank (sheet) to be tested or formed, while the "feature size" could be regarded as the smallest feature (channels, radii, protrusions, etc.) on the final part that these specimens will be formed into. For example, in an extrusion process of micro-pins, the specimen size would be the initial diameter of the rod/billet, while the feature size would be the diameter of the reduced section. In the case of micro-channels formed on an initially flat thin sheet blank, specimen size will be regarded as the thickness of the blank, while micro-channels will be the feature of interest and their dimensions (i.e., width and height) will represent the feature size. Similarly, in a bulge test of thin sheet blank, the specimen size will be the blank thickness, while the feature size will be the bulge diameter. With this distinction between the specimen size and the feature size effects, it is obvious that a tensile test could be used only to study the effect of the specimen size but not the feature size on the material behavior.

Even though these size effects can be distinguished based on the above discussion, as the grain, specimen, and feature sizes get smaller and smaller into the micro-scales, their effects are coupled, and therefore should be considered together. Koç and Mahabunphachai [34] proposed the use of two characteristic parameters N and M to couple and represent these interactive effects, where N is defined as the ratio between the specimen and the grain sizes, and M is the ratio between the feature and the specimen sizes. By defining N and M, all

TABLE 1.1 Type of Size Effects and Characteristic Parameters

	Size Effects		
	Grain Size	Specimen Size	Feature Size
Tensile test	d	t_0, D_0	—
Bulge test	d	t_0	D_c
Stamping process	d	t_0	D_c
Extrusion process	d	D_0	D_c
Characteristic parameter	$N = t_0/d$ or D_0/d		$M = D_c/t_0$ or D_c/D_0

combinations of the interactive effects, that is, grain-to-specimen, specimen-to-feature, and grain-to-feature sizes, can be represented and quantified using N, M, and $N \times M$, respectively. A summary of different types of size effects and their corresponding characteristic parameters is presented in Table 1.1, where d is material grain size, t_0 the specimen thickness, D_0 the specimen diameter, and D_c the die cavity.

The "specimen size effect" (t_0 or D_0) on the material flow curve as a measure of material response was observed in various tensile test conditions for a variety of materials such as CuAl alloy [35], CuNi18Zn20, CuZn15 [36], CuZn36 [37], and aluminum [38,39]. While the grain size shows a strong effect on the material response at all length scales (i.e., from macro- to micro-scale), it is not until the N value is around 10–15 that the "specimen size effect" starts to influence the material response [31,38,40]. In general, the tensile test results showed a decreasing trend of the flow stress with the decreasing specimen size (i.e., decreasing N value) as illustrated in Fig. 1.5a and 1.5b. Similar observations were reported in upsetting tests of copper, CuZn15, and CuSn6 [19] as illustrated in Fig. 1.5c, and in bulging test of CuZn36 [37] as illustrated in Fig. 1.5d. This trend of decreasing flow stress with decreasing N value was rather consistent based on the results of various studies. However, as N is reduced close to a range of 2–4, several researchers had reported an increase in the flow stress as N is decreased further. For instance, the tensile test results of 99.999% Al rods by Hansen [38] showed an increase in the flow stress as N decreases from 3.9 to 3.2 (Fig. 1.5a). Similar results were also observed in micro-/meso-scale hydraulic bulge testing of thin CuZn36 blanks [37], where the flow stress was found to increase as N value decreases from 5 to 3.3 ($d = 60$ μm, t_0 reduced from 0.3 to 0.2 mm) as shown in Fig. 1.5. An increase in the flow stress was also observed as N is reduced close to 1 (single crystal deformation) as reported in bending tests of CuZn15 and aluminum 99.0–99.5% [36,39]. Nevertheless, in the tensile test results of CuNi18Zn20 specimens by Kals and Eckstein [36], a continuous decrease in the flow stress was reported as N decreased from 25 to 2.5 (i.e., $d = 40$ μm, $t_0 = 1.0$, 0.5, and 0.1 mm) as shown in Fig. 1.5b. A summary of the effect of N on the flow stress based on the findings reported in the literature is presented in Fig. 1.6.

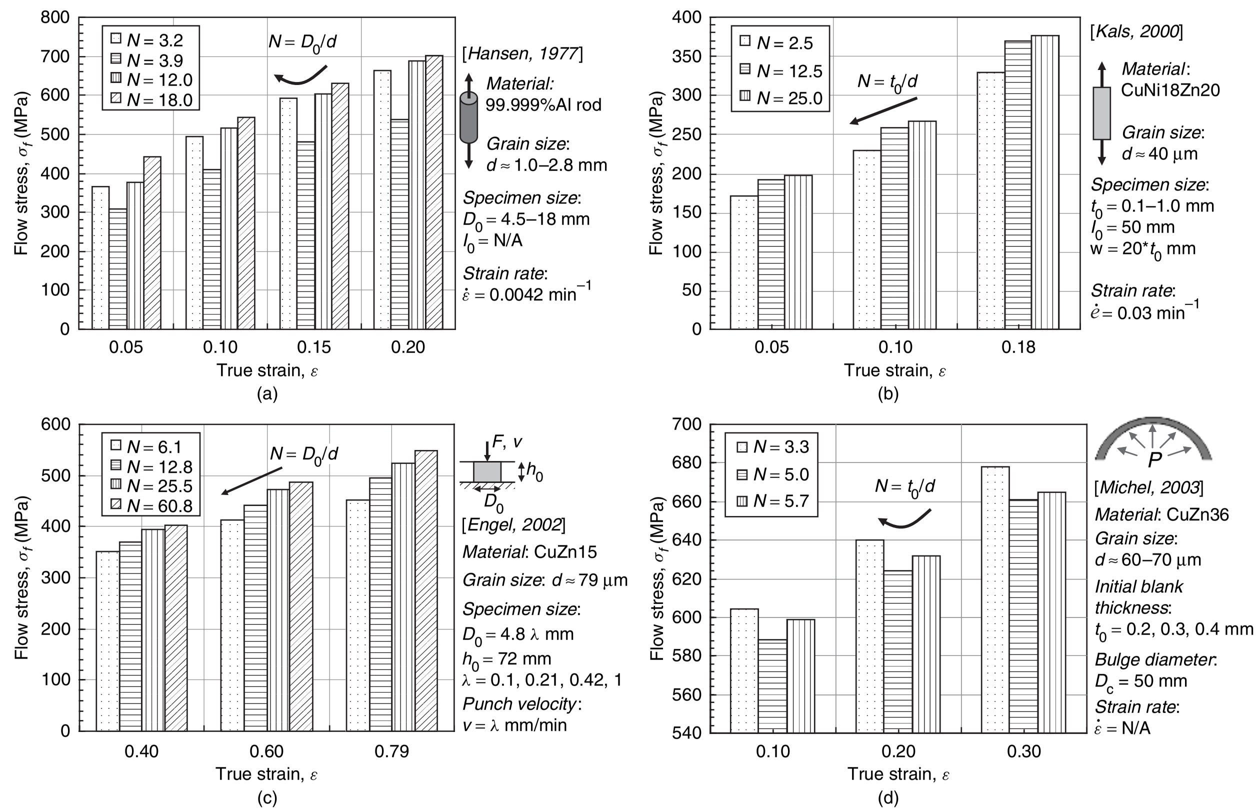


Figure 1.5 Effect of N on material flow stress under different testing conditions.

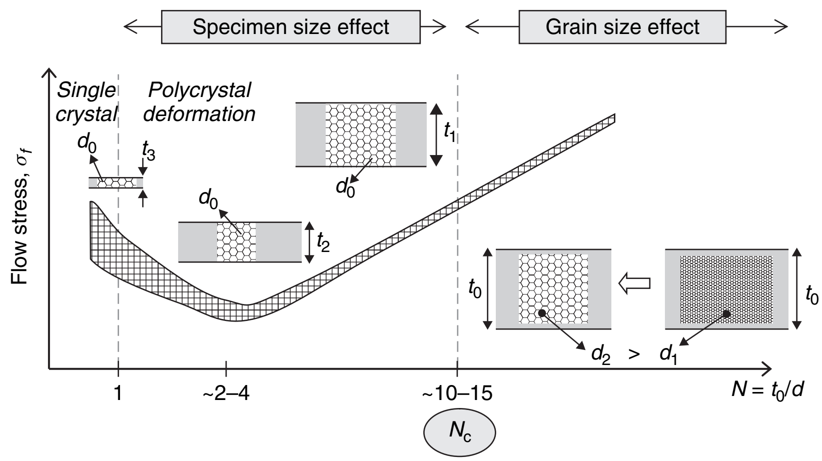


Figure 1.6 Grain versus specimen size effect on the flow stress as a function of N.

In contrast, studies on the "feature size effect" are only few and quite recent. In a study by Michel and Picart [37], thin blanks of CuZn36 with initial thickness of 0.25 mm were bulged using two different bulge diameters of 20 and 50 mm, corresponding to $M = 80$ and 200, respectively. They observed a decrease in the material flow stress when smaller bulge diameter was used. Their results revealed the effect of the feature size on the material response. Unfortunately, no discussion or explanation for this phenomenon was provided in their publication regarding the feature size effect (i.e., bulge diameter). A comprehensive understanding of the feature size effect (D_c or M) is still lacking and requires further investigations, both qualitatively and quantitatively, due to an impressing fact that micro-/meso-scale channel or feature arrays on a large surface area are increasingly used and needed for a wide range of end products for enhanced heat/mass transfer purposes.

1.2.2 Numerical Modeling of Micro-scale Deformation

Finite element analysis (FEA) is an important and respected research tool used to support, and in some cases, explain the results obtained from the experiment or derived from traditional approaches of theory. As with any tool, its effectiveness depends heavily on the skill and dedication of the researcher who guides its use. This is especially true in micro-forming research where properties of material differ from conventional scale, and the ambiguous characterization of the deformation mechanism and surface interaction is not fully understood. Since the length scale of the micro-forming processes is in the range of a few hundred micrometers, which is between the macro-scale (millimeter) and the molecular scale (angstrom), both continuum mechanics and molecular dynamics (MD) simulations appear to be legitimate candidates.

MD deals with simulating the motion of molecules to understand the physical phenomena that derive from dynamics molecular interactions. The goal of MD simulations is to understand and to predict macro-scopic phenomena from the properties of individual molecules making up the system. With continuing advances in the methodology and the speed of computers, MD studies are being extended to larger systems, greater conformational changes, and longer time scales. The results available today make it clear that the applications of MD will play an even more important role in the future [41].

On the other hand, in continuum mechanics, material and structural properties are assumed to be homogeneous throughout the entire structure for a simplifying approximation of physical quantities such as energy and momentum. Differential equations are employed in solving problems in continuum mechanics. Some of these differential equations are specific to the materials being investigated, and are called constitutive equations, while others capture fundamental physical laws such as conservation of mass or conservation of momentum. The physical laws of solids and fluids do not depend on the coordinate system in which they are observed. Despite the fact that continuum mechanics completely ignores the heterogeneity in a structure, the continuum mechanics simulation has been successfully used in a wide range of application in many research fields. Continuum mechanics was originally intended to model the behavior of structural components, with dimensions of order 0.1–100 m or so. To apply the continuum mechanics in micro-scale analysis, the issue we need to address is the actual fact that the material is highly inhomogeneous at this micro-level, and that as a result the stress and strain fields are nowhere being near uniform and homogeneous.

The obvious advantage of the MD simulation over the continuum mechanics simulation is that it gives a route to dynamical properties of the system: transport coefficients, time-dependent responses to perturbations, rheological properties, and spectra. The predictions are “exact” in the sense that they can be made as accurate as we like, subject to the limitation imposed by the computer budget [42]. However, since MD simulations start at the scale of an atom and the time on the order of femtoseconds, running simulations to large size and times is prohibitive. In fact, in terms of computing power, there is a competition between the time and size scales as illustrated in Fig. 1.7 [43]. Note that nonlocal continuum mechanics theories involve adding strain gradients or dislocation density evolution equations that include a spatial length scale.

Figure 1.7 shows that as the simulation time (inversely related to the applied strain rate) increases, the computational power is the main constraint that limits the size of the block material. Similarly, as the block size increases, the computational times require fairly large applied strain rates (i.e., short simulation time). Strain rates lower than the order of $10^6\ s^{-1}$ are not feasible at this time in atomistic simulations. For example, a 10-nm cubic domain of a metal can be simulated only for times less than around 10^{-10} s, even on very large parallel machines [43]. This computational limitation is the major factor that prevents the extensive use of MD simulations in an analysis of structures larger than nanometer scale.

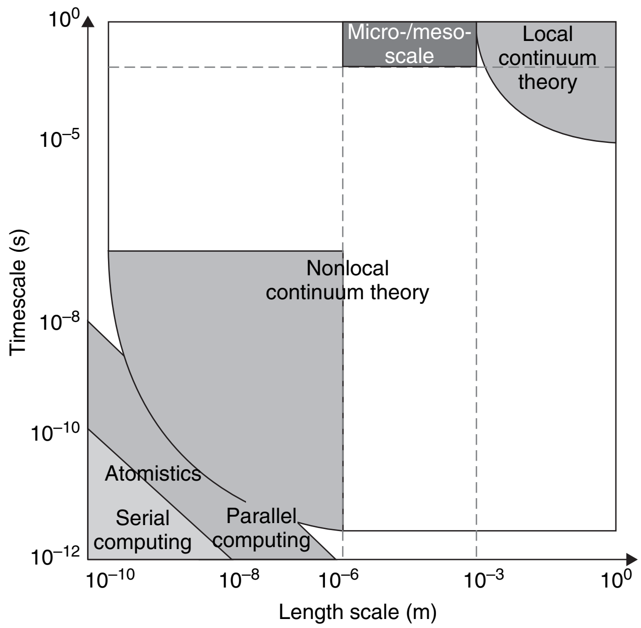


Figure 1.7 Schematic of strain rate and spatial size scale effects on computing and the regions where local and nonlocal continuum theories are applicable [43].

1.3 MICRO-MACHINING FOR DISCRETE PART MICRO-MANUFACTURING

There is a growing need for fast, direct, and mass manufacturing of miniaturized functional products from metals, polymers, composites, and ceramics. The demand for miniaturized meso-(1–10 mm)/micro-(1–1000 μm) devices with high aspect ratios and superior surfaces has been rapidly increasing in aerospace, automotive, biomedical, optical, military, and micro-electronics packaging industries [44,45].

In the last two to three decades, the micro-manufacturing processes such as *wet etching, plasma etching, ultrasonic, and LIGA (German acronym for lithography, electroplating, and molding*), which are a result of the explosion of activities in MEMS, have been developed and widely used for manufacturing micro-parts [44,46]. However, most of these methods are slow, and limited to a few silicon-based materials [46]. Also, the MEMS-based methods are typically planar; that is, 2.5D processes that are not capable of fabricating many of the miniature parts that consist of true three-dimensional (3D) features, for example a micro-mold for a plastic injection of micro-parts [46]. Moreover, a majority of these processes require a high setup time and cost, hence they are not economical for small batch size production. In short, the limitations of the MEMS-based methods in terms of material choices, part dimensions, and production sizes make these processes unsuitable for manufacturing of many complex miniature parts.

Since the MEMS-based methods are not capable of meeting every demand, other alternative processes such as mechanical micro-machining (e.g., micro-milling) combined with numerical control (NC) machine tool technology [47–49]—*micro-electro-discharge machining* (Micro-EDM), *laser beam micro-machining* (LBM), and *focused ion beam* (*FIB*) *machining*—offer alternative fabrication methods [50] to bridge the gap between meso- and micro-scale direct manufacturing of discrete parts or dies and molds for micro-forming micro-injection-molding-type massmanufacturing micro-parts (Fig. 1.8).

Mechanical micro-machining (or tool-based micro-machining) as scaled down versions of turning, milling, and drilling is rapidly gaining momentum in industrial applications because of its viability to directly produce miniature 3D functional parts from a wide range of materials with high precision [48,52–54].

LBM is another alternative to produce features in micron sizes using long (*nanosecond*) and short (*femtosecond*) pulsed lasers as shown in Figure 1.9 on transparent/translucent, nonconductive, and elastic polymers (acrylic, polycarbonate, PEEK (polyetheretherketone), PMMA (polymethylmethacrylate), PDMS (polydimethylsiloxane), elastomers, and others) and difficult-to-process materials (hard metals, ceramics, diamond, and glass) for a variety of applications ranging from biosensors to micro-fluidic devices, solar-cell surfaces (see Figure 1.10), metallic medical devices (coronary stents) to optical and photonic devices.

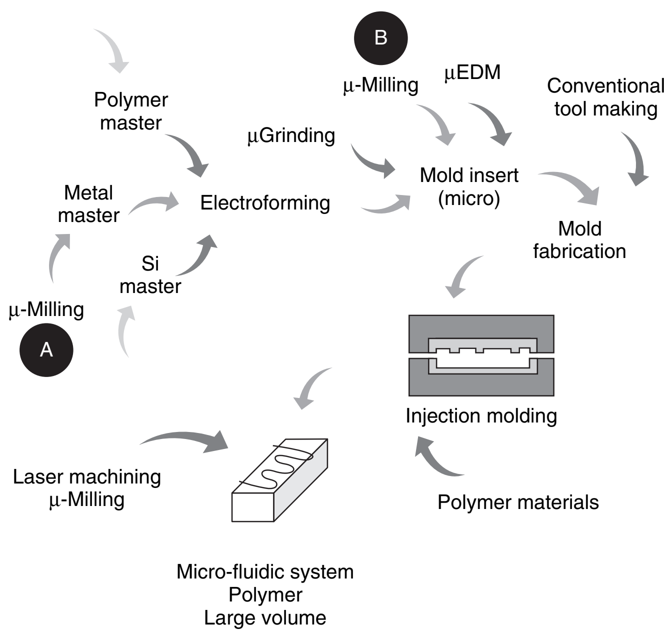


Figure 1.8 Micro-machining processes for micro-injection molding [51].

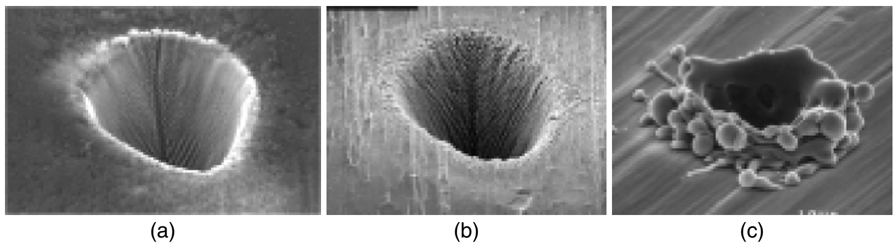


Figure 1.9 Pulsed laser beam micro-machining: (a) Holes drilled with a Ti sapphire system (120 femtoseconds) in air and (middle) in vacuum. (b) A hole drilled by an Nd: YAG laser (λ = 1.06 μm; pulse width = 100 ns, P = 50 mW, 2 kHz). *Source:* All images were taken from the entry side of the Kovar foil. (Courtesy of Sandia Manufacturing Science and Technology Center, http://mfg.sandia.gov).

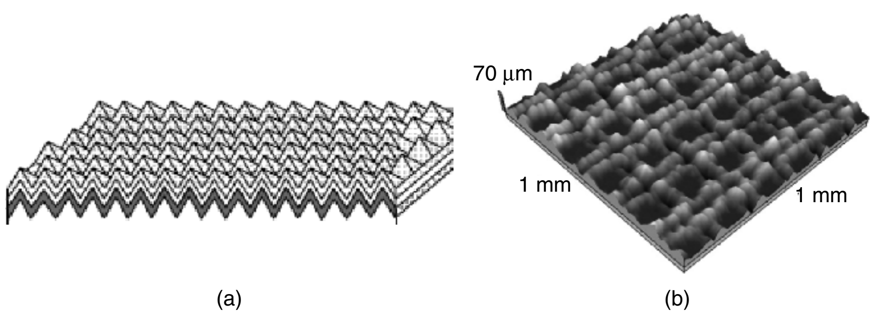


Figure 1.10 (a) Design of multifunctional solar cell surfaces and (b) surface texturing with laser scribing [45,50].

Micro-manufacturing processes have different material capabilities and machining performance specifications. Machining performance specifications of interest include *minimum feature size, feature tolerance, feature location accuracy, surface finish*, and *material removal rate* (Table 1.2). Mechanical micro-machining utilizes miniature cutting tools, ultra-high-speed spindles and high precision machine tools. However, there exist some technological barriers. These can be on the size of the cutting tool; for instance, the diameter of small production micro-drills is about 25 μm, and the diameter of micro-milling tools is about 20 μm [17,48,52,53,55–57]. It can have limitations on feature tolerance with error compensation between 250 and 500 nm, or on the flat and round surface produces; for example, roughness of micro-drilled hole walls is about 10–50 nm and roughness of diamond machined surfaces is about 5 nm [17,48,52,53,55–60]. These limitations are a result of several factors such as lack of technologies to fabricate viable and economical smaller cutting tools, accuracy and repeatability of machine tool drives, tool deflections and vibrations (especially in micro-milling process), size effect, and minimum chip thickness requirements in mechanical micro-machining processes, which is always a problem in ductile- and coarse-grained polycrystalline micro-structure metals [48,53,59,61].

There is also a growing need in parallel for high precision and accuracy metrology instruments. Capability of metrology instruments can be summarized as resolution limit of many *optical instruments* is about 1 µm, of *scanning electron micro-scopes* is about 1–2 nm, of *laser interferometers* is about 1 nm, and of *scanning probe micro-scopy* is about 0.1 nm [45,50].

However; despite its benefits, scaling down the mechanical machining process from the macro- to micro-scale is not as easy as it sounds. Many factors that can be neglected in macro-scale machining suddenly become significant in micro-scale machining; for example, material structure, vibration, and thermal expansion [52–54,60]. As a result, the application of micro-mechanical machining process is still limited. Many technological obstacles need to be resolved, and many physical phenomena need to be well understood. In this chapter, a brief review of micro-mechanical machining is presented.

1.3.1 Size Effects in Micro-machining Processes

Despite its success in manufacturing macro-scale parts, scaling down the mechanical machining process into micro-scale production encounters several difficulties(see example of micro-parts in Figure 1.11). It is important to note that as the mechanical machining is scaled down, many physical and mechanical properties of material removal process, which are less pronounced in macro-mechanical machining, play very important roles in micro-mechanical machining. As a result, there are some specific issues that occur only in mechanical machining at micro-scale; for example, size effect and minimum uncut chip thickness.

The term *size effect* in metal cutting (chip formation) processes is often referred to as nonlinear increase in the specific cutting energy with decreasing undeformed chip thickness. Vollertsen *et al.* [62] presented a decreasing trend in shearing energy per unit volume for machining processes with data for SAE 1112 steel from Taniguchi *et al.* [63] and tensile tests from Backer [64] as shown in Fig. 1.12.

Given that flow stress, in most metals, increases as strain rate increases, the strain rate sensitivity of flow stress also increases rapidly in the range applicable to machining type processes ($>10^4\ s^{-1}$); therefore, specific cutting pressure could increase as undeformed chip thickness decreases.

Performance of mechanical micro-machining processes is influenced by work material micro-structure; for example, anisotropy, crystalline orientation, grain size, and boundaries [65–67]. Most commonly used engineering materials such as steel and aluminum have the length of crystalline grain size between 100 nm and 100 µm, which is comparable to the size of micro-feature. Therefore, in micro-mechanical machining, shearing takes place inside the individual grain

TABLE 1.2 Fundamental Principle, Capabilities, and Performance Specifications of Micro-manufacturing Processes

Process	Principle	Minimum Feature Size	Tolerance	Production Rates	Materials
Micro-extrusion	Plastic deformation by force	50 μm	5 μm	High/mass Fair accuracy	Ductile metals
Micro-molding/ casting	Melting and solidification by heat	25–50 μm	5 μm	High/mass Fair accuracy	Polymers/ metals
Mechanical micro-machining	Chip formation by force	10 μm	1 μm	High MRR High accuracy	Metals/ polymers/ ceramics
Micro-EDM	Melting/ breakdown	10 μm	1 μm	High MRR High accuracy	Conductive materials
Excimer laser	Ablation by laser beam	6 μm	0.1–1 μm	Low MRR High accuracy	Polymers/ ceramics
Short-pulse laser	Ablation by laser beam	1 μm	0.5 μm	Low MRR High accuracy	Almost any
Focused ion beam	Sputtering by ion beam	100 nm	10 nm	Very low MRR High accuracy	Tool—steels, nonferrous, plastics

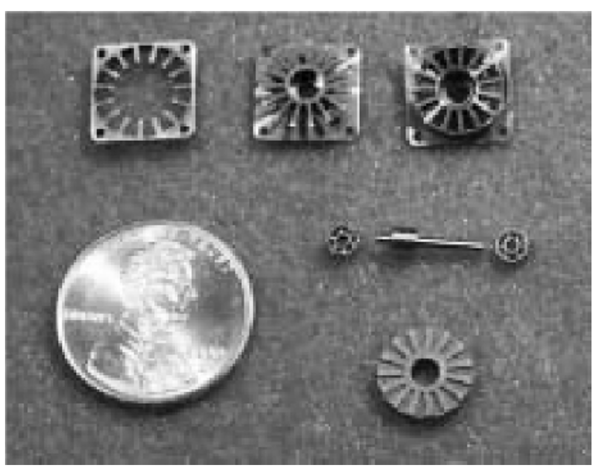


Figure 1.11 Meso-scale stepper motor (10 mm × 10 mm × 5 mm) machined by Micro-EDM process. *Source:* Courtesy of Sandia Manufacturing Science and Technology Center.

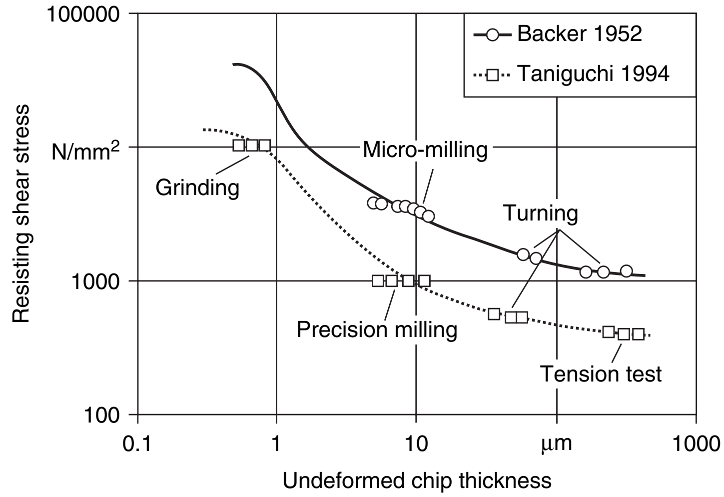


Figure 1.12 Increasing shear stress during material separation for decreasing undeformed chip thickness in several micro-manufacturing processes [62].

instead of along the grain boundary as in macro-mechanical machining. Characteristic dimesions of crystals (grains) on polycrystalline metarials, and phases on multiphase materials, are commensurate with the tool dimensions and uncut chip thickness values. Both elastic and plastic behavior of individual crystals are anisotropic, and therefore the cutting action experiences different mechanical properties when passing through different grains [56,66–68]. Thus, machining force magnitudes, rake face friction, and elastic recovery will vary during the process. In summary, micro-structure of work material plays an important role in mechanical micro-machining.

As an example, the size effect is demonstrated with measured specific forces in flat end milling process using miniature end mills with decreasing feed per tooth, and hence undeformed chip thickness in Fig. 1.13. As it can be seen, the undeformed chip thickness values less than 1 µm create a nonlinear increase in specific cutting forces measured [60].

In micro-mechanical machining, owing to limited strength of the edge of the micro-cutting-tool, the uncut chip thickness is constrained to be comparable or even less than the size of the tool edge, and as a result a chip will not be generated. The chips will be generated, and material removal will be achieved only when the uncut chip thickness reaches a critical value, the so-called *minimum chip thickness* [69]. Minimum (or critical) uncut chip thickness is considered to be a measure of the highest attainable accuracy [70,71]. No chip is produced with a chip thickness less than a critical value, and the entire material is forced under the cutting tool and deformed. Especially, in micro-milling, the elastic portion of the deformation recovers after the tool passes [52,72,73].

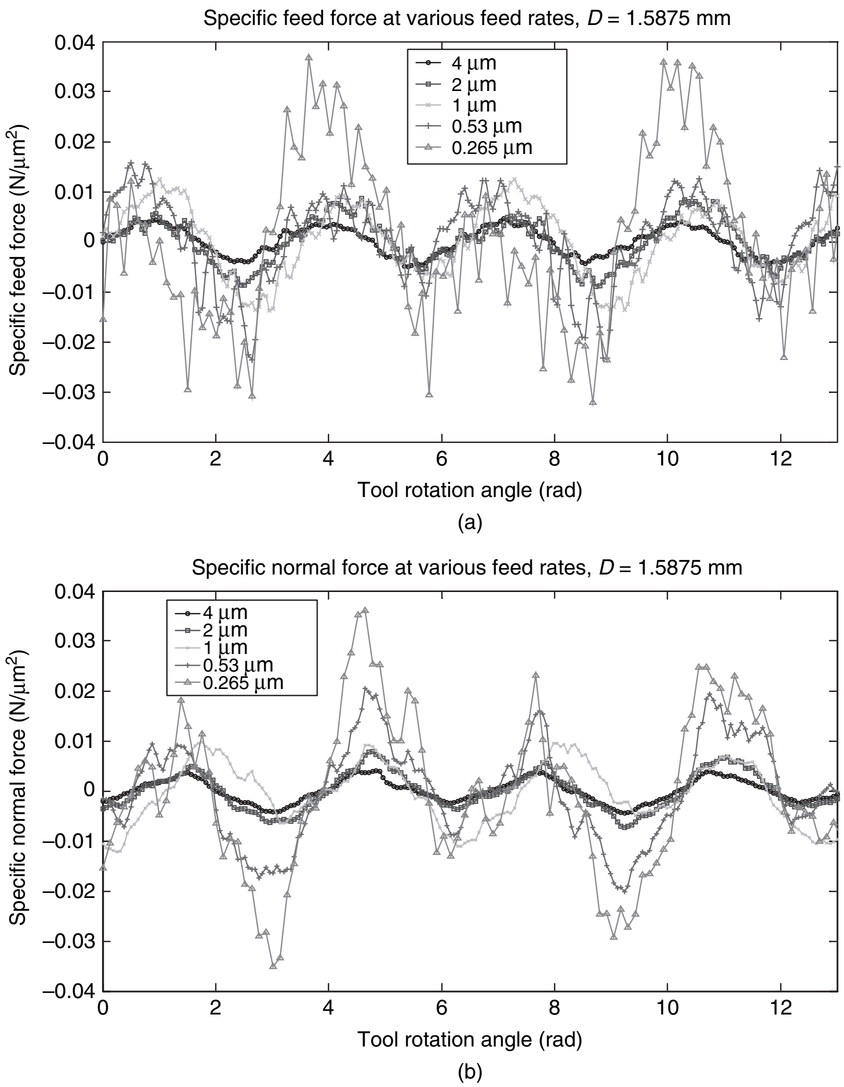


Figure 1.13 Size effect on the forces acting on the flat end milling tool during full immersion milling: (a) effect of reduction in feed per tooth on feed force; (b) effect of reduction in feed per tooth on normal force (two-flute end mill, 30 helix angle, $N = 6000$ rpm) [60].

The minimum chip thickness requirement significantly affects machining process performance in terms of cutting forces, tool wear, surface finish, process stability, etc. [55,72,73]. Hence, knowledge of the minimum chip thickness is important for the selection of appropriate machining conditions. In order to estimate the normalized minimum chip thickness, researchers have resorted to

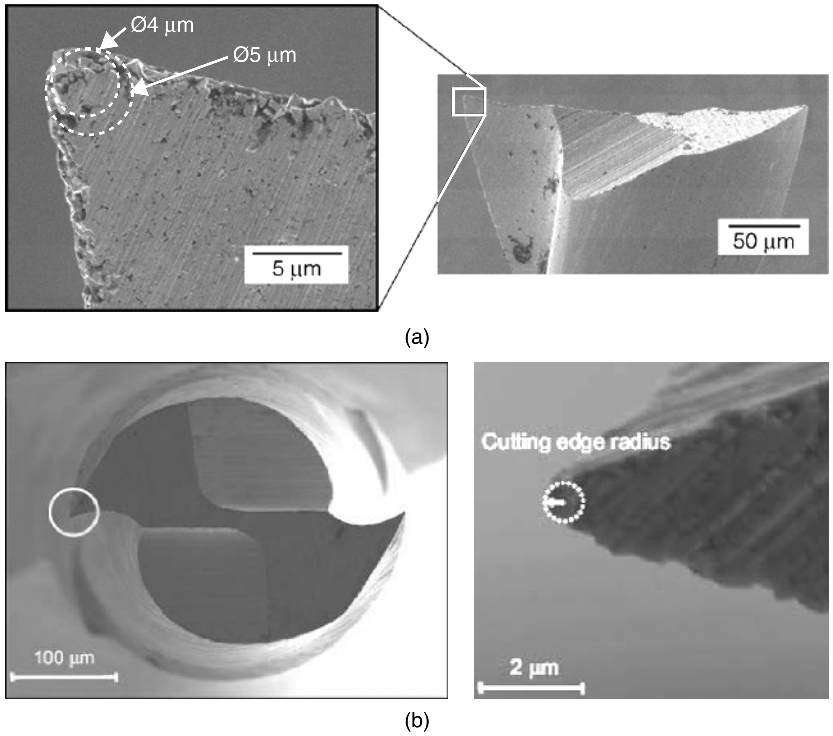


Figure 1.14 (a) Cutting edge of a tungsten carbide (WC) micro-end-mill under SEM indicating a large cutting edge and corner radius [59]; (b) 500 μm diameter micro-end-mill and edge radius [76].

experimentation [72,73], MD simulations [74], and micro-structure-level force models [56], as well as to analytical slip-line plasticity-based models [75].

The minimum chip thickness is considered to be related to the resistivity of the material against plastic deformation, such as indentation hardness. It is found to be strongly dependent on the ratio of chip thickness to cutting edge radius and on the workpiece material/tool combination. Some images depicting tool edge radius are given in Fig. 1.14 as examples. It was seen to be between 5% and 38% of the edge radius for different materials [75].

Numerical models have been created for micro-machining of single crystalline materials (copper and aluminum) and polycrystalline materials (aluminum alloys, cast iron, and steels) with an aim to understanding of deformations including micro-structure and grain size effects and the influence of tool edge radius on micro-milling [56,60,74,76–78]. Micro-machining-induced plastic deformation, white layer formation, subsurface alteration, and residual stresses on the fabricated materials are analyzed through the FEM (finite element method)-based process simulations. Furthermore, by using FEM-based process

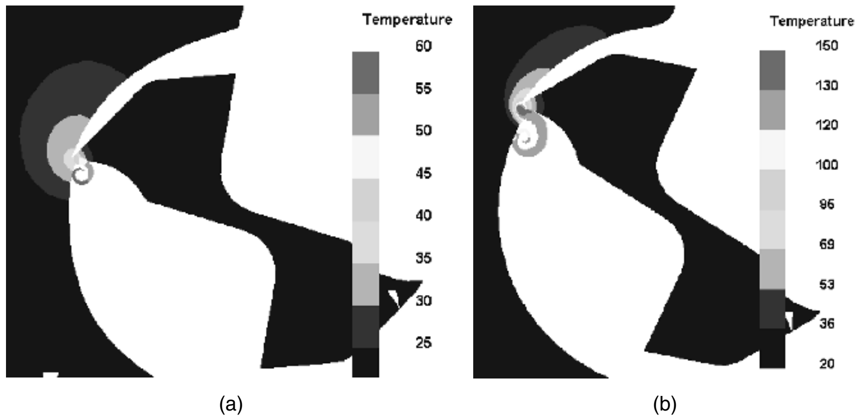


Figure 1.15 FEM simulation of micro-milling: (a) AL2024-T6 aluminum and (b) AISI 4340 steel [60].

simulations, micro-end-mill tool geometry and machining parameters can be investigated (Fig. 1.15) [60].

REFERENCES

1. Rachkovkij DA, *et al.* Heat exchange in short micro tubes and micro heat exchangers with low hydraulic losses. J Microsyst Technol 1998;4:151–158.
2. Lee SJ, *et al.* Design and fabrication of a micro fuel cell array with flip-flop interconnection. J Power Sources 2002;112:410–418.
3. Meng DS, Kim J, Kim CJ. A distributed gas breather for micro direct methanol fuel cell. Proc IEEE 2003:534–537.
4. Khanna R. MEMS fabrication perspectives from the MIT microengine project. Surf Coat Technol 2003;163–164:273–280.
5. Trackenmueller R, *et al.* Low cost thermoforming of micro fluidic analysis chip. J Micromech Microeng 2002;12:375–379.
6. Aoki I, *et al.* Trial production of medical micro tool by metal deformation processes using moulds. Proc IEEE 1995:344–349.
7. Chu M. Design and Fabrication of Active Microcage [MS thesis]. Los Angeles (CA): Mechanical and Aerospace Engineering Department, University of California; 1998.
8. Chovan T, Guttman A. Microfabricated devices in biotechnology and biochemical processing. Trends Biotechnol 2002;20(3):116.
9. Yeh R, Kruglick EJJ, Pister KSJ. Surface-micro machined components for articulated micro robots. J MEMS 1996;5(1):10–17.
10. Hayashi I, Iwatsuki N. Micro moving robotics. International Symposium on Micro mechatronics and Human Science; 1998 Nov. 25–28; Nagoya. 1998. pp 41–50.

11. Dudenhoeffer DD, Bruemmer DJ, Anderson MO, McKay MD. Development and implementation of large-scale micro-robotic forces using formation behaviors. Idaho National Engineering and Environmental Laboratory (INEEL), ID 83415 INEEL Long-Term Research Initiative Program under DOE Idaho Operations Office Contract DE-AC07-99ID13727 and through DARPA Software For Distributed Robotic program contract J933.
12. Kim J, Koratkar NA. Effect of unsteady blade motion on the aerodynamic efficiency of micro-rotorcraft. Proceedings of the 44th AIAA/ASME/ASCE/AHS Structures, Structural Dynamics and Materials Conference; 2003 Apr 7–10; Norfolk, VA. 2003.
13. Eddy DS, Sparks DR. Application of MEMS technology in automotive sensors and actuators. Proc IEEE 1998;86:1747–1755.
14. Fujita H. Micro actuators and micro machines. Proc IEEE 1998;86:1721–1732.
15. Choundhury PR, editor. Handbook of microlithography, micromachining and microfabrication. Volume 2: Micromachining and microfabrication. Bellingham (WA): SPIE Press; 1997.
16. Fukuda T, Menz W, editors. Micro mechanical systems: principles and technology. Amsterdam: Elsevier; 1998. pp 260–271.
17. Friedrich CR, Vasile MJ. Development of the micro milling process for high aspect-ratio micro structures. J MEMS 1996;5:33–38.
18. Ashida K, *et al.* Development of desktop machining micro factory—trial production of miniature machine products. Proceedings of Japan-USA Flexible Automation Conference; 2000 Jul 23–26; Ann Arbor, MI. 2000.
19. Engel U, Eckstein E. Microforming-from basics to its realization. J Mater Process Technol 2002;125–126:35–44.
20. Pacific Northwest National Laboratory Web Site. Available at www.pnl.gov.(accessed on May 1, 2010).
21. Ni J. Meso scale mechanical machine tools and micro milling process development for future micro factory based manufacturing. Proceedings of SATEC '03; China. 2003.
22. Geiger M, Messner A, Engel U. Production of micro parts–size effects in bulk metyaal forming, similarity theory. Prod Eng 1997;4(5):15.
23. Raulea L, *et al.* Grain and specimen size effects in processing metal sheets. Volume II, Proceedings of the 6th ICTP: Advanced Technology of Plasticity; 1999 Sep 19–24; Nuremberg, Germany. 1999. pp 939.
24. Saotome Y, Iwazaki H. Superplastic backward micro extrusion of micro parts for micro-electro-mechanical systems. J Mater Process Technol 2001;119:307–311.
25. Ike H, Plancak M. Coining process as a means of controlling surface microgeometry. J Mater Process Technol 1998;80–81:101–107.
26. Tiesler N, Engel U. Microforming-effects of miniaturization. In: Pietrzyk M, *et al.*, editors. Proceedings of the International Conference on Metal Forming. Rotterdam, Netherlands: Balkema; 2000. pp. 355.
27. Geiger M, Kleiner M, Eckstein R, Tiesler N, Engel U Microforming. Ann CIRP 2001;50(2):445. Keynote paper.
28. Vollertsen F, Hu Z, Schulze Niehoff H, Theiler C. State of the art in micro forming and investigations into micro deep drawing. J Mater Process Technol 2004;151:70–79.

29. Engel U, Egerer E. Basic research on cold and warm forging of microparts. Key Eng Mater 2003;233–236:449–456.
30. Armstrong RW On size effects in polycrystal plasticity. J Mech Phys Solids 1961;9:196–199.
31. Kim G, Koç M, Ni J. Modeling of the size effects on the behavior of metals in micro-scale deformation processes. J Manuf Sci Eng 2007;129:470–476.
32. Hall EO. Deformation and ageing of mild steel. Phys Soc Proc 1951;64(B381): 747–753.
33. Petch NJ. Cleavage strength of polycrystals. J Iron Steel Inst 1953;174:25–28.
34. Koç M, Mahabunphachai S. Feasibility investigations on a novel micro-manufacturing process for fabrication of fuel cell bipolar plates: Internal pressure-assisted embossing of micro-channels with in-die mechanical bonding J Power Sources 2007;172:725–733.
35. Miyazaki S, Fujita H, Hiraoka H. Effect of specimen size on the flow stress of rod specimens of polycrystalline Cu-Al alloy. Scripta Metall 1979;13:447–449.
36. Kals TA, Eckstein R. Miniaturization in sheet metal working. J Mater Process Technol 2000;103:95–101.
37. Michel JF, Picart P. Size effects on the constitutive behaviour for brass in sheet metal forming. J Mater Process Technol 2003;141:439–446.
38. Hansen N. The effect of grain size and strain on the tensile flow stress of aluminium at room temperature. Acta Metall 1977;25:863–869.
39. Raulea LV, Goijaerts AM, Govaert LE, Baaijens FPT. Size effects in the processing of thin metals. J Mater Process Technol 2001;115:44–48.
40. Onyancha RM, Kinsey BL. Investigation of size effects on process models for plane strain microbending. Proceedings of the International Conference on Manufacturing Science and Engineering (MSEC); 2006 Oct 8–11; Ypsilanti, MI. 2006.
41. Karplus M. Molecular dynamics of biological macromolecules: a brief history and perspective. Biopolymers 2003;68:350–358.
42. Allen JP, *et al.* Nested stamped sheet metal plates to make an internal chamber. US patent 6,777,126. 2004.
43. Horstemeyer MF, Baskes MI, Plimpton SJ. Computational nanoscale plasticity simulations using embedded atom potentials. Theor Appl Fract Mech 2001;37:49–98.
44. Alting L, Kimura F, Hansen HN, Bissacco G. Micro engineering. Ann CIRP 2003;52(2):635–657.
45. De Chiffre L, Kunzmann H, Peggs GN, Lucca DA. Surfaces in precision engineering, microengineering and nanotechnology. Annals of the CIRP 2003;52/2:561–577.
46. Madou M Fundamentals of microfabrication. Boca Raton, FL: CRC Press; 1997.
47. Masuzawa T, Tonshoff HK. Three-dimensional micro-machining by machine tools. Ann CIRP 1997;46(2):621–628.
48. Dornfeld D, Min S, Takeuchi Y. Recent advances in mechanical micromachining. Ann CIRP 2006;55(2):745–768.
49. Liow JL. Mechanical micromachining: a sustainable micro-device manufacturing approach? J Clean Prod 2009;17:662–667.
50. Rajurkar KP, Levy G, Malshe A, Sundaram MM, McGeough J, Hu X, Resnick R, DeSilva A. Micro and nano machining by electro-physical and chemical processes. Ann CIRP 2006;55(2):643–666.

51. Bissacco G, Hansen HN, Tang PT, Fugl J. Precision manufacturing methods of inserts for injection molding of microfluidic systems. Proceedings of the ASPE Spring Topical Meeting; Columbus, OH. 2005. pp 57–63.
52. Cao J, Krishnan N, Wang Z, Lu H, Liu WK. Microforming-experimental investigation of the extrusion process for micropins and its numerical simulation using RKEM. J Manuf Sci Eng 2004;126:642–652.
53. Chae J, Park SS, Freiheit T. Investigation of micro-cutting operations. Int J Mach Tools Manuf 2006;46:313.
54. Asad ABMA, Masaki T, Rahman M, Lim HS, Wong YS. Tool-based micro-machining. J Mater Process Technol 2007;192–193:204.
55. Wuele H, Huntrup V, Tritschle H. Micro-cutting of steel to meet new requirements in miniaturization. Ann CIRP 2001;50(1):61–64.
56. Vogler MP, DeVor RE, Kapoor SG. Microstructure-level force prediction model for micro-milling of multi-phase materials. J Manuf Sci Eng 2003;125:202–209.
57. Asad ABMA, Masaki T, Rahman M, Lim HS, Wong YS. Tool-based micro-machining. J Mater Process Technol 2007;192–193:204.
58. Eda H, Kishi K, Ueno H. Diamond machining using a prototype ultra-precision lathe. Precis Eng 1987;9:115–122.
59. Filiz S, Conley CM, Wasserman MB, Ozdoganlar OB. An experimental investigation of micro-machinability of copper 101 using tungsten carbide micro-endmills. Int J Mach Tools Manuf 2007;47:1088–1100.
60. Dhanorker A, Özel T. Meso/micro scale milling for micromanufacturing. Int J Mechatronics Manuf Syst 2008;1:23–43.
61. Özel T, Liu X. Investigations on mechanics based process planning of micro-end milling in machining mold cavities. Mater Manuf Process 2009;24(12):1274–1281.
62. Vollertsen F, Biermann D, Hansen HN, Jawahir IS, Kuzman K. Size effects in manufacturing of metallic components. CIRP Ann—Manuf Technol 2009;58:566–587.
63. Backer WR, Marshall ER, Shaw MC. The size effect in metal cutting. Transact ASME 1952;74:61–72.
64. Taniguchi N. The state-of-the-art of nanotechnology for processing ultra-precision and ultra-fine products. Precis Eng 1994;16(1):5–24.
65. vonTurkovich BF, Black JT. Micro-machining of copper and aluminum crystals. J Eng Ind Transact ASME 1970;92:130–134.
66. Ueda K, Manabe K. Chip formation mechanism in microcutting of an amorphous metal. Ann CIRP 1992;41:129–132.
67. Zhou M, Ngoi BKA. Effect of tool and workpiece anisotropy on microcutting processes. Proc Inst Mech Eng (IMechE) 2001;215:13–19.
68. Egashira K, Mizutani K. Micro-drilling of monocrystalline silicon using a cutting tool. Precis Eng 2002;26:263–268.
69. Ikawa N, Shimada S, Tanaka H. Minimum thickness of cut in micromachining. Nanotechnology 1992;3:6–9.
70. Lucca DA, Rhorer RL, Komanduri R. Energy dissipation in the ultraprecsion machining of copper. CIRP Ann—Manuf Technol 1991;40:69–72.
71. Lucca DA, Seo YW, Rhorer RL, Donaldson RR. Aspects of surface generation in orthogonal ultraprecision machining. CIRP Ann—Manuf Technol 1994;43:43–46.

72. Vogler MP, DeVor RE, Kapoor SG. On the modeling and analysis of machining performance in micro-endmilling. Part I: Surface generation. ASME J Manuf Sci Eng 2004;126:685–694.

73. Vogler MP, DeVor RE, Kapoor SG. On the modeling and analysis of machining performance in micro-endmilling. Part II: Cutting force prediction. ASME J Manuf Sci Eng 2004;126:695–705.

74. Shimada S, Ikawa N, Tanaka H, Ohmori G, Uchikoshi J, Yoshinaga H. Feasibility study on ultimate accuracy in microcutting using molecular dynamics simulation Ann CIRP 1993;42:91–94.

75. Liu X, DeVor RE, Kapoor SG. An analytical model for the prediction of minimum chip thickness in micromachining. ASME J Manuf Sci Eng 2006;128:474–481.

76. Torres CD, Heaney PJ, Sumant AV, Hamilton MA, Carpick RW, Pfefferkorn FE. Analyzing the performance of diamond-coated micro end mills. Int J Mach Tools Manuf 2009;49:599–612.

77. Lai X, Li H, Li C, Lin Z, Ni J. Modelling and analysis of micro scale milling considering size effect, micro cutter edge radius and minimum chip thickness. Int J Mach Tools Manuf 2008;48:1–14.

78. Woon KS, Rahman M, Neo KS, Liu K. The effect of tool edge radius on the contact phenomenon of tool-based micromachining. Int J Mach Tools Manuf 2008;48:1395–1407.