Micro-manufacturing research: drivers and latest developments (Keynote paper)

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Abstract

Increased demands on micro-products and miniaturised systems/devices may have been a main driver to the rapid growth of the interest in research in micro- and nano-manufacturing. It seems, however, not to be the only reason why so much funding has been made available for researchers to be able to conduct research in this emerging field. A review was conducted recently with a view to gaining a clearer view of demands on the applications and on trends in developments in micro-manufacturing, by looking at the market, research topics, projects, interactions with industry, outcomes and applications. It was found that there have been significant changes/advances in micro-manufacturing research, compared to what had been undertaken and achieved in 5 ~ 10 years ago, being reflected especially by: (i). micro-manufacturing research bridging "nano-manufacturing" and "macro-manufacturing" and hence, bringing nano-technology into real-life and affordable products; (ii). addressing multi-length scale manufacturing problems and hence, linking it to macro-sized product manufacturing, which adds its relevance to general manufacturing and wide-sector applications; (iii). micro-manufacturing research being shifted from "process focus" to "market/product" driven research and technological development addressing production capability, product quality, pilot production line demonstration and delivery; and (iv). micro-manufacturing research playing roles in helping to transform traditional industry and products. These new developments may justify past and current significant investment in research and technological development in micro- and nano-manufacturing, and suggest more significant impacts to come in near future.

Keywords: Micro-Manufacturing, Nano-manufacturing, Micro-products, High-value added manufacturing, Research and Technological Development (RTD)

1. Introduction

At the present time, "Micro-manufacturing" refers mostly to the manufacturing of Non-MEMS and Non-Silicone-materials. A comprehesive assessment of micro-manufacturing research was conducted by a WTEC Panel on "International Assessment of Research and Development in Micromanufacturign" [1] more than 10 years ago, which showed the status of worldwide, micro-manufacturing research at that time. Substantial momentum driving the research and applications of micro-manufacturing was generated by the European Commission through the funding of several large-scale 'flagship' projects in micro-manufacturing in Europe, through its Sixth Framework Programme. The research and outcomes from these projects have been widely reported from various sources, e.g. that reported in/from [2-4]. The research effort has been continuing since EU FP6, together with exploitation of the results from these funded projects, which has seen sigificant applications and further exploitation taking place in recent years. At the same time, there have been some shifts on the focus of the research recently, such as fresh engagement with industry, increased interactions with materials and nano-technology research. These are worthy of notice

A review of micro-manufacturing research conducted in 2009 was reported in the literature [5, 6], and this paper intends to give an update on the review. The paper will initially give an overview of the market needs and sector-driven applications, followed by describing recent developments in research concerning micro-manufacturing methods, processes and equipment, outlining EU funded research initiatives, exampled by projects such as MASMICRO, POLYTUBES and the Micro-FAST project. Issues such as adding product values through micro-manufacturing, relevance to traditional industries, and business related issues, will then be commented upon.

2. Products and Market

Micro-products are now widely in use [1, 3, 6-9]. Typical micro-products for automotive and aerospace uses include pressure sensors, thermal sensors, temperature sensors, gas sensors, rate sensors, sound sensors, and injection nozzles, and the components include those for electrostatic, magnetic, pneumatic and thermal actuators, motors, valves and gears. There are more than 200 micro actuators and sensors now integrated into modern automobiles. Micro-products also include sensors for mass flow, micro-heat-exchangers, micro-chemical reactors, tools/moulds for forming/replication, and components include those for miniaturised electronics products such as mobile phones, iPads and laptops. Especially, smart phones are the main targeted market for emerging MEMS devices and micro-sensors, such as those for better communication performance, sound quality, visual experience, navigation and environmental sensing. In the medical sector, micro-fabricated parts span a wide range of implantable applications in various clinical areas. Typical examples are sensors for cardiovascular, micro-machined ceramic packages, implantable devices, and coatings on polymeric or metal micro-parts. Micro- and nano-technology products will also play a significant role in evolving future factory equipment and the production environment, such as enabling the miniaturisation of equipment, lightweight structures, longer life-span, manufacturing intelligence, low energy-consumption, and excellent human–machine interfaces.

The micro- and nano-product market is currently influenced strongly by the following significant trends:

(i). Emerging markets driven by needs from specifical sectors such as energy, transport, healthcare and consumer electronics, which are closely linked to important societal challenges. There have been targeted deveopments of micro- and nano-manufacturing technology for particular sectors and markets, e.g. that for energy sourcing, conversion, storage, transport and ultilisation which involve, largely, thin-film technologies, ceramic technologies, nano-materials and integration into surfaces and bulk-parts.

(ii). Increased introduction/ultilisation of nano-materials and nano-technology into micro- and miniaturised products and devices which offers unique peroformance and extended life such as that used in new medical devices, implentable components, and micro-electronics products.

(iii). Disruptive development of manufacturing technologies, which helped/is helping the development of new products: the development of accelerometers has been helped greatly by the development of precision engineering, piezo-technology, bulk micro-machining and surface micro-machining technololgy. It is expected that new development of micro- and nano-manufacturing technologies (continuous and disruptive) will further enable and accelerate technical and commercial breakthroughs in other application areas such as organic photovoltaics, fuel cells, micro-engines, E-cars, and battery technology.

(iv). Shortened developent time, compared to what happened 20 years ago. Currently, from concept, through research and development, to the diffusion of the product into the market, the time has been shortened considerably: 35 years for pressure sensors to develop from R&D to commercial ramp-up, while it is about 15 yeears for osillators to reach commercial ramp-up. It is expected that the development time will be even shorter, considering the multi-disciplinary collaborations and integrated project approaches being currently utilised in micro-manufacturing RTD as well as the industrial leadership implemented.

There is no accurate data on the current market on micro-products and the forecast for the future market varies from different sources. According to Yole's early forecast [9], in terms of MEMS, a significant volume growth was foreseen (around 20% expected between 2013 - 2019). According to the iSuppli 2011 report [3], the micro-products' CAGR (Compound Annual Growth Rate) for between 2011 and 2016 should be over 20%. Although it is difficult to predict an exact scale of the future market for micro- and nano-technology products, it is very promising, according to the demands of current customers. The functionalities and manufacturing cost will, however, still be key competitive factors, which raise signficant challenges to the development of micro- and nano-manufacturing technologies to meet the requirements for new functions, low-cost and high-quality products.

3. Micro-Manufacturing Research and Technology Development

In micro-machining, predictability, producibility and productivity are still challenging issues being addressed. Effort is being made to achieve complex 3D, intricate micro-features/components, the maching of difficult-to-cut materials such as metal matrix composites, silicon carbide and ceramics, as well as nano surface patterning [10-14]. Significant efforts have also been devoted to the improvement of the precision of machine tools and the development of error-compensation methods. Bench-top machine-tool designs have now become a trend showing the design being shifted from large scale, ultra-high precision designs to miniature structures and low-cost system designs. Besides mechanical machining, research and applications of Micro-EDM, Micro-ECM, Photo-Chemcial-Machining, Laser Machining, etc. have progressed significantly and are now widely used for making products and tools [6].

Over the last 20 years, micro-forming has been researched extensively, due to its potential for higher production-rates, better material integrity, less waste and lower manufacturing costs. To-date, various micro-forming configurations have been investigated [5, 6, 15-20], including: Laser-shock/pulsed/bulging/peening forming and Laser-heating-assisted forming; Micro-cold, -warm, -hot and -isothermal forging; Micro-extrusion and -backward can-extrusion/Ultrasonic vibration micro-extrusion; Micro-rolling/Roll-to-roll forming/Micro-dimple-forming and incremental forming; Micro-stamping (hard and soft tools)/Micro-deep-drawing/Micro-bending (laser); Micro-superplastic-forming; Micro-cold and hot-embossing (on metals)/Micro/nano-imprinting/Micro-coining; Micro-hydroforming (tubes); Liquid impact micro-forming, and Semi-solid micro-forming. There have been good examples of industry applications of micro-forming technologies, and the remaining challenges are still on the micro-tooling, tool life, part quality, material forming-limit, inline inspection, and technology standardisation.

The LIGA technique is seen as a solution for the precision manufacturing of high-aspect-ratio micro-components and systems, while other replication techniques such as micro-hot-embossing, micro-injection-moulding, micro-casting/soft moulding, micro-sintering, are seen as better solutions to the low cost, mass-production of micro-components/features [21-25], reel-to-reel UV embossing being a good example for mass-production. Micro powder injection molding (μPIM) is now one of the most important and widely used micro-manufacturing technologies, and it has been researched intensively during the last 10 years. Its development has been helped greatly by large RTD funding, e.g. recently funded EU projects [26]. μPIM is a low-cost mass fabrication process for manufacturing microstructures and micro-sized components. It has been used for processing many different materials (e.g., ceramics and metals) for very complex geometries. For making small geometries, silicon-mould-inserts may be used, taking advantage of deep reactive ion etching.

As an additive technique, Electro-forming has been used widely, and already produces micro-components and micro/nano-structures. It is, to-date, still a powerful technique for securing fine-geometry and low-cost production [27]. By combining an electric-chemical method and an etching method, Efab (a system developed by MEMGen, USA) has been developed [28]. The method adds layers of from 2 to 20 microns thickness and is able to create 3D metallic features with support of the sacrificial material, which is later etched away. As for rapid manufacturing, manufacturing a micro-part may involve microdeposition, ultrasonic-based micro powder-feeding, dry-powder cladding/sintering, followed by laser micromachining or mechanical finishing. Fabrication of meso- and micro-structured devices by direct-write deposition and laser processing of dry fine powders have already been made successfully, which is seen to be another effective way to fabricate 3D structures and strucutres even with heterogeneous material compositions, such as that undertaken in EU FP6 Manudirect Project and FP7 Micronano Project.

Inkjet technology offers a prospect for the reliable and low-cost manufacture of Flat Panel Displays (FPD). Compared to other conventional processes, an inkjet printing method for colour filters (C/F) in LCD or RGB patterning in OLED offers potential for the mass production of enlarged-display panels with low costs while the possibity of depositing nano-particles offers more potential applications and higher quality of products [29-30].

During the last 15 years various bench-top/desk-top machines and miniature manufacturing systems for micro-manufacturing have been developed and introduced to industry. The development still attracts significant interest from researchers and the industry involved has started commercialising the machine designs already. Conventional facilities for manufacturing miniature/micro-products may not be compatible, in sizes, to the products to be made in miniature/micro-manufacturing. It is, therefore, necessary to reduce the scale of the equipment which could, in turn, reduce 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 of the production rates. Another merit is shorter force/energy loops and control loops for small machinery and hence, the precision of the machinery could be increased comprehensively. Micro-machines/micro-factories are typical examples of such facilities [31].

Multiple-process equipment is another development still attracting a lot of interest. Such equipment is to include various micro-fabrication processes into one machine, such as EDM, ECM, Milling, Grinding, Laser Machining/Heating, and it is an ideal solution to implement various process chains within an integrated platform, which could significantly reduce the number of component handlings during changeover from machine to machine. Another resulting benefit is reduction of the possible accumulation of manufacturing errors. A latest example is the Hybrid µEDM machine made by Mikrotools [32]. The majority of the equipment/devices developed in micro-factories or miniature manufacturing systems may not be classified as multi-process equipment/devices, since each of these is a stand-alone machine which deals with a particular process.

Micro-manufacturing technology is still being developed, and quality assurance plays an even more important role in supporting the transition of micro production processes from non-robust to robust and stable processes [26, 33-35]. 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.

4. EU Funded Initiatives on Micro-Manufacturing

The EC's effort in funding micro- and nano-manufacturing research has been tremandous and this is evident in the EU FP6, FP7 and Horizon2020 programmes. In FP6, there were several large projects funded in the field of micro- and nano-manufacturing [2-4], such as projects MASMICRO, 4M, Launch-Micro, Production4µ, EUPASS, Hydromel, HYTI, NANOSAFE2, Manudirect, Napolyde, PRONANO, NaPa, CHARPAN, NANOIMPRINT, and NanoCMM. The projects covered areas such as Micro-manufacturing (mass-manufacture of micro-products, multi-materials micro-manufacturing technologies and applications, direct manufacturing by laser melting/sintering, and transforming traditional SME industry to micro-manufacturing industry); Precision manufacturing (ultra-precision machining and assembly systems, hybrid ultra precision manufacturing process based on positional- and self-assembly, direct ultra-precision manufacturing); Nano-manufacturing (safe production and use of nanomaterials, nano-structured polymer deposition processes for mass production, nanopatterning, production of parallel intelligent cantilevers, and charged particle nanotechnologies); and metrology for micro- and nano-manufacturing. These efforts enabled the EU to ensure its leading position in these individual areas.

In FP7, besides the projects which have already been completed, such as POLYGLASS, MULTILAYER, NANOMICRO, MIDEMMA, FLEXPAET, INTEG-MICRO, µECM, POLYTUBES, PLAST4FUTURE, SONO“R”US, within the FoF initiative (“Factory of the Future”), a group of projects is currnetly being executed in the field of micro-manufacturing [26], to support the effort of meeting challenges of maintaining high-quality manufacturing in Europe. These projects are working in synergy and created, under the support of European Commission, a “cluster of the micro-manufacturing industrial research”, characterised by common development objectives, complementary technologies and industrial sectors: the HiPr project is developing a novel approach for metal 3D micro-parts production, capable of reducing finishing operations, which could help to bring the research into the forming of small parts into industry applications; the 3D-HiPMAS project is to demonstrate pilot line fabrication of advanced MID-based micro assemblies; the Smartlam project builds on a layer by layer lamination of functionalised film sheets with different material properties, allowing for the manufacturing of small to medium series of micro components in a rapid manufacturing manner; the Hi-Micro project intends to realise an innovative approach for the design, manufacture and quality control of tool inserts, through further developing tooling technologies for micro-injection (powder) moulding (µIM); the HINMICO project is developing and optimising manufacturing processes to produce high quality multi-material micro-components, with a possibility of additional functionalities; the Micro-FAST project is developing a completely new manufacturing system for the volume production of miniaturised components by overcoming challenges in manufacturing with difficult-to-process materials; the FaBiMed project deals with flexible and cost-effective tooling fabrication, precision replication technologies and advanced inspection techniques. The outcomes of these projects will take Europe’s micro-manufacturing research and applications to a new level. MICROAB is a project dealing with micro-machining with abrasive waterjets.

In EU Horizon 2020, new projects in the field of micro-manufacturing also have started, e.g. the R2R Biofluidics project on large scale micro-and nano-fabrication technologies for bioanalytical devices based on roll-to-roll imprinting; the TOP HIT project on transfer-print operations for heterogeneous integration; and the ADALAM project on sensor based adaptive laser micromachining using ultrashort pulse lasers for zero-failure manufacturing.

5. Case Studies of EU funded projects

The EU FP6 MASMICRO Project (2004-2008) is a good example of applying a multidisciplinary and research integration approach to problem-solving for micro-manufacturing. It was a large, integrated project (the first of this kind in EC funded research) , assembling experts from 10 different disciplines, from 36 partners from 13 EU countries, focused on micro-manufacturing which aimed at the development of a series of methods, techniques and manufacturing facilities for the mass production of micro-compoenents [5]. It addressed three apects of the development need: the development of mass production processes based on micro-forming and micro-mechanical machining; the development of miniature/bench-top equipment to bridge gaps between costly large-scale systems and micro-machines; and the application of ultra-precision techniques to improve the precision of previous miniature/micro-machine designs. The project assembled the partners who completed process and supply chains. By the end of the project, it generated 135 publications, 13 patents, 4 spin-off companies and 48 exploitable results. The industrial technologies and new facilities developed included new laser systems for micro-material processing, photo-electro-forming and LIGA techniques, new surface-coating techniques, micro-tooling techniques, precision-handling devices (robotic system and filtering system), micro-actuating materials and devices, a micro-sheet-forming machine, a micro-extrusion machine, a micro-hydroforming machine and a micro/nano-cutting machine, and manufacturing execution system (software). 18 industrial partners participated in the project and some of these had already started implementing the findings during the project period whilst others deployed the results in an exploitation period after the project. Significant industrial applications have been seen since the end of the project in 2008.

Fig. 1 Micro-sheet-forming machine system (University of Strathclyde)

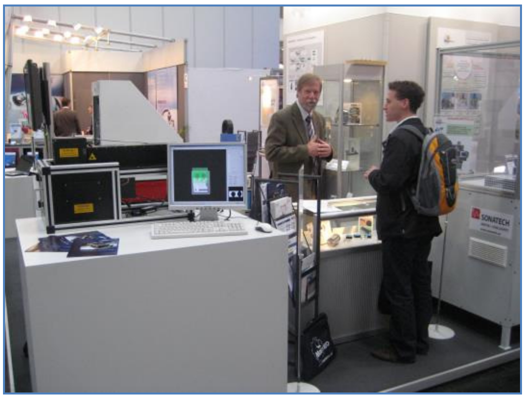

Fig. 2 MASMICRO project manufacturing facilities and demonstrators exhibited at Hannover Messe, 2008

EU FP7 POLYTUBES Project (2009-2012) dealt with manufacturing tubular micro-components for fluidic devices for general applications such as medical analysis, heat management and capillary electrophoresis [37-38]. It bridged the gaps in manufacturing polymeric tubular micro-components by developing a completed process chain, from product design, raw materials preparation, material-shaping processes, tool-fabrication, modular machines, to the manufacturing system and product validation. It developed a common platform integrating several processes (Micro-rolling, Micro-hot-embossing, Micro-blow-forming, Laser-drilling/trimming) in a form of integrating individual, modular miniature machines. The small machines were linked through a global handle system (robotic manipulator), while each of the modular machines has its own inter-handling device that is able to feed the tubes and to pick up the shaped components. In such a way, each modular machine can be a stand-alone machine for different applications but can also be integrated onto a common platform for forming an integrated process chain. Other merits are: high manufacturing flexibility – the process combinations can be programmable, there is high modularity (a highly modular system) and the system is easily re-configured.

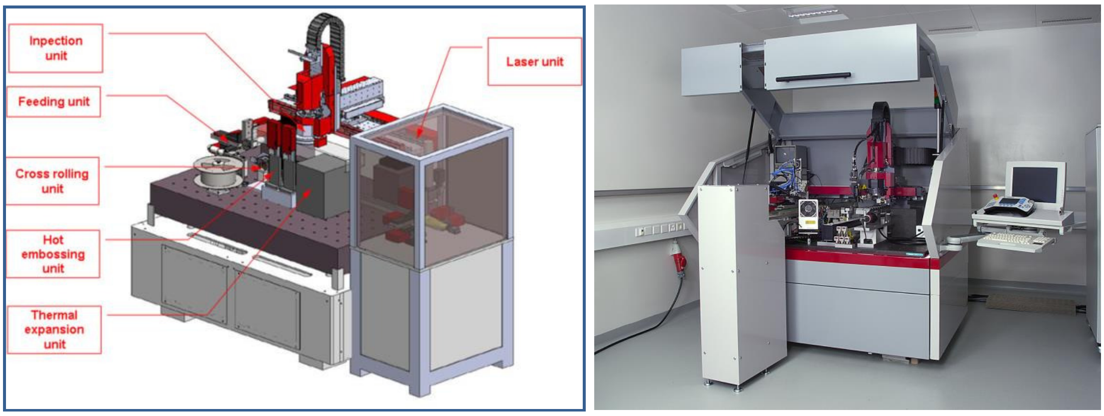

Fig. 3. (a). Graphic illustration of the micro-factory concept; and (b). The manufacturing platform used for testing the concept (POLYTUBES consortium and Sysmelec of Switzerland)

EU FP7 Micro-FAST Project (2013 – 2017) is developing a completely new manufacturing system for the volume production of miniaturised components by overcoming the challenges on the manufacturing with a wide range of materials (metallic alloys, composites, ceramics and polymers), through: (i) developing a high-throughput, flexible and cost-efficient process by simultaneous electrical-forming and electric-fast-sintering

(Micro-FAST); (ii) scaling up the process to an industrial scale; (iii) further developing it towards an industrial production system for micro-/nano-manufacturing. These are enabled/supported by developing: (a). a new press-machine with an innovative handling-system; (b). an innovative inline monitoring and quality inspection system; (c). innovative multiscale modelling techniques for the analysis of the micro-structural behaviour of materials prior to and after forming and its interactions with the production processes; (d). new tool-designs and tooling-techniques for high-performance tools, and (e). high-quality nano-material systems. The whole development takes into account energy savings, cost and waste reduction, and material-recycling issues, which are being studied thoroughly through an expertise Life-Cycle Assessment. Within its first 18 months, the project has: completed the selection of manufacturing components and material systems; produced sample powder-materials; conducted process experiment; generated a series of detailed designs concerning tools, forming press, handling system, inspection system and monitoring and control system. These are being assessed through industry experts, experiment and numerical simulations. The plan is to complete construction of the machine/subsystems, manufacturing validation and optimisation of the manufacturing system in the first half of 2016, production trials and demonstrations until the early of 2017.

6. Comments on the Micro-Manufacturing Research and Technological Development

6.1 Adding value to products through Micro-manufacturing

The requirments for micro-manufacturing may be classified into two levels: the component level and the product level (assembly/packaging). Micro-manufacturing technology is being developed not only to meet these manufacturing requirements but also for adding new value. For example, to be able to make metallic and ceramic micro-components for micro-robots and micro-engines, produce high-quality 3D electrical interconnections for 3D micro-assemblies, create micro/nano structural surface/parts for batteries and micro fuel cells, develop standard mechanical and mechatronics parts/elements for micro-machines or miniaturised equipment, would itself add value to the associated products.

Considering where value could be added to a product through micro-/nano-manufacturing, the following are some observations:

- Improving surface quality through ultra-precision manufacturing (e.g., nano-machining and FIB machining);
- Adding surface functionalities of the component/system surfaces through surface texturing (e.g., micro-machining, laser ablation, micro-EDM, micro-ECM) and coating (e.g. multi-layered nano-coating);
- Creating new functional structures of the components/systems through micro/nano-forming/raplication/sintering and additive manufacturing (e.g. hollow-sectioned, channelled, functionally graded structures);
- Converting low-value materials into high-value products such as nano-materials/nano-composite products (e.g. micro/nano-forming, casting and sintering for high-quality components);
- Creating value by high-quality assembly from low-value components/materials (e.g. micro-injection moulding assembly, high-precision mechanical, micro-joining and self-assembly)..

6.2 Relevance to traditional industries

The micro-/nano-manufacturing industry may still be small, compared to other industries, such as automotive, aerospace, energy, and healthcare. However, it can play significant roles in driving other industries to a new level. For example:

- Traditional industry needs breakthrough/transformation/improvement, considering significant competition and demands on the new products and higher quality. Achieving these cannot rely on organisational improvement only, but also requires, significantly, technological acquisition. Research in micro-/nano-manufacturing is one of the most promising areas that could help to deliver the required technological solutions.
- Research in developing new micro-/nano-materials will meet many material challenging issues faced in the traditional materials and manufacturing industry - an area in which many current industries are seeking better solutions.

- Manufacturing-process concepts evolved in micro-/nano-manufacturing research will significantly change/improve traditional manufacturing concepts, these being due to the need of better understanding and control of the manufacturing processes as well as due to the new way in which the products could be manufactured. No matter which length scale is to be dealt with, the process development in micro-/nano-manufacturing is of general significance to all length-scales manufacturing.
- To be able to meet much more stringent requirements in tool-fabrication for micro-/nano-manufacturing 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, such as that on the tool dimensional precision and surface quality, tool-materials and tool-performance
- New manufacturing machine and system concepts, such as bench-top, miniature, micro-machines, reconfigurable systems and control strategy, will have significant impact on all manufacturing sectors in design, construction and use of the manufacturing machines.
- Products, especially micro-/nano-technology products, designed in other sectors, may have to be manufactured through micro-/nano-manufacturing techniques.

6.3 Business related issues

Correct assessment of an emerging technology to be utilised with a view to fully understanding the implication and impact on the business is very important. Experience should be learnt from previous cases concerning MEMS manufacturing which saw some companies struggling to survive or disappearing from the business. A business built on immature prototype-designs and products with low volumes always takes a risk. Micro/Nano-manufacturing has been seen as an expensive business that is characterised by high investment in resources (facilities, knowledge and skills), often low volume production, and lack of a complete supply chain locally. Decision-making on the development or utilisation 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.

Completing supply chains for micro-manufacturing-based business is another important issue to be addressed. Forming an effective micro-manufacturing business chain is often affected by the lack of the required raw-materials and high-quality tool supply, as well as auxiliary facilities such as that for inline inspection and efficient handling, 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.

The recently funded RTD projects had/have been making effort to address these issues, such as developing high-yield, low cost manufacturing processes, low-cost equipment, and complete process chains; engaging with the whole supply chain when the projects are being executed; and largely involving end-users in the early stage of the development.

One of the main challenges also results from the fact that significant numbers of enterprises in micro-/nano manufacturing are small and only of a short time in business. Other difficulties encountered include: insufficient knowledge on the cost implications concerning materials and tooling, lack of advanced MRP systems exclusively for micro-/nano-manufacturing; and lack of standards for the manufacturing processes and tooling.

7. Summary

Significant progress has been made recently in micro-manufacturing research and technological development, and the scope of the research and applications has been very wide, according to the sources of reporting. Micro-manufacturing may be redefined as manufacture that covers:

- Micro-/nano-precision manufacturing of macro-sized components;
- Micro/nano-feature manufacturing over small and large areas;
- Manufacturing of micro-sized components;
- Manufacturing with micro/nano-structured materials;

- Manufacturing with controlled micro-structures of materials,

and hence, micro-manufacturing should not be seen as manufacturing small-sized components only.

The continuing trend of miniaturisation of products, devices and equipment has been a major driver to the development of micro- and nano-manufacturing technology. Compared to the development of 10 years ago, which saw micro-manufacturing research focused significantly on fundamental issues concerning the scaling down of conventional processes and equipment, recent development has been largely applications-driven. During the last 10 years, the number of manufacturing processes investigated has increased significantly; manufacturing processes such as micro-machining, laser machining, Micro-EDM, Micro-ECM, hot-embossing, roll-to-roll forming, micro powder injection moulding, photo-electro-forming, have been mature areas for applications; RTD effort has been shifted significantly to the transforming of laboratory processes into items of production equipment; and the development has been targeting onto sector-specific applications. In addition to the effort in developing multi-materials processing capabilities, low-cost equipment and pilot production lines, other aspects such as advanced tools and analysis software, high-quality materials and nano-materials, automation, inline inspection, quality assurance, and standardisation, are also being addressed. Considering that micro-manufacturing bridges between potential, high-impact nano-science and nanotechnology and real-life, low-cost products, it will achieve further significant development over the next 10 years.

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