4M Network of Excellence in
Multi-Material Micro Manufacture

A roadmapping study in Multi-Material Micro Manufacture

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A roadmapping study in Multi-Material Micro Manufacture

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Abstract

This paper reports findings from a roadmapping study conducted by the FP6 Network of Excellence in Multi-Material Micro Manufacture (4M). The main aim of this study is to help inform European research and industry about current trends and application requirements in the development of Micro- and Nano-manufacturing Technologies (MNT) for the batch-manufacture of micro- components and devices. The results are based on a roadmapping workshop attended by 30 senior researchers and parallel questionnaires administered to 38 associated industrialists. Primary application areas addressed were micro-fluidics, micro-sensors & actuators, and micro-optics, while the technologies covered were surface modification and structuring processes, energy assisted and mechanical processes, and replication processes. Reported results include the main market sectors for these three application areas as perceived by the industrialists together with the main application requirements for developing/manufacturing micro products and the important current and future micro manufacturing technologies. Generic and specific conclusions are derived about the existing trends in developing micro technologies and their applications.

Keywords: micro manufacture, multi-material, roadmap

1. Introduction

Microsystems-based products are envisaged to be an important contributor to Europe's industrial and economic future, as a key value-adding element for many sectors of industry - and the predicted nanotechnology future will also be largely delivered by microtechnologies. While the late 20th century has seen a silicon-based microelectronics revolution, the 21st century looks forward to the adoption of micro- and nano- manufacturing technologies (MNT) making use of a variety of materials, components and knowledge-based technologies that provide functionality and intelligence to highly miniaturised systems. Markets for microsystems are predicted to double over 5 years from 2004 to 2009 [1].

According to a recently conducted study of research and development in micromanufacturing [2], the technologies that underpin the creation of production capabilities for innovative microsystems-based products have four main characteristics:

- They are *enabling* the widespread exploitation of nanoscience and nanotechnology developments;
- They are *disruptive* having the potential to change drastically the existing manufacturing paradigms;
- They are *transforming* the existing manufacturing systems and the way they are designed;
- They are *strategic* for the industrial competitiveness.

In this context, it is very important to study carefully the existing trends in developing micro technologies and their applications, and define research agenda and knowledge transfer provisions that reflect correctly the significance of this field for European industry. Such studies represent a background research that informs the EC 7th Research Framework Programme about the research and development priorities in establishing a new industry in Europe for the manufacture of products based on emerging micro- and nano-technologies.

This paper reports a roadmapping study conducted by the 4M Network of Excellence, one of the European knowledge communities in MNT. The main aim of this study is to help inform European research and industry about current trends and application requirements in the development of MNT for the batch-manufacture of micro-components and devices. According to its original scope shown in Fig. 1 [3], the approach adopted by the 4M Network is to link technologies, business drivers, and application requirements by establishing capabilities for Multi-Material Micro Manufacture. This generic approach is applied in the Network's roadmapping activities to examine the business and application drivers, and the corresponding trends in MNT development to meet demands for:

- Product miniaturisation through innovative integration and development of knowledge-based technologies and production concepts (especially micro and nano) for processing of non-silicon materials;
- Prediction of product and process performance to reduce/manage the risk during product development and production, and reduce time to market for the next generation of microsystems-based products;
- Future product platforms to meet the requirements of the next generation of microsystems-based products, and of more stringent regulations and environmental legislation;
- Production scale-up to ensure an effective and efficient transfer of product and technology ideas from laboratories to serial production.

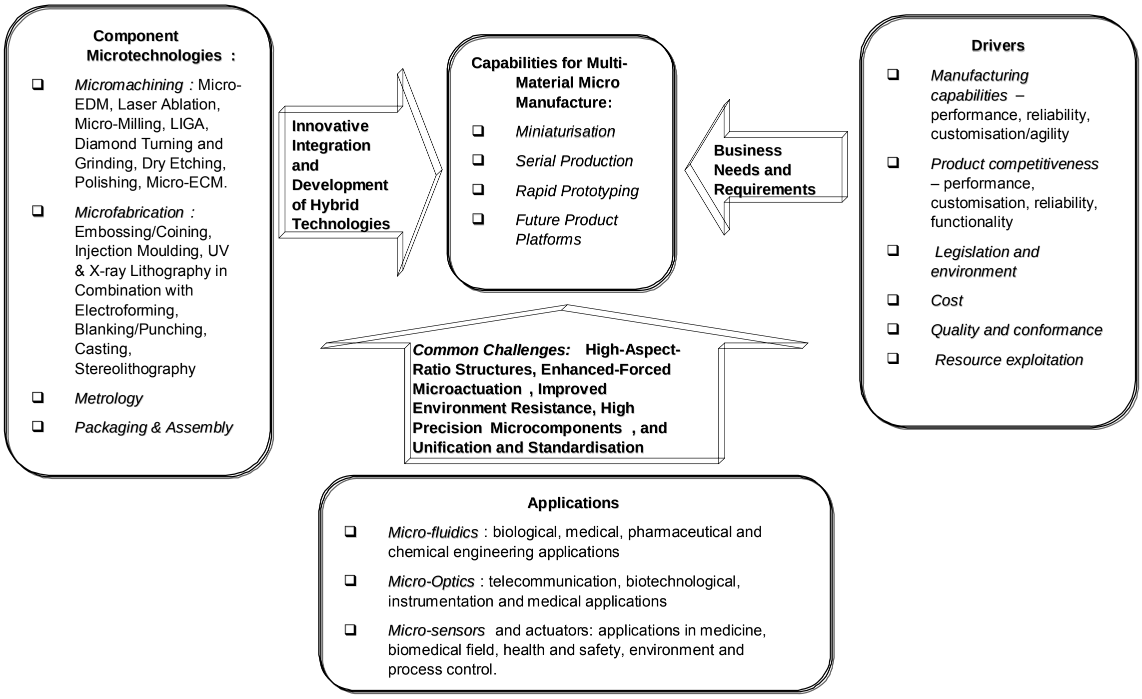


Fig. 1. 4M Scope: technologies, business drivers, and technical application requirements lead to required or provided capabilities.

In considering the above demands, this paper discusses the key factors affecting technology and application developments and tries to answer the following four main questions:

- What are the application requirements and the corresponding trends in technology/process development?
- Is there a potential mismatch between future application requirements and 4M capabilities?
- What is the current level of maturity and future potential of the 4M manufacturing technology areas?
- Are there 4M manufacturing technologies requiring further investment to meet perceived future application requirements?

2. Study Scope

Fig. 2 depicts the relationship between top-down and bottom-up manufacturing in developing technologies for future microsystems-based products [4]. The 'top-down' approach represents the technology developments in reducing the feature sizes towards nanoscale including continuous improvements of their accuracy and surface finish. At the same time, the figure presents the significant advances in chemical technologies for 'bottom-up' processing and control of ever-larger structures. As a result of this technology convergence the structures that can be produced by either approaches are of a similar order and leads to development of new hybrid methods of manufacture.

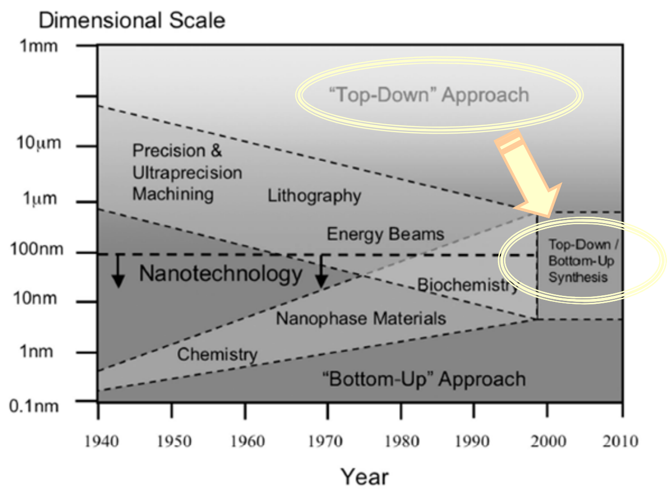


Fig. 2. The convergence of top-down and bottom-up production techniques [5]

Taking this into account, the roadmapping studies being conducted by the 4M Network address issues related to:

- Processing technologies for non-silicon materials;
- Development of top-down technologies towards the creation of top-down/bottom-up hybrid production platforms;
- Applications that will be underpinned by the establishment of such micro/nano manufacturing capabilities.

Fig. 3 represents the overall scope of the roadmapping studies being conducted by the the 4M Network of Excellence. This paper reports only the generic findings concerning application requirements and current and future technological trends. Other studies initiated by the 4M Network are focused on creating specialised application and technology roadmaps.

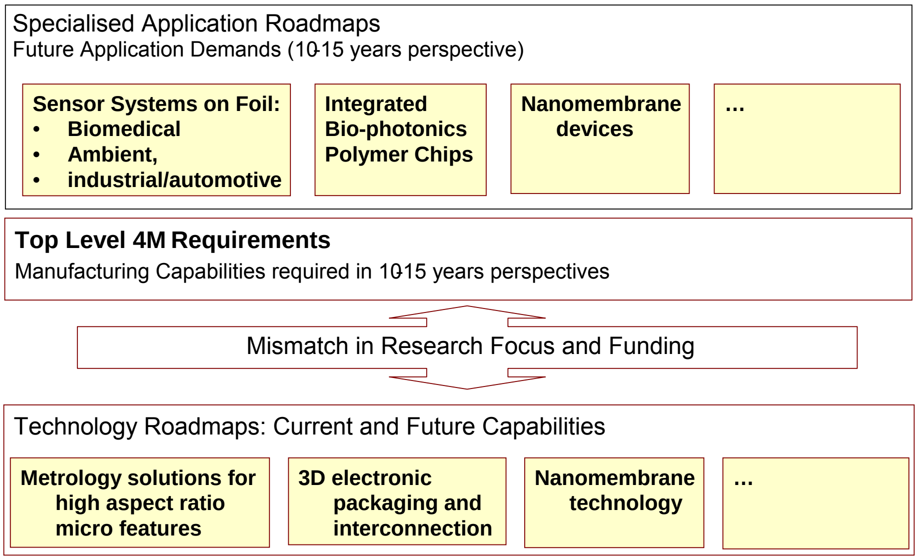


Fig. 3. The overall scope of the roadmapping studies conducted by 4M

In particular, the following roadmapping studies undertaken by Application and Technology Divisions of the 4M Network are currently on-going:

Applications:

- Sensor systems on foils;
- Integrated bio-photonics polymer chips;
- Nanomembrane devices;
- Micro fluidics on foil.

Technologies:

- Metrology solutions for high aspect ratio micro features;
- 3D electronic packaging and interconnection;
- Nanomembrane technology;
- Ceramic hybrid gravure printing process and microPIM for active μ-systems;
- Micro Scale Batch Self-Assembly of Microparts;
- Next generation Micro/Nano-metrology equipment.

The results of these specialised application and technology roadmaps will be reported separately from the findings of this “top-level” study.

The detail of the original 4M approach to mapping application requirements and technology capabilities is shown in Fig. 4 [3]. Common requirements from three application areas in the form of design/functional features are mapped onto manufacturing features produced by a range of micro manufacturing technologies to provide a set of ‘Design for Manufacture and Assembly’ rules. The objective of carrying out such analysis is to assist designers of new multi-material microsystems-based products and also to identify discrepancies between technological requirements of a range of applications and current and future manufacturing capabilities. In line with this approach, this study focuses on three application areas specifically addressed by the 4M knowledge community:

- A1: Micro-fluidics;
- A2: Micro-sensors and actuators;
- A3: Micro-optics.

It also covers three technology areas representing the range of the component technologies that constitute the 4M capabilities:

- T1: Surface modification and structuring processes;
- T2: Energy assisted and mechanical processes;
- T3: Replication processes.

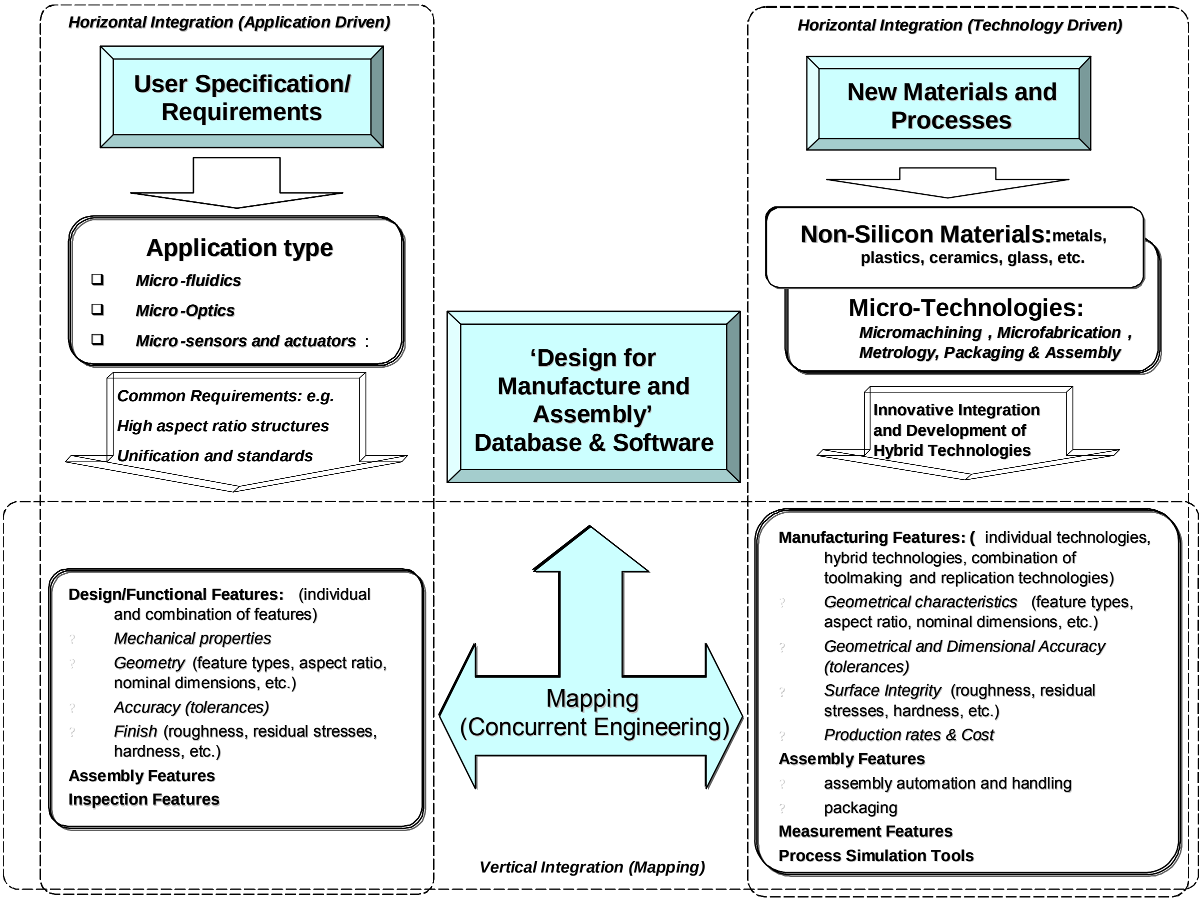


Fig. 4. 4M Approach: detail of mapping between application requirements and technology capabilities towards the creation of a new 'Design for MNT Manufacture' system

The technologies covered during this study are represented pictorially in Fig. 5, according to their material removal/addition/forming capabilities [6]. The first group of technologies performs material removal and deposition employing a 1D processing, e.g. structuring by a milling cutter or a laser beam. The second group includes technologies that utilise multiple 1D processing, e.g. 3D printing. Next, the technologies falling in the group of 2D processes perform structuring by employing masks, e.g. photo lithography. Finally, 3D processing can be carried out using technologies for surface modification and deposition, e.g. PVD, CVD and electroplating, or technologies for volume structuring such as injection moulding and embossing. Generally, the manufacturing flexibility of the technologies increases from right to left, e.g. less time and effort are required to setup the process, while the production speed increases from left to right. Usually, a combination of technologies in the form of a process chain is required for economic production of micro components and devices, incorporating micro/nano features. In Fig. 5, the numbers in brackets show the frequency of occurrence of technologies in the process chains suggested at the roadmapping workshop as described later.

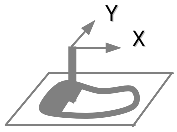
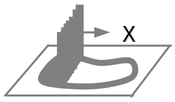
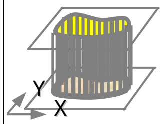
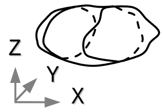
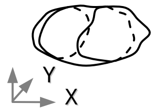
3. Methodology

3.1 Researcher workshop

A one day workshop was held in February 2006 at Cranfield UK, facilitated by Cardiff University's Cardiff Business School and Manufacturing Engineering Centre. The 30 participants comprised the 17-strong 4M Executive Board and invited experts from among the 4M partners. A methodology was devised to answer application requirement and technology capability questions, based on the initial discussion round from a Delphi type study, supplemented by SWOT and timeline analyses.

After an introductory session, participants were split into 3 applications groups (A1, A2, A3 above) according to their area of expertise. During 3 parallel sessions, each group addressed 3 questions:

- What are the main drivers for developing micro-fluidic* products? (*or -optic or -sensor & actuator)
- What are the main barriers to the successful manufacture of micro-fluidic* products?
- What are the main 4M technical capabilities that are important for the successful manufacture of these micro-fluidic* products?

Dimension:	1D Processing 	Multiple 1D Processing 	2D Processing 	3D Processing (Surface) 	3D Processing (Volume) 
Metals	LH, EDM (4), ECM, Grinding (6),	MF (6), Grinding (6)	Lap, Pol (5), MF (6)	Lap, Pol (5), ECP, EF (3), EP (4)	EDM, MF (6)
Polymers	3DL	3DP (4)	EBL, IBL (2), LL, PUL (8), XL (1)		HUE (4), NIL (2), NI (2), R2RE (3), IM (17)
Ceramics	3DL, Grinding (6)	3DP (4)	IBL (2), LL,	Lap, Pol (5)	NIL (2), NI (2), R2RE (3
Any material	EBM (2), FIB (7), LA (9), PM, AWJ, Drilling (1), Milling (11), Turning (4), SLS		Etch (1), PMLP (2), SP (4)	PVD (9), CVD (2), SC (1), SA	Casting (2), MCIM, PIM (1)

Key:

3DL	3D Lithography	Lap	Lapping
3DP	3D Printing	LH	Laser hardening
AWJ	Abrasive water jet	LL	Laser lithography
Casting	Casting	MCIM	Multi-component injection moulding
CVD	Chemical vapour deposition	MF	Metal Forming
DL	Direct LIGA	Milling	Milling
Drilling	Drilling	NI	Nano-imprinting
EBM	Electron beam machining	NIL	Nano-imprint lithography
EBL	Electron beam lithography	PIM	Powder injection moulding
ECM	Electrochemical machining (ECM)	PUL	Photo / UV lithography
EDM	Electrical discharge machining (EDM)	PM	Plasma machining
EF	Electroforming	PMLP	Projection mask-less nanopatterning
ECP	Electro-chemical polishing	Pol	Polishing
EP	Electroplating	PVD	Physical vapour deposition
Etch	Etching	R2RE	Reel to reel embossing
FIB	Focused ion beam	SA	Self assembly
Grinding	Grinding	SC	Spin coating
HUE	Hot/UV embossing	SLS	Selective laser sintering
IBL	Ion beam lithography	SP	Screen printing
IM	Injection moulding	Turning	Turning / Diamond turning
LA	Laser ablation	XL	X-ray lithography

Fig. 5 Map of technologies according to process ‘dimension’ and material relevance.

In each session above the question was first “brainstormed” by the group - members were free to call out their ideas and proposals. Handouts were provided with ideas and prompts. After this, group members were asked to write down three answers each on sticky notes, which were then placed on posters. The group facilitator then brought similar notes together under common headings – in agreement with, and under the guidance of, the group members. Once under these headings, group members were asked to allocate their “budget” of 5 stickers to what they considered the most important headings. For drivers and technical capabilities (technical requirements), each group jointly placed the identified headings along a timeline, according to when they would have impact. For barriers and technical requirements, participants considered collectively what were considered to be the Strengths, Weaknesses, Opportunities, and Threats (SWOT) for Europe (barriers) or 4M (technical requirements) in relation to the rest of the world.

Participants were likewise split into 3 technology groups (T1, T2, T3 above) according to their area of expertise. During parallel sessions, each group addressed 3 questions:

- What are the 4M technologies/processes with the highest impact on the market currently?
- What are the key capabilities that can be used to characterise the 4M technologies in your group?
- What are the 4M technologies/processes that are currently under development and promise to become economically viable in 10 to 15 years?

Brainstorming, note writing, and budget allocation occurred as in the previous sessions. This resulted in ranked lists of current and future technologies and a ranked list of capabilities. The groups then ordered the top 10 current technologies within their group, according to their ability to satisfy each of the top three scoring capabilities.

An additional session combined applications and technologies by asking participants in each application group individually to write down promising process chains for specified products in their application area. Approximately 40 process chains were identified across the 3 application areas.

After the workshop, additional information was collected on the breakdown of research funding among 4M partner projects integrated within 4M. Project funding relevant to multi-material micro manufacture from institutional, national/regional, EC, and industry projects was broken down according to the technology areas shown in Fig. 5.

3.2 Industry questionnaire

A supporting questionnaire was prepared following, and based on the results from, the workshop, to canvas the views of industrialists through face-to-face interviews between 4M partners and associated industrialists.

For the application questions, interviewees were asked to select which of micro-optics/-fluidics/-sensors & actuators (or other ….) they would answer questions on. This was followed by additional questions on market shares and on market sectors, before moving to the 3 main application questions. The questions were altered slightly to try to obtain an 'industry-wide' viewpoint, and the third question mentioned 'technical requirements' and 'batch manufacture' explicitly, these being implicit in the workshop. Initial brainstorming was mimicked by first asking interviewees to answer questions before allowing them to see a list of answers (including an 'other' category) to vote on (invest a budget in), again with 5 votes. Common lists of answers for each application session were devised from the results of the workshop by combining answers from the 3 application areas, as shown in Table 2. This involved some interpretation in order to group similar answers across and sometimes within application areas. Timelines were mimicked by asking interviewees to choose a short (0-3 years) medium (3-8 years) or long-term (8-15 years) timescale for those answers voted on. SWOT analyses were mimicked by asking interviewees whether Europe was in front, comparable, or behind the rest of the world in for those answers voted on. An additional question asked which manufacturing capabilities and materials were most important for the application group chosen.

For the technology questions, interviewees were free to choose technologies from a composite list of technologies (T1, T2, and T3 combined), as shown in Table 4, when answering the first and third questions on current and future technologies. This list was based on an existing 4M technology classification augmented by the results from the workshop. The second question was not asked directly, but rather interviewees were invited to say how well their top two current and future technologies met a composite list of 8 capabilities, derived from the workshop. There were additional questions on which materials and application groups the technologies were most suitable for.

4M partners were free in their choice of industrialists, only aiming to find individuals with good technical and market knowledge. In total 38 industrialists from 38 companies (in 1 case a trade association) responded, normally by interview. The following indicates the profile of the companies involved:

- **Business descriptions**: tooling, injection moulding, etc. [5]; research & development, e.g. in MEMS [7]; machine tool manufacture [3]; micro- including electronic assembly & packaging [4]; sensor production [2]; heath service products [3]; coatings [2]; other product manufacture [6]; not specified [4]
- **Country**: Austria [2], Bulgaria [2], France [2], Germany [10], Greece [1], Hungary [2], Italy [1], Netherlands [1], Spain [3], Sweden [4], Switzerland [2], UK [6], International [2]
- **Technology provider/user**: technology provider [25], technology user [29]
- **Number of employees**: 1-10 [8] 10-50 [15] 50-250 [4], 250-2500 [4] >2500 [5], not specified [2]
- **Application area** (on which questions were answered): micro-fluidics [9], micro-optics [8], micro-sensors & actuators [10], other [7], although in 14 cases more than one category was chosen and in 2 cases no category was chosen. 'Others' were dental / medical / shaving products, display coatings, micro-tooling, metal processing, and electronics and semiconductors

No attempt was made to account for bias in those participating in the exercise and not all results from the workshop and questionnaires are reported in this paper.

4. Results: Applications

4.1 Market sectors

The market sectors perceived by industry as being most significant especially for micro-fluidic, micro-optic, and micro-sensor & actuator applications are shown in Table 1. Top sectors overall in order of their perceived importance are medical/surgical, automotive and transport, biotechnology, and consumer products. Second level sectors are information and communication technology, energy/chemical, academic/scientific, and pharmaceutical.

Table 1. Perceived market sector importance for micro products

Sector	Micro-fluidics	Micro-optics	Micro-sensors & actuators	Overall (inc. other)
Medical/Surgical				
Automotive and Transport				
Biotechnology				
Consumer Products (Electrical, Games, ...)				
Information and Communication				
Energy/Chemical				
Scientific/Academic Community				
Pharmaceutical				
Construction				
Domestic Products (Clothing, Furnishings, ...)				
Food				
Aerospace/Space Science				

4.2 Application requirements

Table 2 contains results from the three application questions regarding the perceived drivers, barriers and technical requirements for developing/manufacturing micro products. ‘Other’ answers from industry were ‘(total) flexibility’ and ‘automation’ (both drivers), however their score was small compared to those of the pre-defined categories.

It is posited that the results from these three application questions and from the three application areas might be combined to form a common set of application requirements for micro products for these application areas. Table 3 shows the results of such a combination, where the results have been grouped into 11 categories, indicating both research and industry results. The entries are ordered according to their perceived importance, using a combined research plus industry score, though this ordering is clearly dependent on how the requirements have been grouped, which is in turn a matter of judgment. Market and product functionality / performance related answers have been excluded as not being application requirements. ‘Tolerance & accuracy’ and ‘Metrology’ answers were also excluded due to their very low score.

The top application requirement is for low cost / volume production. The second is for knowledge / training, including knowledge transfer to industry. The remaining categories are of roughly comparable importance. The two industry led requirements are low cost / volume production and quality. This might be interpreted as addressing short-term cost and quality imperatives. The research led requirements include integration, at the product, component, and process level, indicating a longer term viewpoint, though perhaps still aiming for low cost quality output in the end. The other research led requirements are for materials and for assembly & packaging.

Multidisciplinarity, process/technology knowledge (sharing), integrated process chains, and assembly & packaging, all address recommendations from the 4M Industrial and Scientific Advisory Boards at the time of the 4M2005 Conference, though the Boards’ recommendation for metrology is not highlihgted here. The concentration of industry on cost and quality and of researchers on longer-term issues is also in line with the Advisory Boards’ recommendation to recognise the different functions of industry and the research community. Design (for manufacture rules) corresponds to the ultimate 4M goal in Figure 2 of this paper as well as helping to fulfill the Advisory Boards’ recommendation to provide ‘toolboxes, characterising a broad range of technologies, that can be selected/ adopted in the design’. The importance of process chains may suggest the need to characterise processes not only for their individual capability but also for their suitability for integration into process chains. Novel combinations of processes may provide required capabilities not available through the conventional use of individual technologies.

Table 2. Results from application questions

Category[1]	Research				Industry
	Fluidics	Sensors	Optics	Overall	Overall inc. other
DRIVERS					
A Lower cost	■■■■	■■■■■■■	■■■■	■■■■■	■■■■■
A Volume production					■
M New markets/applications	■■■■■■■■	■■		■■■■	■■■■
P Improved product functionality		■■■■■■		■	■■■■
E Product function integration			■■■■■■	■	■
E Physical product integration		■■■■	■■■■■	■■	
P Sensitivity + precision		■■■			■■
H Integrated production (process chains)			■■■■	■	
F Quality, efficiency + reliability	■■■			■	■
M Safety and environment			■■■	■	
M Biological epidemic risk	■				
BARRIERS					
A Cost	■				■■■■
M Conservative markets	■■■■			■	■■■
M Competition from silicon					
M No successful exemplar product					
G Material availability		■■■■■		■	
B Design knowledge	■■■				■
B Interdisciplinary knowledge	■■■		■■■	■	■
B Lack of trained people	■				
B Knowledge about processes/technology[2]	■		■■■■	■	■■■
D Immaturity/lack of technology	■■■■■■	■		■■■	■
H Integrated process chains		■■■■	■■■■■■■■	■■■■	
D No prototyping		■■■■		■	
C Process complexity for 3D		■■■			
D Technology diversity / lack of standards		■■■			
J Packaging & assembly			■■■■■	■	■
-- Metrology			■■		
TECHNICAL REQUIREMENTS					
A Scale-up/replication	■■■■			■	■■■
E Functional/system integration	■■■■	■■		■	
K Nano-micro or micro-meso integration	■■■■	■	■■■■■	■■■■	■
C 3D freeform structuring			■■■■	■	
C Surface properties	■		■■■	■	■■■■
-- Tolerance & accuracy		■			■
G New/improved/multi materials	■	■■■■■■	■■■	■■■■	■
B Design for manufacture		■■			
I Process/machine technologies		■■■■■	■■■■■■	■■■■	■■■
B Modelling					
F Quality/reproducibility/reliability			■■		■■■■
D Standards	■				
J Assembly & packaging	■■■■	■■■		■	

[1]A-J - common application requirements (Table 3); M - markets; P - product functionality / performance
[2]In the workshop this answer included the idea of knowledge sharing

Table 3. Common application requirements

Category	Importance	Time ordering	
		Research	Industry
A Low cost / volume production		5	4
B Interdisciplinary, design, and process/technology knowledge		-	-
C 3D features, surface properties		7	3
D Technology / maturity / standards		10	10
E Function and physical integration		4	7
F Quality/reproducibility/reliability		2	5
G New/improved/multi materials		9	6
H Integrated process chains		2	2
I Process / machine technologies		1	9
J Assembly & packaging		5	8
K Nano-micro or micro-meso integration		8	1

Key: Research Industry

Also indicated in Table 3 is a possible time ordering for when these requirements will have impact. Due to the groupings of results, timelines only being available for drivers and technical requirements, and the limited data for the lower scoring industry results, this must be considered only as a tentative ordering. Given this proviso, notable differences between research and industry results are the much earlier position given to process / machine technologies by researchers compared to industry and conversely the much later position given to nano-micro or micro-meso integration by researchers compared to industry.

The list of application requirements in Table 3 is a significant output of this study and might be considered potential research areas for multi-material micro manufacture.

4.3 SWOT analysis

Fig. 6 shows composite results from SWOT analyses carried out for the three application groups (see A1, A2, A3 above) with respect to barriers to the successful manufacture of micro products, for Europe versus the rest of the world. This represents the view only of researchers. Possible interpretations from the diagram are as follows:

- The strength of Europe is in the availability of trained people, well established machine tool industry and multidisciplinary product development expertise. These are the most important ingredients for the establishment of knowledge-intensive production capabilities in Europe.
- The main weaknesses that may slow down the take up of MNT in Europe are the costs required to adopt these technologies, the conservatism of some industrial sectors, the lack of knowledge sharing between R&D actors and industry, and lack of standards and metrology support.
- The possible opportunities for Europe in regard to the rest of the world are in integration of process chains, creation of capabilities for 3D processing, establishment of prototyping capabilities, effective implementation of design for manufacture, and improved research efficiency and focus.
- The indicated threats for Europe come from standards and packaging solutions developed outside Europe, and the dominance of Far East in key consumer markets.

5. Results: Technologies

5.1 Current and future technologies

Results from the two technology questions regarding the micro manufacturing processes with highest perceived current or future impact on the market are shown in Table 4. Technologies are divided according to the three workshop application groups (see T1, T2, T3 above) and further into the seven categories within the 4M technology classification. 'Other' answers from industry, one respondent for each, were glass moulding and soft embossing. Note that the scores within each of the three workshop groups were nominally constrained to be approximately equal; however there was some 'leakage' between groups, i.e. groups would sometimes choose technologies from one of the other two groups. Note also that in some cases scores were allocated to a category of technologies rather than to individual technologies.

Strengths	Weaknesses
A1 Trained people (linked to Opportunity)	A1 Lack of technology (linked to Opportunity)
A1 Multidisciplinarity	A1 No successful exemplar products
A1 Technical expertise	A1 Lack of awareness (linked to Opportunity)
A2 Technology diversity and many new ideas	A2 Infrastructure costs (ie funded by tax) (also Threat)
A3 Deep expertise in fundamental technologies	A3 Lack of shared knowledge with industry
A2 Technology maturity	A3 Labour cost
A3 Machine tool industry	A3 Need critical mass of research in design for manufacture
A3 Leaders in precision engineering	A3 Metrology is imported (Nano)
A3 Capability to adapt existing technology to new products/technologies	A3 Duplication of R&D efforts
A3 Political & economic stability	A3 Lack of students/education
	A3 Bureaucracy in funding R&D
	A3 State aid issues
	A3 Spread versus Focus of funding allocation

Opportunities	Threats
A1 Design knowledge (linked to Weakness)	A1 Conservative markets (Linked to Weakness)
A2 Infrastructure	A1 Risk/investment (Linked to Weakness)
A2 Competition from silicon (also Threat)	A2 Materials – stringent regulations in EU
A2 3D Capability	A2 Packaging
A2 No prototyping	A3 Materials development is occurring outside Europe[1]
A2 Integration (processes) EU strong in this	A3 Lack of shared knowledge …. leading to increased development time
A3 Integration of process chains	A3 USA sets metrology standards
A3 Exploit development of integrated lines	A3 Reliance on adapted solutions
A3 Established machine tool industry	A3 Dominance of Far East in key consumer markets
A3 Standardisation & unification of metrology stnds	
A3 Links to product development	
A3 Increase efficiency of collaboration	
A3 Funding agency "top of bill" research (military)	
A3 Deep vs Broad	
A3 Centres of Excellence for field development	[1]This threat is from the technical requirements SWOT

Key: Workshop groups: A1 = micro-fluidics, A2 = micro-sensors & actuators, A3 = micro-optics

Fig. 6. Barriers to the successful manufacture of micro products SWOT

The first analysis of current and future technologies may be made using the summary shown in Table 5. The research and industry results show reasonable agreement as regards the importance of current technology areas. Changes in the future, according to the research results, indicate an increase in the importance of beam-based processes, a large decrease in the importance of electrical / chemical processes, and a very large increase in the importance of prototype / layer-based processes, in particular 3D Printing and to a lesser extent SLS. These latter trends were not seen at all in the industry results, where EDM for example continues to be important. There is broad agreement on the trends for the remaining technology groups, which mostly retain the same relative importance, with the exception of coating that shows a decrease in importance.

With respect to the importance of individual technologies within the technology groups, there is some agreement as well as some noticeable differences. In addition to the prototype / layer-based processes differences noted above, there is particular discrepancy with regard to replication processes as to which technologies are important both now and in the future. While researchers highlighted metal forming, SLS, and particularly reel to reel embossing for the future, industry highlighted multi-component injection moulding, nanoimprinting, and powder injection moulding. Finally Table 6 lists individual technologies according to their perceived importance for the future. A consistent pattern to account for the differences between research and industry results has not been identified.

Table 4. Results from technology questions

	Technology	Importance				Process chain[1]	4M partner funding[2]
		Research		Industry			
		Current	Future	Current	Future		
Energy assisted and mechanical processes	Beam-based						
	E beam						
	Focussed Ion Beam (FIB)						
	Laser ablation						
	Laser hardening						
	Plasma machining						
	Projection Mask-Less Patterning PMLP)						
	Electrical / Chemical						
	Etching						
	Electrical discharge machining (EDM)						
	Electrochemical machining (ECM)						
	Electrochemical polishing						
	Electroforming						
	Mechanical machining						
	Abrasive water jet						
	Drilling						
	Milling						
	Grinding						
	Lapping						
	Polishing						
	Turning / Diamond turning						
	Prototype / layer-based manufacture						
	3D Printing						
	3D Lithography						
	Selective laser sintering						
Surface modification and structuring processes	Lithography						
	E beam lithography						
	Ion beam lithography						
	Laser lithography						
	Nanoimprint lithography (NIL)						
	Photo / UV lithography						
	X-ray lithography						
	Coating						
	Physical vapour deposition (PVD)						
	Chemical vapour deposition (CVD)						
	Electroplating						
	Spin coating						
Replication processes	Replication						
	Casting						
	Direct LIGA						
	Hot/UV Embossing						
	Injection moulding						
	Metal Forming						
	Multi-component injection moulding						
	Nanoimprinting						
	Screen printing						
	Powder injection moulding						
	Reel to reel embossing						
	Self assembly						

[1]The relative frequency of occurrence of technologies in the process chains
[2]The relative R&D funding of 4M NoE partners categorised according to the technology classification.

Table 5. Summary results from technology questions

Technology	Importance				Process chain[1]	4M partner funding[2]
	Research		Industry			
	Current	Future	Current	Future		
Beam-based						
Electrical / Chemical						
Mechanical machining						
Prototype / layer-based manufacture						
Lithography						
Coating						
Replication						

[1]The relative frequency of occurrence of technologies in the process chains
[2]The relative R&D funding of 4M NoE partners categorised according to the technology classification.

Table 6. Perceived important future technologies

Technology	Perceived importance	Technology	Perceived importance
3D Printing			
Milling		Hot/UV Embossing	
Powder injection moulding		Self assembly	
Reel to reel embossing		Projection Mask-Less Patterning (PMLP)	
Nanoimprint lithography (NIL)		Electrochemical machining (ECM)	
Injection moulding		Electroforming	
Nanoimprinting		Electroplating	
Multi-component injection moulding		Direct LIGA	
Laser ablation		Lapping	
Selective laser sintering		Photo / UV lithography	
Metal Forming		Physical vapour deposition (PVD)	
Plasma machining		Etching	
E beam lithography		Polishing	
Electrical discharge machining (EDM)		E beam	
Screen printing		Grinding	
Drilling		Ion beam lithography	
X-ray lithography		Laser lithography	
Turning / Diamond turning		Chemical vapour deposition (CVD)	
3D Lithography		Casting	

Key: Research Industry

5.2 Process chains

Technologies selected as important for the future may also be compared to the frequencies with which technologies are mentioned in the process chain exercise. There is partial overlap in the results in Table 4. There may be technologies in process chains that are not considered important in their own right but could become important because of their presence in an important process chain. The frequency of occurrence of technologies in the process chains is also indicated in Fig. 5. Examples of processes within the process chains that are not otherwise individually identified as important are:

- E beam
- Focused ion beam
- Polishing
- Ion beam lithography
- PVD
- Casting

5.3 4M technology funding

56MEuro of funding for partner projects integrated into the 4M Network and currently ongoing or recently completed (within the last year) were categorised according to the technology classification in Table 4. As an indication, the split by funding source for 113MEuro of partner projects integrated into 4M to date is approximately: institutional 14%, national/regional 53%, EC 18%, industrial 15%.

Analysing Table 5, in terms of groups of technologies, shows a reasonable fit between perceived importance of future technologies (research / industry) and 4M funding, with the exception of prototype / layer-based technologies ('deficit' of funding), and to a lesser extent electrical / chemical and coating processes ('excess' of funding). An examination of individual technologies (Table 4) likewise shows a relative excess or deficit of 4M project funding over the perceived level of future importance of the technologies. Technologies where the relative 4M project funding is significantly greater than the perceived future importance of the technology are:

- Focused ion beam
- UV/hot embossing
- Metal forming

Technologies where the relative 4M project funding is significantly less than the perceived future importance of the technology are:

- 3D printing
- Multi-component injection moulding
- Nanoimprinting
- Powder injection moulding
- Reel to reel embossing

This could indicate in which direction future research funding might move, although such an interpretation might be misleading since (a) full consideration of the technologies necessary for a complete process chain is not included, (b) funding decisions for some current 4M projects will have been made some while ago, (c) these 4M funded projects only cover part of the total research funding within these technology areas, and (d) 30MEuro of the 56MEuro funding is accounted for by only two 4M partners, with funding for some technologies, such as FIB, metal forming, laser ablation, plasma machining, and NIL, mostly accounted for by a single partner.

6. Conclusions

This paper reports the finding of the top-level roadmapping study conducted by the 4M Network of Excellence. The breadth and depth of technologies for multi-material micro manufacture are studied to identify mismatches between current and future application requirements and manufacturing capabilities. The following generic conclusions could be derived from the response of the research community and industry:

- There is no one technology that will prevail – the "breakthroughs" if any will come from an innovative integration of complementary technologies and their implementation in new manufacturing platforms.
- A "tool box" of technologies exists to support the move from designing MST-based products for specific materials and processes to designing processes/process chains to satisfy specific functional and technical requirements of new emerging multi-material products.
- There are signs of bridging the "gap" between "mechanical" ultra-precision engineering and "MEMS/IC-based" technologies. Many promising process chains suggested by the research community integrate component technologies from both groups.
- The breadth of micro-manufacturing technologies makes it difficult to select the most appropriate manufacturing route. Therefore, it is very important to advance the existing design for manufacture knowledge.
- The strength of Europe is in the availability of trained people, well established machine tool industry and multidisciplinary product development expertise. These are the most important ingredients for the establishment of knowledge-intensive production capabilities in Europe.
- The main weaknesses that may slow down the take up of MNT in Europe are the investment required to adopt these technologies, the conservatism of some industrial sectors, the lack of knowledge sharing between R&D actors and industry, and lack of standards and metrology support.

In addition, the following specific conclusions could be made based on the conducted roadmapping study:

1. The **market sectors** perceived by industry as most significant especially for micro-fluidic, micro-optic, and micro-sensor & actuator applications in order of importance were: medical/surgical, automotive and transport, biotechnology, consumer products, information and communication, energy/chemical, scientific/academic community, and pharmaceutical.

2. The **application requirements** for developing/manufacturing micro-fluidic, micro-optic, and micro-sensor & actuator products identified by the study in order of importance were: low cost / volume production; interdisciplinary, design, and process/technology knowledge; 3D features / surface properties; technology / maturity / standards; function and physical integration; quality / reproducibility / reliability; new / improved / multi materials; integrated process chains; process / machine technologies; assembly & packaging; and nano-micro or micro-meso integration.

3 The **manufacturing technologies** identified by the study as most promising for future batch-manufacture of micro products in order of importance were: 3D printing, milling, powder injection moulding, reel to reel embossing, nanoimprint lithography, injection moulding, nanoimprinting, multi-component injection moulding, laser ablation, selective laser sintering, metal forming, plasma machining, and e-beam lithography

Finally, Fig. 7 shows the interdependence of technologies and applications in developing new manufacturing platforms.

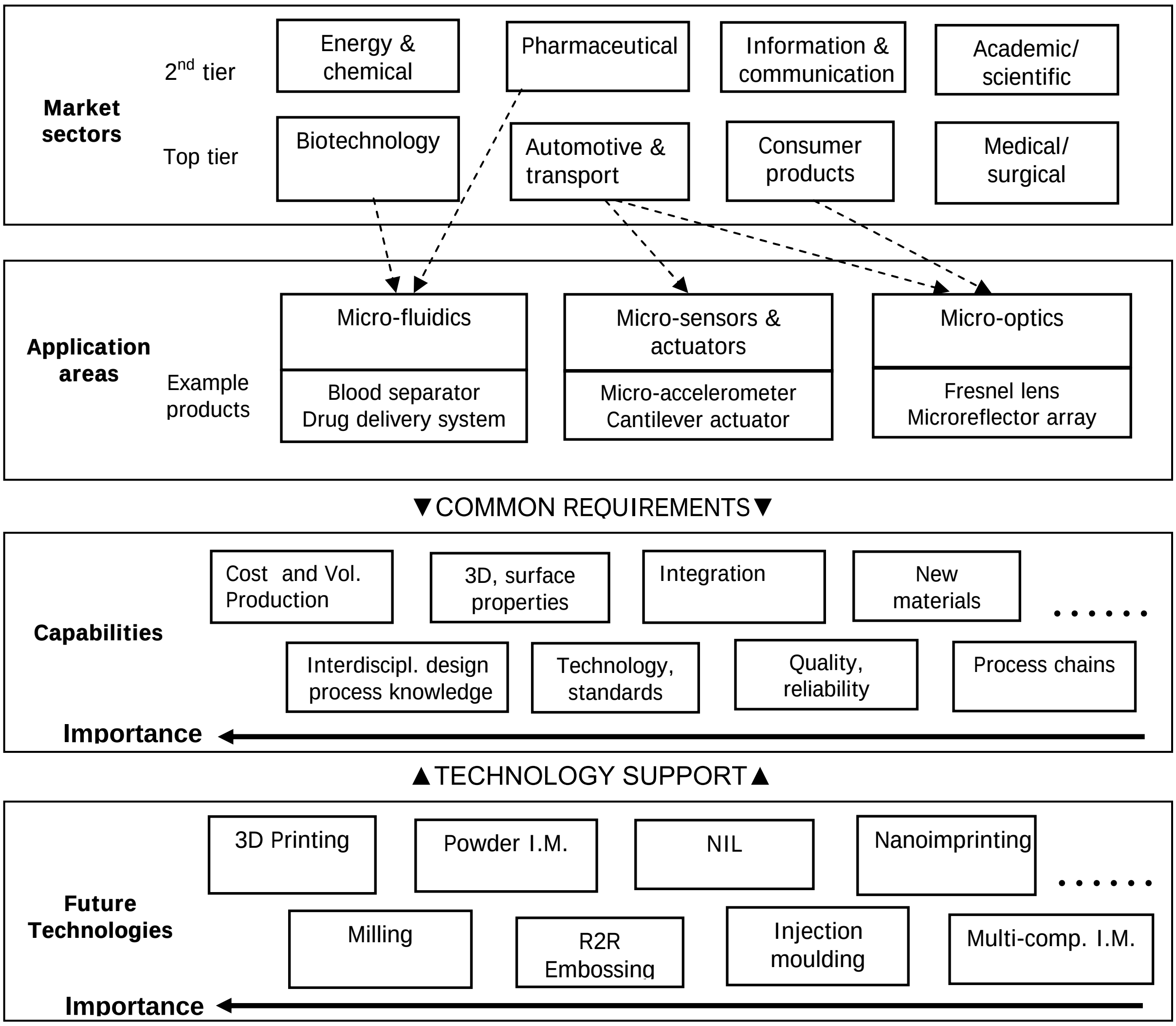


Fig. 7. Common application requirements and technology support

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