

# Overview of Micro-Manufacturing

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## **INTRODUCTION**

Manufacturing, as a general term referring to industry, is to make products that have been designed for certain applications. The meaning of 'manufacture' has, however, changed, especially during the last 20 years, in terms of what is being made, how it is made, how manufacturing is organized, etc. Manufacturing has been influenced not only by the increased demands on producing routine products and creating new products but also by social, economic and even political changes. The desire for a better quality of life, good health and high working efficiency has been one of major drives in the innovation of many products, such as new models of computers, cars, mobile phones, CD players, MP3 players, wide flat-screen displays, medical instruments/implants, etc. Dramatic changes in global, economic development during the last 15 years have significantly influenced how manufacturing is organized and implemented, e.g. new concepts concerning supply chains, new patterns for collaborations, etc., to such an extent that in a lot of cases, how to organize manufacturing becomes even more important than how the products are to be manufactured. How to achieve a balance between quality and cost is another major issue, since many industries are fighting for survival. Nevertheless, some general issues still apply to all sectors concerned, e.g. issues on how to quickly deploy new technologies and management

methods to improve manufacturing capability, efficiency and quality, no matter whether they belong to traditional, developed countries/regions or developing countries/regions. For the developed countries to compete with low-cost production, the manufacturing industry will need more innovations and changes of the focus. Reducing the cost by significantly improving efficiency and supply chains, maintaining technological advantages by continuously developing leading technologies/capabilities, and delivering higher quality and innovative products are being pursued. For the developing countries, low-cost manufacturing may only be a short-term solution and not the ultimate goal, as this will have limited impact/effect in the long term. From these considerations, as a contribution to competitive manufacturing, this book provides a useful reference for the manufacture of emerging miniature/micro-products, especially for improving mass-manufacturing capabilities and their applications for the manufacture of these products.

There are ever increasing demands on miniaturized/micro products/systems and components, e.g. MEMS (micro-electric-mechanical systems) and micro-systems, micro-reactors, fuel cells, micro-mechanical devices, micro-medical components, etc., which are now popularly used in vehicles, aircraft, telecommunication and IT facilities, home appliances, medical devices and implants. Manufacture of these products has received great

attention during recent years. At the same time, as nanotechnology becomes more and more mature and influential, more nanotechnology-based products have emerged, such as nano-devices for sensors, communication and medical treatment, nano-materials and coating/functionalized surfaces for enhanced performances, etc. To make these products in a volume production scale, effectively linking macro- and nano-world manufacturing is essential. Micro-manufacturing is the bridge between macro-manufacturing and nano-manufacturing.

Micro-manufacturing concerns manufacturing methods, technologies, equipment, organizational strategies and systems for the manufacture of products and/or features that have at least two dimensions that are within sub-millimeter ranges. Micro-manufacturing engineering is a general term which concerns a series of relevant activities within the chain of manufacturing micro-products/features, including design, analysis, materials, processes, tools, machinery, operational management methods and systems, etc. There is a huge diversity in micro-products, the main types being micro-electronics products, micro-optical electronics systems (MOES), micro-electronics mechanical systems (MEMS) and micro-optical electronics mechanical systems (MOEMS), depending on the combinations of product functionalities and/or working principles. Correspondingly, there are different methods and strategies which could be used to manufacture these products. Micro-manufacturing, in a wider context, should cover all these aspects relating to manufacturing these products/features. The definition of micro-manufacturing, or its gravity/focus, often varies from different sources.

There is an enormous amount of literature on the manufacture of MEMS and micro-systems. The technologies relating to design and fabrication of these micro-systems are sometimes referred to either as micro-system technology (MST) or MEMS techniques. In order to differentiate from other manufacturing techniques, micro-manufacturing techniques are often categorized respectively as MEMS manufacturing and non-MEMS manufacturing. MEMS

manufacturing involves, largely, techniques such as photolithography, chemical etching, plating, LIGA, laser ablation, etc. while non-MEMS manufacturing often involves techniques such as EDM, micro-mechanical cutting, laser cutting/patterning/drilling, micro-embossing, micro-injection molding, micro-extrusion, micro-stamping, etc. Regarding the materials used, micro-manufacturing is also sometimes categorized as silicon-based manufacturing and non-silicone material manufacturing. The purpose of differentiating these is sometimes to emphasize the importance of the latter as an urgent need for development, since silicon-based manufacturing is often seen as a 'mature' business.

For people who are involved in MEMS-based manufacturing, micro-manufacturing may be not a new term, as they may feel that manufacturing various MEMS has been undertaken by industry for many years, which has also been performed at volume-production scales. For people who are newly engaged in non-MEMS-based manufacturing, micro-manufacturing is somehow seen as a recently emerging field of significant challenges. This is not only because manufacturing will have to deal with much wider ranges of materials, which cannot be handled by traditional MEMS-based manufacturing techniques alone, but also because scaling down the processes, tools and machinery from conventional ones such as mechanical/thermal cutting/forming to meet the needs of achieving much smaller dimensions and sophisticated features is new and extremely challenging. In this sense, the emerging micro-manufacturing techniques often refer to non-silicon-based and even non-MEMS-based manufacturing. A new definition of micro-manufacturing, therefore, may be the 'manufacture of micro-products/features with scaled-down conventional technologies/processes'. These include processes such as micro-machining (mechanical, thermal, electric-chemical, electric discharge methods), micro-forming/replication, micro-additive (rapid methods, electro-forming, injection molding, etc.) and joining. Another focus of micro-manufacturing is the manufacture of products/components with miniature

machines/systems, rather than conventional, large-scale machines/systems.

This book is focused on the description of non-silicon-based manufacturing, especially non-MEMS manufacturing techniques and systems, although there are several chapters dealing with the techniques for both MEMS and non-MEMS manufacturing. This chapter is intended as an introduction to micro-manufacturing.

## **MICRO-PRODUCTS AND DESIGN CONSIDERATIONS FOR MANUFACTURING**

Typical micro-products include MEMS and micro-systems for automotive and aerospace use such as pressure sensors, thermal sensors, temperature sensors, gas sensors, rate sensors, sound sensors, injection nozzles, etc., and the components include those for electrostatic, magnetic, pneumatic and thermal actuators, motors, valves and gears [1]. The products also include sensors for mass flow, micro-heat exchangers, micro-chemical reactors, tools/molds for forming/replication, etc., and the components include those for miniaturized electronics products such as mobile phones, MP3 players, CD players, iPods, etc. In the medical sector, the micro-fabricated parts span a wide range for implantable applications in various clinical areas. There are 94 active and 67 commercial 'end items' out of a total of 142, according to the literature [2]. Typical examples are sensors for cardiovascular, micro-machined ceramic packages, implantable devices, coatings on micro-polymers or metal parts, etc. It is fair to say that micro-products and components are almost everywhere in our lives.

Table 1-1 presents some examples of the products/parts which can be made with micro-fabrication techniques, particularly with mechanical and/or thermal micro-manufacturing processes.

Design of products for micro-manufacturing needs to address production issues fully, compared with the prototype products based on micro-technologies. High volume production of micro-components should be a target for design for micro-manufacturing. When these products

are designed, not only will functional requirements need to be considered but also micro-manufacturing related factors will have to be taken into account. This is because, as briefly described above, manufacturing these products renders more significant challenges, compared to the manufacture of macro-products. The following are some typical issues to be addressed at the design stage:

- **Overall dimensions of the parts/products:** overall dimensions of a part/product, like diameters, widths, lengths and thicknesses, are very much constrained by the overall capabilities of the processes and manufacturing facility (machines, handling devices, tools, etc.). Both maximum and minimum dimensions are the parameters to be checked with reference to the manufacturing system's capabilities. Complexity around dimensional scale issues is a dominant factor in micro-/nano-manufacturing. The question often asked may be how small rather than how large a part can be handled.
- **Part/component local features:** design of local features, such as hole/pocket radii and aspect ratios, widths/depths of channels or aspect ratios, wall thickness, area reductions, density of the local features, will be largely constrained by the processing capability in micro-/nano-manufacturing, especially those relying on the use of tools such as replicating processes. There is also the factor of relevant grain size effects of the material to be used. Local features will not only determine the tool geometry, but also affect stiffness/rigidity of the part/product structures, and hence affect the manipulation of the part/product. Manufacture of local features spread over a large area also renders challenges to many micro-manufacturing processes and equipment, even nano-manufacturing.
- **Shape capability:** shape capability considers the capability/limitation of a manufacturing process in dealing with the shapes to be produced. For example, a lot of processes are only able to deal with 2D/2.5D shapes while 3D shapes may need much more significant efforts such as new processes and expensive equipment. Rotational symmetry is probably favorite for micro-

TABLE 1-1

Components/ Parts	Sample Geometry/ Features	Possible Enabling Techniques	Typical Part Materials	Processing Accuracy	Typical Products/ Applications
Surface 2.5D functionalized structures	Local features in hundred nanometers to 10s of microns	Hot embossing/coining/ imprinting, ink-jetting, plating, direct writing, laser ablation, etc.	Polymers, glass, aluminum, copper, brass, steel, etc.	Several microns to nanometers	Micro-optical, fluidic devices, force transmit. surfaces, dies/ molds, etc.
Lead frames	Various geometry, local features as small as ten microns, thicknesses vary, such as between 0.3 and 0.01 mm	Micro-stamping, with/ without laser assistance, laser cutting, photo- chemical etching, etc.	Copper and alloys, nickel steel, etc.	Several microns or to 10% of the sheet thickness	Electronics products
Micro-pins	Diameters in 0.2–1 mm ranges, wall thickness in 50 to 200 microns possible, and tolerances <5 microns	Forward, and/or combined with backward extrusion, micro-shape rolling, micro-machining/EDM.	Various types of metals	Several microns to sub-microns	Various applications as IC carrier, micro- device assembly, electric contacts, etc.
Electro-thermal- mechanical actuator	2.5D/3D structural parts, various sectional geometries	Chemical etching and micro-stamping, laser cutting, efab.	SMA and other metal materials	Several microns	Micro-actuating devices
Micro-cups	Micro-cups, less than 1 mm in diameter, various thicknesses	Micro-deep drawing, micro-stamping, micro-spinning, micro-machining.	Molybdenum, copper, aluminum, steel	Several microns	Electron guns, pressure sensors, UV sensors, etc.
Micro-gears	Diameters of 1 mm or less, local features in 10s of microns	Micro-forging, micro-extrusion, micro-stamping, LIGA, micro-casting, PCE, micro-EDM, efab., etc.	Metals, polymers	Several microns to sub-microns	Micro-mechanical devices, watches
Shafts for micro- mechanical drivers	Less than 1 mm in diameters	Micro-extrusion, micro- machining/EDM.	Steels and alloys	Several microns to sub-microns	Micro-driving- devices, e.g. micro-spindles
Micro-screws, micro-cans	Diameters in 0.1–0.5 mm ranges	Micro-forging, extrusion, shape rolling, micro- machining.	Various metals	Several microns to sub-microns	Micro-devices, housing and assembly, etc.
Micro-gear shafts	Local features in 30–50 microns	Extruded with local heating, micro-radial extrusion, micro- machining, EDM.	Metals	Several microns to sub-microns	Micro-mechanical driving devices, watches

Components/ Parts	Sample Geometry/ Features	Possible Enabling Techniques	Typical Part Materials	Processing Accuracy	Typical Products/ Applications
Casing/housing of micro-devices	Thin sheets, from 0.1 to 0.01 mm	Micro-stamping, dipping, drawing, hydro- forming.	Stainless steel, aluminum, copper, etc.	Several microns	Micro- mechanical, electronics, medical, optical, chemical devices, etc.
Micro-tubular components	Outer diameters less than 1 mm, wall thickness larger than 20 microns	Micro-hydro-tube- forming, micro-rolling, micro-bending, laser machining, etc.	Metals	Several microns	Micro-shafts, micro-heat exchangers, micro-medical devices/implants
Micro-molds, dies and punches	Die-bore or inner pockets in less than 1 mm; punch diameter from 0.05 to 1 mm	Micro-EDM, laser- cutting, micro- machining, electro- forming, sintering, etc.	Tool steels, glass, powder, etc.	Several microns to sub-microns	Forming/ replicating processes, e.g. injection molding, embossing, extrusion, etc.

extrusion, for example, considering the effects of grains and grain sizes on the process. Any asymmetry may create difficulty in controlling the quality in micro-shaping. Excessive material accumulation, large reductions in area and sudden changes of the sections should also be avoided in forming/shaping. Others include the design of the draft for the workpiece for micro-forging, permitted drawing ratios and profiles of the drawn products in micro-sheet forming, etc. Conventional rules on shape capability of manufacturing may not be applicable to micro-manufacturing largely due to the sizes to be considered and limitation of the tool shapes that could be produced.

- **Tolerance and surface quality capability:** design of a macro-product would expect the designer to consult handbooks/standards before specifying a grade of tolerance and surface quality requirements. Design for micro-manufacturing may not be as straightforward as the design of a macro-product. Standards on manufacturing tolerances for design for micro-manufacturing, especially for non-MEMS-based manufacturing, have not been established

fully, while most of the data is 'in-house' determined/used. The designer may have to consult with the manufacturing engineers who are responsible for their own manufacturing capability.

- **Material capability:** selection of a material for micro-manufacturing will be constrained largely by availability of the material for volume production, due to the limited number of the suppliers currently operating in this field; however, the trend is improving, such as with nano-material suppliers, the number of which has increased significantly recently. New study/qualification of material properties may be needed if the material suppliers are not able to provide the material data relevant to micro-manufacturing, such as size effects and material property descriptions. The properties will have to be qualified for design uses, with consideration of size effects, and these have to be available with the inclusion of mechanical, thermal, electrical and magnetic properties, as appropriate, and others including biocompatibility, chemical compatibility, hydrophile and hydrophobe properties, etc. Grain sizes of the

material to be selected must also be known for most of the micro-manufacturing processes. Ultimately, the designer has to know which processes are most suitable for the materials selected, or materials suitable for available processes, etc.

- **Part/component material properties after processing:** involvement of large plastic deformations, damages, possible significant local temperature rise and thermal stresses during mechanical and thermal processes may, very likely, result in alteration of the material properties after processing. The micro-part/component material properties will play significant roles in determining part/component performance under working conditions than that for macro-components, such as those used in micro-sensors and medical implants. Part/component design is, therefore, constrained by the applicability of certain micro-manufacturing processes, e.g. chemical and high temperature processes, due to considerations of possibly adverse effects on the material properties.
- **Characteristics of volume production:** the design should also address significant characteristics of volume production in micro-manufacturing. Prototyping in a lab scale is significantly different from manufacturing the products in a production-scale. Achievable/targeted production yield, which is prescribed largely by the capability of the processes, machinery, tools and auxiliary equipment, will have an influence on the selection of the materials for manufacturing and design of the part/component and its features. Among those factors, handling the parts/components and interactions with tools are particular concerns that should be taken into account at the design stage.
- **Manufacturing cost:** Manufacturing cost is a major issue to be addressed. This is largely because micro-manufacturing often involves high investment in facilities and human resources and low product quantity requirements from each customer. Many factors prescribe the manufacturing cost, and a balance,

however, will have to be maintained between the feasible reduction of the cost for core processes and the cost involving the use of auxiliary processes. Some sophisticated geometry and tight tolerances may not be achievable solely with a single process, and using a process chain which may involve various processes is often inevitable. The designer has to be aware of how the design specifications will impact on planning for the manufacturing chains. He/she has to realize that the cost for tooling for some micro-manufacturing processes may be very high. A comparison among available manufacturing processes/chains and even involving supply chains may be needed, even at the design stage.

- **Synthesis factors:** design synthesis may be conducted by considering all factors discussed above. The results can be a basis for design optimization. Strong dependences of the component/part design on the manufacturing processes in micro-manufacturing suggest that design iterations and interactions with manufacturing personnel are often inevitable and necessary.

The design of micro-products is still a challenging task due to lack of sufficient standards, design/manufacturing rules and understanding of the manufacturing processes themselves. There is also a lack of effective software to support the design activities. Incorporating size effects into conventional design and analysis software and/or developing domain-specific design and analysis tools (software) will help to improve the situation. Modeling for different length scales such as micro-mechanics modeling, molecular dynamics modeling and multi-scale modeling, and integration of these into commercial software, are urgent needs for design for micro-manufacturing. Some of these will be mentioned in several chapters of this book.

## **MATERIAL FACTORS**

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Material properties have much more significant impact on the design/planning for micro-manufacturing, compared to that in

macro-manufacturing, which, for example, is reflected in the following aspects:

- Size effects on mechanical, thermal, electrical and magnetic properties, biocompatibility and chemical compatibility, hydrophile and hydrophobe properties, etc. need to be understood, and some of these may be significantly different, compared to the material behaviors in the macro-scale.
- As a consequence of the above, mechanisms of material conversion processes (separation, deformation, joining/deposition chemically and physically) will be different or affected, as well as interactions between the materials and processing tools (for tool-based processes).
- As a consequence of the above, selection of the means for enabling material conversion processes will be affected, the considerations including effectiveness and efficiency and effects on the material properties of the processing methods (mechanical, chemical, thermal, electric-chemical methods, etc.).
- Grain and grain boundaries, which may have less impact on the material conversion processes in macro-manufacturing, will have a more significant impact on the material conversion mechanisms as the dimensional scale decreases and the sizes of the grains become more relevant, such as influence on the interfacial friction and dislocation of grains and damages. This is particularly relevant in mechanical material conversion processes.
- Emphasis on the importance of the material-related issues in micro-manufacturing is also due to lack of sufficient, effective means for qualifying some material properties in the micro-scale, and hence insufficiently understanding these.

In design and planning for micro-manufacturing, special attention should be given to the micro-structures of materials such as grain sizes, grain boundaries, precipitations and intermetallics as second phase particles and their size and distribution in multi-crystalline structures, against the sizes of micro-products/features (less than 1 mm in dimension). Developing new materials and increasing volume of the materials available for

particular micro-manufacturing processes are needed: otherwise, micro-manufacturing will be constrained significantly by the limited number of the materials which could be processed in the micro-scale with the required quality and efficiency. A typical example is that the type of the materials usable in micro-replication/forming processes is quite limited by material flowability, strength, hardening and surface adhesive behaviors. For a volume production, fine grains and high plastic flowability of the material either at room temperature or at elevated temperature are preferred.

The following are some examples of the materials used in micro-manufacturing: materials with finer grain sizes; alloying of elements with high purity grades; modification of surface roughness, e.g. laser defined micro-structured surfaces; materials with defined strain hardening; materials originated from galvanic processes; single crystal material with mono-crystalline structure; materials by thin wire processing, e.g. bond wires for microelectronics; materials by thin foil precision cold rolling; materials with special coatings; materials with total or selective plating of strips; materials for thin film coating; materials for roll cladding strips; etc.

## **CONSIDERATIONS ON MANUFACTURING METHODS**

Compared to the manufacture of macro-products, manufacturing methods and strategies in micro-manufacturing may be different. Manufacturing macro-products may be carried out by manufacturing individual components/parts by removing and/or deforming and/or adding materials, and then assembling them. These can be carried out either at a single industrial site or at different sites. Manufacturing micro-products may be carried out with patterning, deposition and layering methods within a single machine/manufacturing platform, e.g. integrating components/parts fabrication with assembly/packaging is often used in MEMS and micro-systems manufacturing. Micro-manufacturing largely uses non-traditional manufacturing methods or scaling down or

modifying the traditional methods, as appropriate, to fully address issues related to manufacturing in the micro-world. Further, manufacturing chains may also be different, compared to traditional manufacturing. These may be due to:

- **Material property:** conventional manufacturing methods may not be able to cope with special material properties, e.g. either too hard or too weak for a process, sticking onto micro-tools, not compatible to the mask materials, or original material properties cannot be altered during manufacturing, e.g. affected by mechanical work-induced heat or direct heating processes, etc.
- **Structural strength and stiffness:** components/parts may be too fragile to sustain any mechanical forces needed for processing materials, or too difficult to handle during processing and/or assembly/packaging.
- **Shape and size – length scale factors:** all factors associated with small dimensional scale manufacturing apply, e.g. inability of tool fabrication for mechanical cutting and plastic forming may force the consideration of non-mechanical approaches. Normal geometric shapes such as holes, slots, pockets, threads, etc. may not be a problem in macro-scale manufacturing, but these may be extremely difficult to achieve if the dimensions decrease to sub-millimeters. Alternative manufacturing methods to conventional ones such as patterning, deposition and layer manufacturing methods may have to be considered.
- **Difficulties for clamping/releasing:** due to the sizes and structuring strength/stiffness issues, it may be difficult to clamp/release the components/parts to be made by mechanical manufacturing methods such as mechanical cutting and forming. Alternative methods such as laser ablation, electro-forming and chemical etching may be considered.
- **Residual stress and surface integrity:** existence of the residual stresses and weakened surface integrity, induced by plastic deformations, cyclic loadings, thermal gradients, etc., may not be acceptable for some critical components/parts for micro-products, e.g. those for

medical implants and high grade sensors. Selection of processes may have to consider such issues and process chains may have to be optimized to address these issues.

Fundamentals of the roles that the reduced length scales could play in various processing mechanisms need to be understood, e.g. roles of the surface at different length scales and in different manufacturing processes with respect to surface fabrication and micro-/nano-manipulation, surface metrology, etc. [3–4]. These play a significant role in selecting manufacturing methods and in optimizing the manufacturing chains.

## **MANUFACTURING METHODS AND PROCESSES**

Both conventional and non-conventional methods have been used to manufacture micro-products. There have also been emerging methods such as hybrid manufacturing. According to the type of energy to be deployed, manufacturing may be classified as mechanical, chemical, electro-chemical, electrical and laser processes. The working principles include mechanical forces, thermal, ablation, dissolution, solidification, recombination, polymerization/lamination and sintering [5]. According to the way in which the components/products are to be made, general manufacturing processes can also be classified into subtractive, additive, forming, joining and hybrid processes. The classification is equally applicable to micro-manufacturing. Typical manufacturing methods for producing components/products are as shown in Table 1-2.

Some typical micro-manufacturing methods/processes are detailed in this book. The following texts give an overview of some key methods and processes, as well as the current state of the development.

### **Mechanical Machining**

Mechanical machining is a technology that has been widely investigated in the field of precision engineering. Micro-machining may be seen as an ultra-precision material removal process which is



**TABLE 1-2 Typical Methods/Processes of Micro-Manufacturing (edited based on a table presented in [5])**

Subtractive processes	Micro-mechanical cutting (milling, turning, grinding, polishing, etc.); micro-EDM; micro-ECM; laser beam machining; electro beam machining; photo-chemical machining; etc.
Additive processes	Surface coating (CVD, PVD); direct writing (ink-jet, laser-guided); micro-casting; micro-injection molding; sintering; photo-electro-forming; chemical deposition; polymer deposition; stereolithography; etc.
Deforming processes	Micro-forming (stamping, extrusion, forging, bending, deep drawing, incremental forming, superplastic forming, hydro-forming, etc.); hot-embossing; micro-/nano-imprinting; etc.
Joining processes	Micro-mechanical-assembly; laser-welding; resistance, laser, vacuum soldering; bonding; gluing; etc.
Hybrid processes	Micro-laser-ECM; LIGA and LIGA combined with laser-machining; micro-EDM and laser assembly; shape deposition and laser machining; efab.; laser-assisted micro-forming; micro-assembly injection molding; combined micro-machining and casting; etc.

able to achieve micro-form accuracy and several nanometer finishes [6]. From precision machining to micro-machining, some challenging issues are met such as predictability, producibility and productivity in micro-scale manufacturing [7]. It may be difficult to achieve complex 3D, intricate micro-features/components with mechanical micro-machining, although it is still a powerful technology in developing micro-components for various systems such as those operating on electronic, mechanical, fluidic, optical and radiative signals [8], e.g. the systems for micro-instrumentation, inertial sensing, biomedical devices, wireless communication, high density data storage, etc. as well as producing dies and molds for other manufacturing processes such as micro-forming and injection molding [6–8].

Due to the working principle of removing chips by mechanical forces, significant efforts have been devoted to the improvement of the precision of machine tools and development of error-compensation methods to ensure the required precision of the machine-tool-workpiece system. Main issues addressed include understanding of chip formation mechanisms and micro-machining mechanics, machine tool design with ‘optimal’ dynamics stiffness, optimal cutter geometry/materials and motion control, in-process inspection with high resolution metrology, etc. [6–7]. The trend for bench-top machine tool designs has now shifted from large-scale, ultra-high precision designs to miniature structures and low cost system designs. Ultra-high precision and high speed spindle design

is another topic attracting many researchers and industries. Diamond cutting tools, tools with nano-crystalline diamond coating [9], etc. are also important in micro-machining.

### Micro-EDM

Electro-physical and chemical micro-machining processes play important roles in micro-manufacturing due to their special material removal mechanisms [10]. Electrical-discharge-machining (EDM) is especially suitable for manufacturing micro-components/tools due to its thermal material removal mechanism, which allows almost process force-free machining independently of the mechanical properties of the processed material. High precision EDM can process functional materials like hardened steel, cemented carbide and electrically conductive ceramics with sub-micron precision [11]. Its applications have extended far beyond dies/molds fabrication such as micro-gears, micro-fluidic devices, medical implants, etc. The processes include micro-wire electrical discharge machining, micro die sinking, micro-electrical discharge drilling, micro-electrical discharge contouring and micro-electrical discharge dressing.

Compared to conventional EDM, micro-EDM places more emphasis on the following:

- Precision of the machine, e.g. high precision control of the motion of the electrodes;
- Qualification of the wear of the electrodes, damage on the wire, and compensation for the wear/damage;

- Careful control of the frequency of discharge, level of the energy input, e.g. current and voltage;
- Better understanding of material properties, thermal conduction of the workpiece, melting and recasting processes, and their effect on the surface finish/integrity;
- Careful considerations of the set-up of gaps, component forms to be produced, flash of the debris, etc.

Besides the miniaturization of the tool electrodes, compared to conventional EDM, the minimum discharge energy of  $0.1 \mu\text{J}$  is obtainable, which causes only very small material removal at one single discharge. This results in an extremely small gap width ranging from  $1.5$  to  $5 \mu\text{m}$  [11]. To achieve a reasonable material removal rate, spark generators which are able to produce extremely high impulse frequencies have to be used, e.g. capable of impulse frequencies of up to  $10 \text{ MHz}$ .

### Micro-electrochemical Machining (MECM)

ECM is another popular choice for making micro-parts, due to less effort needed for handling during the ECM, easy control of the process, relative simplicity in machine design/set-up (CNC possible) and the capability to process various materials, including high strength materials. Other attractive characteristics include burr-free surfaces, no thermal damage, no distortion of the part and no tool wear. The issues needing to be addressed in micro-manufacturing applications include controlling material removal, machining accuracy, power supply, design and development of micro-tools, roles of inter-electrode gap and electrolyte, etc. [12–13]. High surface roughness, relatively poor fatigue properties, difficulty to make sharp corners, etc. are some negative aspects to be taken into account when considering this process for manufacturing. For micro-machining, masks may be used (one side or two sides possible) for making finer geometry. For precision manufacturing, a pulsed power of relatively short duration (about  $1 \text{ ms}$ ) may be used, which may enable

shorter inter-electrode gaps ( $< 50 \mu\text{m}$ ) to be utilized. These small gaps with good process control could yield accuracies of the order of  $\pm 1 \mu\text{m}$  on  $50 \mu\text{m}$  and surface roughness of  $R_a 0.03 \mu\text{m}$ .

### Micro-forming

Micro-products may be produced with forming configurations, i.e. micro-forming. Metal forming offers some attractive characteristics that are superior to those of other processes, e.g. machining and chemical etching, considering such features as higher production rates, better material integrity, less waste, lower manufacturing costs, etc. Various forming/forging configurations are possible such as forging, extrusion, stamping, bending, hydro-expansion, superplastic forming, etc. Micro-forming may be achievable by effective scaling down of the process configurations, tools and even machines [14–17]. Some challenges do arise when the sizes/features reduce to tens or hundreds of microns, or the precision requirements for macro-/miniature parts reduce to less than a few microns. Major issues to be addressed include understanding of material deformation mechanisms and material/tool interfacial conditions, materials property characterization, process modeling and analysis, qualification of forming limits, process design optimization, etc., with emphasis on the related size effects. The following observations have been established based on a series of studies and RTD efforts:

- Conventional metal-forming process configurations such as forging, extrusion, stamping, coining, deep drawing, etc., may be equally used for the forming of miniature/micro-parts; process capabilities are likely to be constrained further due to additional material and interfacial and tooling considerations in micro-forming.
- The types of materials which could be formable at the micro-level are prescribed more significantly than for forming at the macro-level by the micro-structures and grain-boundary properties of the materials. The forming limits for these materials are, therefore, somewhat different, compared to those for the forming of macro-parts.

- Size effects may exist in material property and tool/material interfacial property characterization, depending largely on the micro-structures of the materials, which lead to the requirement of the definition of these parameters with reference to the actual materials and interfaces to be used.
- Machines, forming tools and handling devices are critical in the industrial applications of micro-forming technology.

Some traditional forming machine designs may be scaled down for micro-forming needs, as long as the machines are able to cooperate with the use of micro-tools of acceptable quality and efficiency. However, more particular considerations will have to be incorporated into machine design to meet engineering applications requirements, e.g. greater precision, handling of micro-parts/materials with higher rates and positional precision, etc. [18–20]. Several chapters of this book deal with the machine development for micro-forming, the results taken from an EU-funded project – MASMICRO [16–17]. Applications of the micro-forming technology also rely largely on the development of micro- and even nano-machining technologies. The latter is key to the fabrication of micro-tools and the preparation of micro-materials.

## Laser Technology

Laser technology is qualified as an efficient micro-technology because of its high lateral resolution by minimized focusability down to a few microns, low heat input and high flexibility. One major advantage is its capability of processing various, non-silicon materials that are increasingly needed for manufacturing micro-products. Some examples for laser applications are micro-cutting, micro-drilling, micro-welding, soldering, selective bonding, micro-structuring and laser assisted forming [21]. Femtosecond laser micro-machining is a new approach emerging in the MEMS area, and some promising results have been shown in micro-machining and micro-system applications, including industrial material processing, biomedicine, photonics and semiconductors

[22]. The ultra-fast or ultra-short laser means that the laser pulse has a duration that is somewhat less than about 10 picoseconds – usually some fraction of a picosecond (femtosecond) (a picosecond =  $1 \times 10^{-12}$  second) [23]. It utilizes the ultra-short laser pulse properties to achieve an unprecedented degree of control in sculpting the desired micro-structures internal to the materials without collateral damage to the surroundings. It has been proven that micro-structuring with femtosecond laser pulses is an excellent tool for free design micro-fabrication of almost all kinds of materials [24]. With the filament, spatial scanning and other methods, many types of optical microstructures (including 3D) such as optical memory, waveguides, gratings, couplers and photonic crystals were produced successfully inside a wide variety of transparent materials of solid state and also liquid state [24].

Heating has been widely used for assisting in forming processes, largely due to the improvement of the material followability and reduced strength at elevated temperature. Therefore, the forming processes can be easier and forming loading can be reduced. The influence on the forming tools is a mixture of the reduction of the forming pressures and superimposition of thermal loads from the heating. Introducing heating helps to process materials with higher strength and/or to extend forming ability including component/part forms and dimensions and aspect ratios. Heating with laser is especially effective for the forming of sheet metals or thin sections from bulk materials [25]. By selectively applying the laser beam to the focused area(s), the laser can be used in processes such as bending, deep drawing, stamping, can extrusion, tube forming, etc. [21]. Transparent tools made of sapphire permit the guidance of the laser radiation directly onto the workpiece within the closed tool set during the process. This means that no separated preheating step is needed and extended processing time is avoided.

## Replication Techniques

Replication techniques like LIGA, micro-injection molding, micro-casting and micro-embossing

are seen as solutions to low cost, mass production of micro-components/features, reel-to-reel UV embossing being a good example for mass production. Materials that can be processed with replicating techniques include metals, glass, polymers, etc. Especially, embossing, molding and casting are very effective for fabricating microstructures for optical elements/devices [26], which can produce high resolutions possibly in the nanometer ranges with some processes, and allow the fabrication of large areas and complex micro-structures. Processes for gratings, holograms and diffractive foils are well established. Efforts are continually being made to extend the process capability such as increasing the aspect ratios of the micro-structures, producing these in larger areas (such as replicating micro-structures with optical functions with dimensions between 200 nm and 50  $\mu\text{m}$  on areas of up to half a square meter), combining embossing with other processes such as lithography, dry etching and thin-film coating, etc. Micro-powder injection molding ( $\mu\text{PIM}$ ) is a potential low cost mass fabrication process for manufacturing micro-structures and micro-components [27]. It could be used for processing many different materials (e.g. ceramics and metals) for very complex geometries. For making small geometries, silicon mold inserts may be used, taking advantage of deep reactive ion etching. The processing parameters need to be carefully set in order to produce the required quality and small features. LIGA, an alternative micro-fabrication process combining deep X-ray lithography, plating-through-mask and molding, enables the highly precise manufacture of high aspect ratio micro-structures with large structural height ranging from hundreds to thousands of micrometers thickness which are difficult to be achieved with other manufacturing techniques. Significant progress in MEMS manufacturing is largely due to the introduction of the LIGA process. The polymer LIGA process is especially suitable for mass production. There is a chapter in this book specially describing this process.

## Deposition Methods

The methods are seen as effective ones for fabricating multi-material devices with no need to increase the process chain. Possible methods for micro-manufacturing include laser-assisted chemical vapor deposition (LCVD), laser guided direct write (LGDW) and flow-guided direct write (FGDW), shape deposition modeling (SDM), localized electrochemical deposition, etc. [28]. For example, a similarity between the silicon-based MEMS methods and shape deposition manufacturing (SDM) is that 'both integrate additive and subtractive processes and use part and sacrificial materials to obtain functional structures' [29], while the latter is able to deal with more types of the materials.

A micro-rapid prototyping system based on a deposition technique may include micro-deposition, ultrasonic-based micro-powder feeding, dry powders cladding/sintering, laser micro-machining (a laser beam with a wavelength of 355 nm, for example) [29]. Fabrication of meso- and micro-structured devices by direct-write deposition and laser processing of dry fine powders is also possible [30], which is also seen to be an effective way to fabricate 3D structures with heterogeneous material compositions. The direct-write deposition system is able to produce a '100  $\mu\text{m}$  minimum attainable feature size for device footprints ranging from sub-millimeter to a few centimeters' on a movable substrate. The prototype devices produced included micro-battery, interdigitated capacitor, fractal antenna, Swiss-roll micro-combustor, and functionally graded polymeric bioimplants. By combining an electric-chemical method and an etching method, a new manufacturing technique, so-called Efab manufacturing (a system developed by MEMGen, USA), has been developed [31]. The method adds layers from 2 to 20 microns thickness and is able to create 3D metallic features with support of the sacrificial material that is etched away late.

SDM combining micro-casting with other intermediate processing operations (CNC machining and shot peening) was also attempted to create

metallic parts [32]. The better product quality could be achieved with proper control of inter-layer metallurgical bonding (through substrate remelting) and the cooling rates of both the substrate and the deposited material. Another good example of fabricating complex metallic micro-structures is to use lithography and etching techniques to make sacrificial silicon molds. The multiple silicon layers are stacked and the metallic glass is then forced into the cavities under heat and pressure in an open air environment. Such an approach could be a solution for low cost manufacturing [33].

The inkjet technology offers a prospect for reliable and low cost manufacture of flat panel displays (FPD). Compared to other conventional processes, an inkjet printing method for color filters (C/F) in LCD or RGB patterning in OLED offers potential for the mass production of the enlarged display panels with low costs [34].

### Assembly/Packaging

Basic processes for micro-assembly and packaging include mechanical placement/insertion/pressing, micro-welding; resistance/laser/vacuum soldering, micro-casting/molding, bonding; gluing, etc. Interconnection and packaging solutions (e.g. 3D molding of interconnect devices) are the key technologies for connecting micro-systems to the macro-world. Molded interconnect devices (MID) technologies include insert molding, one shot molding and two shot molding. Assembly/packaging gains more importance with the growth of complexity and miniaturization of the products and systems. Although significant progress has been made in the manufacture of individual micro-components/parts, as well as MEMS, there is still a significant amount of manual work involved in assembly/packaging of micro-products and systems. Assembly of individual technical components to hybrid micro-systems is often a bottleneck to large-scale production [35], which is evident especially in the areas of heterogeneous assembly, online inspection and quality control. Integration of micro- and nano-devices through

assembly is still a new area of challenge. A method for achieving electrical and mechanical interconnects for use in heterogeneous integration was combining metal reflow and a self-aligned, 3D micro-assembly [36], which allows for the batch processing of a large number of heterogeneous devices into one system without sacrificing performance. Micro-assembly injection molding gives another option for joining plastics and some inlay part such as fiber reinforced needle and other elements [37]. The use of lasers for welding has exhibited tremendous growth over the last decade for improving efficiency and reducing costs in a broad range of industries for the manufacture of both macro- and micro-components [21,38]. Efforts are continually being made for the better understanding of processes and for controlling key parameters for better quality and efficiency. Online inspection on joint quality is an important issue for industry. For some micro-device assemblies, there was almost no efficient online inspection system available for industry to use, and therefore quality control was extremely difficult. Another key issue for both MEMS- and non-MEMS-based manufacturing is the need for effective and efficient gripping techniques/systems and corresponding manipulation strategies/means for micro-assembly [39].

### PROCESS CHAINS AND HYBRID PROCESSES

Manufacture of a component/product often cannot be completed with a single process: it may involve a process chain. Better quality and efficiency of the manufacture could be achieved with a properly defined process chain. This also applies to micro-manufacturing which often needs several processes to complete a component. A typical example is combination of plating/coating, chemical etching and stamping to make 3D micro-sheet components. If micro-tooling is considered, the process chain is extended even longer. Various process chains are possible in order to meet various design and manufacturing specifications. For example: combining lithographic tooling and

injection molding techniques could enable mass production of micro-components with various materials such as polymers, metals and ceramics [40]; and an LIGA process could be improved by fabricating micro-molds with direct femtosecond laser micro-machining [41] – an approach that may lead to practical, cost-effective 3D MEMS with various materials. Ultra-precision manufacturing of self-assembled micro-systems (UPSAMS) is another example of this kind of development, which combines ultra-precision micro-machining such as milling, turning, drilling, and grinding with sacrificial/structural multilayer manufacturing processes to produce self-assembled, 3D micro-systems and associated meso-scale interfaces from a variety of materials for MEMS applications [42]. With this process, a new class of micro-systems could be developed that is highly three dimensional, precisely machined, and automatically assembled. Rapid fabrication of micro-components may also be effected with a combination of UV-laser assisted prototyping, laser micro-machining of the mold inserts and replication via photo-molding [43] which deals with materials such as polymers and composites. Another example is equipment development and applications of the pulsed laser for micro-machining of large-area polymer substrates with micro-structures which involve rapid prototyping, bow-tie scanning, synchronized image scanning (mask projection technique), etc. The applications include flat panel displays, solar panels, super-long inkjet printer nozzles, micro-lenses, diffusing structures fabrication, etc. [44].

Ideally, a process chain for micro-manufacturing should be short in order to achieve high efficiency, reduce manufacturing errors, and eliminate unnecessary handling/transport/packaging of micro-components among different processes. Hybrid manufacturing processes may take advantage of the merits of individual micro-manufacturing methods/processes while some of the inherited disadvantages may be reduced or eliminated, e.g. shortening the process chains. For example, micro-EDM and laser assembly may be combined to fabricate 3D metal

microstructures [45]. The system may use a micro-EDM process to fabricate micro-parts and laser welding to assemble these micro-parts. By such a combination, increased numbers of the patterns, higher aspect ratios and higher joint strength of the microstructures could be achieved. Another merit is reduction or elimination of the number of post-assembly operations which may involve various efforts in handling and high precision positioning. A new technology based on laser transmission welding, combined with a photolithographic mask technique, enables assembly of plastic micro-fluidic devices, MOEMS and micro-arrays which require high positioning and welding accuracy in the micrometer range [46]. The system created consists of a diode laser with a mask and an automated alignment function to generate micro-welding seams with freely definable geometries. A fully automated mask alignment system with a resolution of less than or equal  $2\ \mu\text{m}$  and a precise, non-contact energy input allows a fast welding of micro-structured plastic parts with high reproducibility and excellent welding quality, as reported [46]. Combining the ECM and EDM, i.e. so-called hybrid ECM/EDM, is another example of improving the material processing efficiency. In EDM, sparks are needed (dielectrics), while these are unwanted for ECM (electrolyte, short circuit). The sparks would be encouraged for combined ECM/EDM with appropriate control. The applications include drilling of small holes in hard alloys, wire-machining removal of metallurgical samples, manufacture of dies and molds, etc. Other hybrid processes include laser-ECM and ELID processes.

## **MANUFACTURING SYSTEMS/ EQUIPMENT**

Traditionally, some micro-manufacturing processes (non-MEMS manufacturing) were often effected with large-scale equipment, such as that for micro-mechanical machining, micro-EDM and micro-metal forming. To perform micro-manufacturing tasks with such equipment,

significant efforts were made to improve the precision of the machine structures, to compensate for mechanical and thermal errors, as well as to increase the functionality, resolution and reliability of the monitoring systems. The cost paid to achieve these has been very high, while the resulting equipment is too expensive, which actually limits their applications.

### **Miniature Manufacturing Systems and Bench-top Machines**

During the last 15 years bench-top/desktop machines or miniature manufacturing systems have been gradually developed and introduced to industry. The development of such machines/systems has attracted a lot of interest from research organizations and industries. A main consideration is that conventional facilities for manufacturing miniature/micro-products are not compatible, in sizes, to the products to be made in miniature/micro-manufacturing. Therefore, it is necessary to reduce the scale of the equipment which could, in turn, reduce the energy consumption and material requirements, reduce pollution, create a more user-friendly production environment, reduce equipment cost, etc. At the same time, as the scales of the machinery and auxiliary equipment are reduced, the mass of the mechanical parts is reduced dramatically and, as a result, the speed of the manufacturing tools could be increased, which could result in increase in production rates. Another advantageous feature often mentioned is that the force/energy loop and the control loops are significantly shorter for small machinery; therefore, the precision of the machinery could be increased comprehensively. Micro-factories are typical examples of such facilities.

During the last 15 years several demonstration micro-factories (also called miniature manufacturing systems) have been developed [47], notably in Japan, but now also worldwide: a review was provided in the literature [16]. These systems and machines indicate a trend of developing the equipment for micro- and nano-manufacturing. The development of a

micro-factory itself renders significant challenges to the development of manufacturing facilities, e.g. stringent requirements on machine elements and assembly, as well as monitoring and inspection. In turn, the development of miniature machines or micro-machines also promoted the development of a micro-factory, which has resulted in various new micro-factory concepts. To date, many miniature machines/desktop machines have come to market, such as desktop milling machines, EDM machines, injection molding machines, laser-processing equipment, miniature-forming presses, multi-process equipment, etc. Compared to the traditional micro-machine concepts, currently commercially available desktop machines are relatively larger but closer to industrial application requirements. These may be seen as bridging the gaps between the micro-machines and conventional, large-scale machines.

Led by the Institute of Product Development (IPU) of Denmark, a miniature press and flexible tool system was developed for the forming of micro-bulk products [18]. The press is driven by a linear servo motor and is capable of fast and accurate motion. The tool system enables eight different bulk-forming processes to be carried out by changing only small portions of the tool elements. Precision of the tool system is crucial due to narrow tolerances on the dimensions of the micro-components to be formed, which requires the manufacture of die cavities within the sub-millimeter range in diameter and within a few microns in geometrical accuracy.

A linear motor-driven micro-sheet-forming machine system (bench-top machine) was developed at the University of Strathclyde, UK [19], in collaboration with Pascoe Engineering of Scotland, Tekniker of Spain and other EU partners. The machine is capable of a series of micro-sheet-forming processes for forming thin sheet-metal parts with thicknesses below 100 microns. The machine has a capability of up to 800–1000 strokes per minute, a force capacity of 5 kN, and machine precision of 2–5 microns, with modular and flexible set-up. The machine is equipped with a newly designed, linear-stage driven, high

speed feeder which enables feeding accuracy (thin strips) of less than 5 microns. With properly designed pilot pins deployed in micro-sheet forming, higher positioning accuracy could be achieved. Another novel development was to transport the parts directly out of the tooling system with a novel part-carrying system. The machine is also equipped with a force-displacement monitoring system which reads the data directly from the tooling.

The Institute of Production (IFP) of the University of Applied Science Cologne, Germany, leads the development of the first generation hydroforming machine for the forming of miniature/micro-tubular components [20]. Hydroforming processes were employed successfully in industry for mass production predominantly relating to lightweight automotive components. The mass production of such components at present is, however, limited largely to parts with cross-sections of above about 20 mm in width. There was a lack of experience in the hydroforming of tubular, miniature/micro-parts. A machine system has been developed for forming miniature tubes down to 0.8 mm with thicknesses down to 20 microns. The applications of the system will significantly extend micro-manufacturing capabilities, especially the manufacture of hollow sectioned parts, such as those used in micro-housing, fluidic devices, light-weight structures in micro-mechanical devices, etc., which have not been achieved before.

A bench-top, multiple-axis machine tool capable of machining intricate 3D geometries in components with nano-scale tolerances was developed [48–49], led by Brunel University and Ultra-Precision Motion Ltd of the UK. The associated new series developments include an air bearing slideway and a rotary table with improved damping capacity (patented) and an ultra-high-speed air bearing spindle (Loadpoint Ltd/Ultra-Precision Motion Ltd of the UK), a piezo-driven fast tool servo system and piezoelectric actuation unit for vibration assisted machining (CEDRAT Technologies SA of France), new micro-diamond tools (Contour Fine Tooling Ltd of the UK), a robotic arm unit for

micro-components/tools handling and management (Carinthian Tech Research AG of Austria), and a tool and spindle condition monitoring system (University of Patras of Greece).

## Multiple-process Equipment

Multiple-process equipment is an ideal solution to implement various process chains within an integrated platform, which could significantly reduce the number of component handlings. Another resulting benefit is reduction of the possible accumulation of manufacturing errors. The majority of the equipment/devices developed in micro-factory or miniature manufacturing systems cannot be classified as multiple-process equipment/devices since these are stand-alone machines which deal with a particular process.

The idea of multiple process equipment has received a very positive response in Asia, typical developments in this region including the multifunctional micro-machining equipment developed in a Chinese university which is able to perform several micro-machining processes on the same machine tool [50] – micro-electro discharge machining (EDM), micro-electrochemical machining (ECM), micro-ultrasonic machining (USM) as well as a combination of these. Using micro-EDM, micro-rods with a diameter of less than 5  $\mu\text{m}$  were ground on a block electrode, and micro-holes and 3D microstructures were obtained. Shaped holes were machined with a combination of micro-EDM and micro-USM. Another similar multifunctional micro-machining system was developed in Ibaraki University of Japan, which is capable of micro-milling, turning, grinding, buffing, polishing, EDM, ECM, laser machining and combinations of these [51]. The applications included the fabrication of micro-lens molds. A recent development undertaken in National Taiwan University was a multi-function high precision table-top CNC machine [52]. With this machine, the machining processes such as micro-high speed milling and micro-EDM (die-sinking and wire EDM) can be performed on the same machine without need of unloading, reloading and readjusting the workpiece



for the subsequent operations. The system was also equipped with an in-process workpiece/features geometrical measurement system. Micro-electrodes as small as  $8\ \mu\text{m}$  in diameter and diameter/slenderness ratios as high as 100 could be achieved. Similar development is also seen in Singapore [53] – a multi-process miniature machine tool which includes processes such as micro-EDM, micro-ECM, micro-turning, drilling, and milling, as well as electrolytic in-process dressing (ELID), grinding and single point diamond tool cutting. A micro-factory as a whole may be seen as a platform that integrates several processes through several micro-machines on the same platform [47].

Another interesting development which targeted low cost equipment was a five-axis milling machine for machining micro-parts [54]. The machine presented was mainly composed of commercially available micro-stages, an air spindle and PC-based control board. The machine was used for machining micro-walls, micro-columns and micro-blades. Although this development does not involve multiple processes, it explores an interesting concept that targets low cost equipment which may be exploited for the development of multiple-process equipment.

### **Supporting Technologies/Devices/ Systems for Micro-manufacturing**

Considering handling at the micro-scale, factors such as gravity cannot be considered as a main force applied to the parts to be handled. Unwanted surface forces such as van der Waals, electrostatic and surface tension forces are dominant at such a scale [55]. The pick-and-place issue has to be addressed fully, due to the existence of adhesive forces. In micro-handling the possible joint backlash and structural vibration due to link flexibility may have to be controlled at the level of several microns during automated positioning. Higher care on manipulation and cleanliness are required also. The problems associated with micro-handling may be well understood, but a key challenge is still handling to match the high production rates to be deployed with some

miniature/micro-manufacturing machines such as micro-stamping machines. This is far more difficult to achieve, compared to that in a slow assembly/packaging process.

Sensor systems play an important role in many fields of manufacturing. Their applications in micro-manufacturing such as that in equipment and that for online inspection require high levels of accuracy/resolution of the sensors. Data processing near the sensors, extracting more information from the directly sensed information by signal analysis, system miniaturization, multi-sensor uses, etc. are the new demands [56]. Single-function transducers may now not be sufficient to meet the needs, and the system-based sensors as system components are being introduced: systems containing sensors, actuators and electronics are being developed.

Micro-manufacturing technologies are still being developed, and quality assurance plays an even more important role in order to ‘efficiently support the transition of micro production processes from non-robust to stable processes’ [57]. Quality assurance faces particular challenges at the production level – some common quality methods for macro-length scale manufacturing may be difficult or even impossible to be applied/implemented. The need for the development of the technologies and systems for dimensional metrology at different length scales and integrating them is evident. As critical dimensions are scaled down and geometrical complexity of the objects increases, the available technologies and systems may not be able to meet current and development needs. ‘New measuring principles and instrumentation, tolerancing rules and procedures as well as traceability and calibration, etc. will have to be developed’ [58]. There are no micro-specific tolerance guidelines for general tolerances and these currently largely rely on experience, which is, normally, not statistically established in a factory site and/or has not been approached in a systematic way [59]. 3D measurement technology that would enable fast, accurate measurement of solid shapes in sub-micron and even nanometer regions is essential for micro-manufacturing tasks, e.g. triangulation and optical interferometry may be used in the 3D

measurement of the dynamic behavior of the MEMS devices [60]. Concerning surface inspection methods and the performance of non-contact profilers, there is no single system which is able to offer all the features that a general purpose user would like simultaneously [61]. Providing all possible means available and integrating them into a flexible system to allow users to deal with different inspection requirements may be a solution to meet the manufacturing needs.

### **DEVELOPMENT AND UTILIZATION STRATEGIES OF MICRO-MANUFACTURING TECHNOLOGIES**

A series of methods and technologies has been developed in the micro-manufacturing field and the trend will continue. These methods and technologies are, mostly, materials and products oriented. This is particularly the case for manufacturing since many particular considerations need to be taken into account in the manufacture of micro-products, as discussed in previous sections. As far as a method and technology developer is concerned, it is particularly important to understand how the end-users assess the methods and technologies developed, and how a decision is made on the selection and utilization of the manufacturing methods and technologies, even when the product manufacturing requirements are known. Since significant knowledge gaps still exist, especially for those emerging micro-manufacturing technologies, plus significant lack of standards and manufacturing/production guidelines, selecting an appropriate technology/process for the manufacture of a particular micro-product may not be a straightforward task.

A methodology for the evaluation of the emerging technologies, particularly MEMS technologies, was proposed [62] which involves a 'triple-gateway' analysis, in terms of considering commercially or socially worthwhile features of the technologies:

1. A market gateway analysis on new uses, user skepticism about 'improved' performance characteristics, requirements for behavior

adjustment by the user, competitive technologies, unpredictable technological development and legal barriers.

2. A systems-management gateway analysis on the organizational structures of the company and business.
3. Across the technology/gateway threshold concerning four elements of technology uncertainty: innovativeness of technology, number of constituent technologies, manufacturing difficulties, and institutional changes required to introduce the new technology [62].

In some cases, to have a clear view on the issues such as competitiveness of the technologies and unpredictability of the technological development is not easy to achieve, while the issues relating to possible manufacturing difficulties and institutional change needs are particularly important to an industry. Similarly, lifecycle assessment (LCA) methods may be introduced to the assessment of emerging technologies such as micro-/nano-manufacturing technologies, e.g. assessment on the impact on the environment (eco efficiency improvement) which may consider materials, production, uses and disposal, possibly taking future changes into account [63]. Other methods for assessing micro-manufacturing methods and technologies are also possible, each of which may be focused on a particular issue such as scientific and technological issues, collaborative issues, etc.

Assessment of the emerging technologies to be utilized with a view to fully understanding the implication and impact on the business is very important. Experience should be learnt from previous cases in the MEMS field which saw that some enterprises were struggling to survive or disappeared from the business. A business built on immature prototype designs and products with low volumes always takes a risk. Micro-/nano-manufacturing, at the moment, may still be an expensive business which is characterized by high investment in resources (facilities, knowledge and skills) and often by low volume production and lack of a complete business chain locally. Decision making on the development or utilization of the technologies should take these factors into account, together with other technological issues,

such as dealing with multi-materials, small geometries, increased and complex functionalities of products, etc.

In particular, the following aspects should be looked at strategically in relation to the strategies of the development and utilization of micro-manufacturing methods and technologies.

### **Manufacturing and Supply Chains**

Development of micro-manufacturing technologies largely depends on the demands and enthusiasm from industry. The industry's decision is influenced significantly by the perspectives of new business to be brought or improvement which could be made to the existing business. Besides the efforts in developing individual manufacturing technologies, completing manufacturing chains and providing industry with flexibility to optimize the manufacturing chains are also very important. This is not because significant numbers of micro-parts/components often cannot be produced/completed with single technology alone but also because an optimized manufacturing chain may result in better quality and efficiency. Since no single technology could claim to be dominant, a possible solution to the industrial applications of micro-manufacturing is to provide various technologies and means for the industry to be able to effectively and efficiently form the required process chain(s), with lower cost. Completing supply chains for micro-manufacturing-based business is another important issue to be addressed. Forming effective micro-manufacturing business chains is often affected by the lack of the required material and high quality tool supply, as well as auxiliary facilities such as that for inspection and testing, although demands on micro-parts/components is highly evident. Without complete and efficient and manageable supply chains, a sustainable micro-manufacturing industry cannot be established. Strategic efforts should be made to complete manageable micro-manufacturing supply chains regionally and/or globally.

Advanced methods and systems for supply chain management for the semiconductor

industry, and the micro-electronics manufacturing industry in general, are mature and have been applied to the industry widely. These have not been developed exclusively for addressing the emerging micro-manufacturing industry. One of the main challenges also results from the fact that significant numbers of enterprises in micro-manufacturing are small and only of a short time in business, etc. Development in material and production planning with good knowledge of cost implications is insufficient for emerging micro-manufacturing, including lack of the advanced MRP systems exclusively for micro-manufacturing. The lack of standards exclusively for micro-products, materials, manufacturing methods and technologies also makes management of the supply chains more difficult. Good strategies are needed for marketing and financing, considering the nature of micro-manufacturing for a new business. Attention should also be paid to recycling and reusing micro-manufactured products and materials.

### **Integration with Other Manufacturing Activities/Sectors**

A good solution for fostering a micro-manufacturing industry may be to become associated with some other business or to give support to micro-manufacturing at an early stage of the development. There are two considerations. First, micro-manufacturing cannot be an isolated activity and it should be an efficient means for linking macro- and nano-manufacturing. There will only be limited impact from nano-manufacturing if it is not effectively integrated with micro-manufacturing. It is the same for micro-manufacturing – effectively building micro-systems or integrating results from micro-technologies and science, into the macro-systems, will be a key measure to the success of micro-manufacturing. Second, development of new micro-manufacturing business needs strong backing from successful businesses in macro-manufacturing, technologically and financially. Currently, significant numbers of business and research activities in micro-manufacturing are actually transformed from

macro-manufacturing, which has helped the development of micro-manufacturing tremendously. More attention should, however, be paid to the issues associated with the micro-world for which some methods and technologies cannot be simply 'scaled down' from the macro-world.

The micro-/nano-manufacturing industry may be still small, compared to other industries like transport, space, health, etc. However, it should really play roles in driving other industries to a new level. These may be reflected in the following aspects:

- Traditional industry needs breakthrough/transformation/improvement, considering significant competition and demands on the new products and higher quality. Achieving these cannot rely on organizational measures alone, but also requires, significantly, technological measures. Research and technological development in micro-/nano-manufacturing is one of most promising areas that could deliver the required solutions.
- Research in developing new micro-/nano-materials will meet many material challenging issues faced in traditional material and manufacturing industry – an area in which, currently, significant competitions exist.
- Manufacturing-process concepts evolved in micro-/nano-manufacturing research will significantly change/update traditional manufacturing concepts in terms of effectiveness and efficiency, these being due to the need for better understanding and control of the manufacturing processes as well as to the new way in which the products are manufactured in micro-/nano-manufacturing. No matter which length scale is to be dealt with, the process development in micro-/nano-manufacturing is of general significance to all length scale manufacturing.
- To be able to meet much more stringent requirements in tool fabrication for micro-/nano-manufacturing the process will deliver new knowledge and enabling techniques for the whole tool industry, which will better equip the traditional tool industry for meeting

new challenges and competition. Typical examples include tool dimensional precision and surface quality, tool material performance, etc.

- New manufacturing machine and system concepts, such as bench-top, miniature, micro-machines and systems, will have a significant impact on all manufacturing sectors in design, fabrication and use of the machines, in relation to performance, impact on users and environment, energy-saving, etc.
- Micro-/nano-technology products designed and/or prototyped in other sectors may have to be brought to market in order to have real impact/economical gains – micro-/nano-manufacturing is a sector that can make it happen.

### Technological Performance/Maturity Level

Compared to macro-manufacturing, one of the difficulties in assessing the technological performance/competitiveness of a micro-manufacturing process and the equipment lies in the significant number of existing uncertainties. Capabilities on material, geometry, tolerance, production rate, ease to link with other processes and equipment, etc., are often difficult to be defined in general terms, as these are often affected by many factors as described respectively in several sections of this chapter. The strong material, dimensions and environment dependence in micro-manufacturing, including the skills of the workers, make comparison of different processes and equipment very difficult to achieve. Nevertheless, the following aspects should be examined in terms of assessing the technological performance and maturity level of a micro-manufacturing process and equipment:

- Geometry associated performance: achievable overall dimensions, feature geometry, tolerances, surface finish, possibility for length scale integration manufacturing, etc.;
- Material associated performance: type of materials processable, material property requirements/constraints (e.g. micro-structures and surface integrity), post-processing requirements, etc.;

- Production associated performance: yield, reliability, scalability, online/in-process monitoring/inspection ability, ease for integration into process chains, dependence on skills/environment, impact on the environment, etc.;
- Cost factors: all costing items including that for auxiliary processes and equipment (e.g. that for handling, assembly/packaging, cleaning, etc.).

## Other Issues

Besides a series of activities such as economic analysis, decision analysis, technological forecasting, information monitoring, risk assessment, market analysis, externalities/impact analysis, etc., education and training are important for the micro-manufacturing industry. These are needed due largely to micro-manufacturing being generally a knowledge-intensive business.

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