Investigation on the International State of the Art of Micro Production Technology

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Abstract

The study "microPRO" dealing with the international state of the art of micro production technology was conducted by the above named institutes. The objective of this study was to determine the worldwide state-of-the-art technology and research in micro production technology by means of scientific investigations and technical discussions with the technology leaders and, based on this, to identify the required research and development as well as the future potentials of these technologies in view of the market-overlapping economic utilization of miniaturized products [1].

Introduction

Due to the manifold advantages of micro-technological solutions the micro systems technology (MST) is worldwide considered as a key technology of the 21st century and various market studies predict an exponential growth for MST. Presently however, a reluctance can be identified regarding the transfer to practice of realizations made in research, since only some few products have come up to the predicted sales expectations so far. In this context, the following core problems can be determined: high complexity of the products and processes, revolution in the component size, necessity of an extensive knowledge covering various technological areas, necessity of high investments and high risk in case of failures, often only economically reasonable for a mass production, limited product flexibility through adaptation of the microelectronic production processes. In a study carried out in 1999, in which the economic potentials of miniaturization from the industrial point of view were examined, the development of an industrially applicable micro production technology that is adapted to the requirements of product miniaturization is rated high to make this transfer into practical applications possible [2].

In this context the above named institutes have cooperated in executing a survey of the international state of the art of micro production technology, supported by the German Federal Ministry of Education and Research. In this survey the following "conventional" micro manufacturing processes were focused on: micro cutting, material removal processes (electro-discharge machining, laser), micro molding and micro forming, automated microassembly and metrology and quality assurance. By recording the worldwide state of the art in the field of micro production technology, the current possibilities, the deficits and the future potentials of these technologies were identified with respect to the market-overlapping economic use of miniaturized products on the one hand. On the other hand, this study of micro production technology aimed to realistically estimate the perspectives of these technologies for the German industry as well as to outline the deficits and the respectively required research.

For this purpose, a profound literature and internet search was made at the beginning, complemented by a patent search. Additionally, about 50 personal technologically oriented interviews were made in Switzerland, Japan/Taiwan/Singapore and the USA with experts from leading enterprises and research institutions in the field of miniaturization and ultra-precision machining. The determined worldwide state of the art of micro production technology, separated into the single technologies, was assessed with respect to the general potentials but also technological deficits regarding the realization of a sector-overlapping miniaturization.

Micro cutting processes

By extending the process limits of cutting processes towards a miniaturization of tools and an increase in precision of the machine tools, new opportunities are offered for a cost-efficient way of micro-structuring of three-dimensional micro components out of a wide variety of materials. Practically all cutting processes common in the conventional area like turning, milling, drilling and grinding, appear in the micro area, with turning being the most important one, followed by milling. A distinction is made between ultra-precision (UP-) cutting and micro cutting. The former usually refer to large-surface components with sub-micrometer accuracies and optical surfaces, the latter mostly refers to structures with dimensions of several ten to 100 μm. Fig. 1 shows several examples.

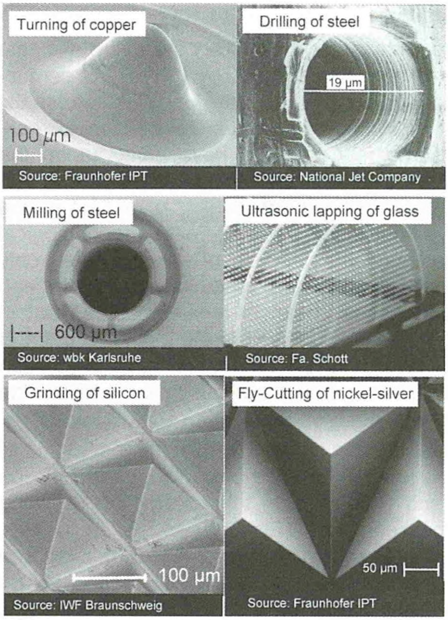

Fig. 1: Micro structures manufactured by cutting

In UP-cutting, cutting tools made of mono-crystalline diamond are almost exclusively used. Its main advantages are its great hardness and the possibility of producing a cutting edge of an almost atomic sharpness, thus enabling optical surface qualities. The production of extremely sharp cutting edges therefore belongs to the most important tasks for micro-cutting [3]. Examples of UP-turned components are molding tools made of non-ferrous metals, e.g. for Fresnel lenses or for roughness standards.

Compared to UP-turning, UP-milling is more flexible [4]. Single-point diamond fly-cutters e.g. allow the production of grooves which can be crossed one or more times in corresponding angles so that columnar or pyramidal structures are created. The materials used in diamond cutting are aluminum, copper, brass, nickel silver and nickel. For cutting steel, carbide milling cutters are used. They are not suitable for obtaining optical surfaces due to the single grains, which appear in the form of micro-notches at the cutting edge. The comparably low price and the possibility of machining steels, however, justify their application. These miniature milling cutters have been used for several years for the structuring of copper electrodes for micro electrical-discharge machining as well as for the manufacturing of filigree parts in the jewelry and watch industry, but also for the manufacturing of molding tools in quenched and tempered steels [5]. The diamond and sintered carbide tools required for micro milling are presently commercially available with diameters ranging within one hundredths of a millimeter. Micro drilling is particularly well established in the mechanical machining of printed circuit boards (PCBs). The majority of micro drilling tools consists of HSS and solid cemented carbide with smallest diameters of partly below 40 μm.

Micro grinding allows the production of even surfaces or grooves as well as smallest components, such as miniature shafts or drills. Since the materials to be ground are mostly semiconductor materials, glasses, ceramics or cemented carbides, diamond tools are primarily used. Straight-lined microstructures are ground by means of cross-peripheral face grinding. The grinding wheels used for this may have very small tool widths of approx. 1 mm to 15 μm. A special type of grinding is the so-called dicing, in which wafers are divided into single chips using grinding wheels with a typical width of smaller than 100 μm, the so-called dicing blades [6]. Abrasive pencils are applied e.g. in the watch industry, in precision engineering and in the manufacture of punching and pressing tools. Especially in the textile industry, the production of aluminum oxide thread carriers with diameters of 0.4 to 4 mm is a field of application for micro abrasive pencils. For more complex component geometries such as the manufacturing of ceramic dental prostheses the process of jig grinding can be used on 5-axes machine tools. Regarding the production of microforms with complex geometries and especially micro holes, the ultrasonic lapping is a reasonable and sometimes the only alternative to grinding. This process has the advantage of working with very low forces and in parallel enabling the production of a multitude of cavities. Thus, cavities with a diameter of smaller than 1 mm can be produced and thin substrates can be machined.

Altogether, micro cutting is a reasonable and promising extension of the spectrum of micro manufacturing processes. An important future objective in research is the ultra-precision machining of steel, regarding the production of heat and wear resistant molding tools [7]. In this connection, promising approaches are especially seen in the ultra-precision steel machining with ultrasonic support [8, 9], in micro drilling and milling with newly and further developed cutting materials for sharp-edged tools as well as in micro grinding with profiled CBN grinding tools.

Micro-machining technologies using non-contact methods

The investigation of the current status of the technology of μ-machining using non-contact methods was performed for electrical-discharge machining (EDM), laser-caving and electro-chemical machining. At the consulted companies and research organizations the dissemination of these technologies was found out to be country specific. Wire electrical-discharge machines (WEDM) are highly developed not only in Japan but also in Switzerland. By the applied generators the machines are capable of producing surface roughnesses better than 0.1 Ra. Additionally, the machines are being developed to use wires with diameters of 20 μm (fig. 2).

Within the interviews of companies in the USA it was discovered that they barely use *micro-electrical-discharge machining.* There are only a few research activities in this field in the USA.

In Japan, EDM was intensively used in industry. Additionally, this state supports the university related research activities of EDM which were very advanced. The overall trend towards developing miniaturized machines was here observed for EDM-machines as well. In μ-EDM, there was found a lot of potential for enhancement and utilization e.g. through the development of an efficient electrode fabrication, the adaptation of machines for μ-machining and the communication between CAD/CAM.

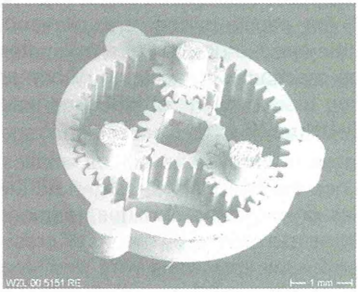

Fig. 2: Microgear cut by a fine wire (Source: WZL)

It was noticed that there is an insignificant usage of *lasercaving* at the companies visited in Japan. On the contrary, in Germany a multiple of activities both in research organizations as well as in many companies were identifiable. Opportunities for further development lay in machining of high aspect-ratio vertical structures and the fabrication of grooves with widths less than 50 μm. Utilization of the *electrochemical removal process (ECM)* is used widely for machining features on millimeter scale and larger. However, it is not used for μ-machining due to the rounding of edges of μ-scale features. Although *lasercaving* is a relatively new manufacturing process, it shows a huge potential for competing with manufacturing processes like micro-electrical discharge-machining and micro-milling. A total substitution will never happen as every method has advantages and disadvantages. Moreover, an appropriate combination of these technologies and their further development allow a new economic perspective in miniaturization.

Micro Molding and Micro Forming

The wide-spread use of injection molding is due to the capability of the process of fabricating three-dimensional geometries with a high output for sectors like optics, fiber optics, medical engineering, etc. [10]. Product examples as well as test structures of research and industry are shown in fig. 3 with minimal structures of 2 μm and maximum aspect ratios of clearly above 100. The cavities are manufactured with the help of EDM, micro-milling as well as the LiGa-process [11].

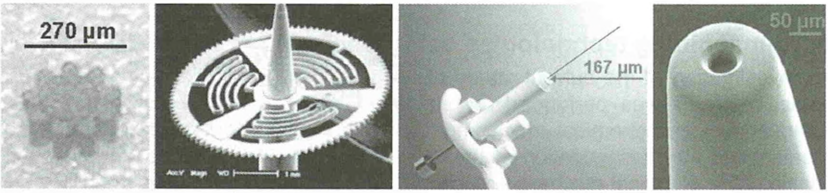

Fig. 3: Products manufactured by micro plastic and powder injection molding (Source: Juken (J), Nivarox (CH), Inmatec (GER), SPT Roth (CH))

To fabricate three-dimensional, wearout and precise micro-parts from a wide range of metal and ceramic materials the process of micro powder injection molding (PIM) was developed. The main fields where the PIM process is presently applied are telecommunications, dental and medical engineering as well as the manufacture of semi-finished products for the semiconductor industry [12]. Products of research and industry are shown in fig. 4. Structure sizes below 100 μm, aspect ratios of nearly 100 and tolerances below ±0,05 % of mean value can be achieved.

In parallel to the development of the MEMS technology, the development of the micro forming technology has progressed. Single technologies like punching or bending are required for the large-scale manufacturing of products in the mass market of the electronics sector, especially consumer goods [13]. Leadframes with single conducting paths (thickness of 150 μm) are produced with an output of up to 2000 parts per minute. Within the cold solid forming the smallest manufactured components using the full forward and backward cup extrusion process are copper pins with a shaft diameter of 0.8 mm and a wall thickness of 125 μm (industry) and with minimum wall thicknesses of 50 μm and a shaft diameter of 500 μm (research).

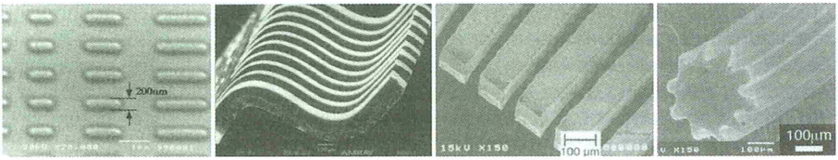

Fig. 4: Products manufactured by micro forming
(Source: Gunma University (J), LFT (GER), Shinko (J), Gunma Univ.)

Micro embossing is a technology that can be mainly used in the fields of micro-fluidics, micro reactor technology, micro-optics and in information technology with minimal structures are in the size of 200 nm to 2 μm [14]. The hot solid forming process is used to manufacture large-scale 2.5-dimensional components with high aspect ratios. The smallest extruded toothed micro-gear has a modulus of 10 μm with a reference diameter of 100 μm.

Automated Microassembly

Under the general term of *automated microassembly*, the investigation was focused on manufacturing and assembly concepts and handling systems, i.e. precision robots and assembly systems, grippers, storage and feeder systems.

When developing automated solutions for the assembly of complex hybrid systems, the cost is an important factor, since 80% of the production costs of miniaturized systems or hybrid systems run up in the assembly [15, 16]. It was stated worldwide that the "development of economically efficient assembly processes" is a main motivation for automating microassembly processes. But also "enabling new technologies" was frequently stated as a motivation. These statements were especially made by the interview partners from the USA, Germany and Switzerland in connection with the aim of "achieving higher accuracies" and "reaching constant high quality". This would open up new fields of application like fiber optics and opto-electronics with higher requirements. In research, also parallel assembly strategies are pursued by means of which the cost and time advantages of batch manufacturing in micro technology are to be transferred to the assembly, whereas in industry the serial assembly process was considered to be necessary with respect to the required accuracies. Depending on the product and thus the process, parallel assembly steps – even combined with serial ones – are not excluded.

Besides the still frequently existing manual work places and microscope work places equipped with micro-manipulators, robots and assembly systems based on cartesian axes arrangements are mainly used in industry for the assembly of micro components. Here, certain systems allow assembly accuracies of ± 1 μm or even ± 0.3 μm when combined with a complex camera system and a superimposed intrinsic control system in which the information is gained through the positional deviation from the element to be mounted. These systems, however, are often developed on customer request for the special requirements of a single product so that accuracies are reached at the expense of a very low flexibility. But a high flexibility is considered to be essential for MST products since a multitude of various products with the most different functions are to be produced in rather small numbers of quantities. Basically, it was seen that there is a demand for functional extensions for assembly systems which allow a positioning and orientation in more than four degrees of freedom in order to be applied in other product areas than in the present 2D pick-and-place chip assembly. In addition, a cost-effective equipment technology is required for a broad automation, for an automated assembly process to be able to economically compete with the manual assembly. In research, this is increasingly attempted by developing a size-adapted equipment, also in combination with the aim of reaching higher assembly accuracies. Particularly in Japan, a great potential is attributed to the subject of the "μ-factory".

A future demand for automation in the total process chain is especially seen by the European and North American interview partners. This also includes both a continuous process automation in the individual micro production processes and an integration of the manufacturing processes into the total process. In the foreground of the considerations always was the aim to achieve low production costs by production process chains that can be automated so that chances for new products or production technologies would arise on the world market.

Micro Metrology

The fabrication of micro components requires a flexible and high-precision quality inspection of microstructures. Basically four tasks of measurement are distinguished: Material testing, integrity inspection, positional and dimensional measurement and the test on functionality. However, 90 % of all metrological requirements account for dimensional and positional measurement tasks [17]. Micro-electronic devices mainly feature 2D-structures that can be comparatively easily measured and functionally tested in the production process by means of optical methods (X-ray inspection, see [18]), for micro-mechanical components those methods exist on a very limited scale.

Basically three different kinds of measuring methods can be applied. Scanning probe microscopy, optical and tactile measurement principles. While the first two groups show weaknesses in the measurement of high aspect ratios (>10-12) and in terms of precision due to strong reflection behavior of the metal probes, possible bevels and effects of edges, the third group has got important difficulties with regard to relied measurement forces as well as appropriate stylus geometries. Opto-tactile instruments are located in the intersection of tactile and optical methods which want to meet with the weaknesses of both groups by using special contact stylus instruments made of fiber glass. The crucial point of micro metrology is to analyze the measuring task far before fabrication in order to define an optimized measurement process. The area of conflict is located between necessary resolution, minimum measuring scale (as well as measuring time) and costs of the measurement equipment. Additionally it is important to determine the functional relevant inspection characteristics for each fabrication part and additional information need in terms of measurement strategies in order to assure a measurement comparableness. There are no standard solutions for the measurement of 3D-micro parts and there are none recognizable in the foreseeable future. Tab. 1 shows a summarizing overview on actual measuring methods and their main field of application in consideration of resolution and measuring scale which can be consulted as a first qualifying basis for the choice of a appropriate measuring method for microstructures.

Measurement method		Resolution [nm]		Range up to ..[mm]	Application
phys. principle	technique	lateral	vertical		
tactile	CMM (NanoMM)	0,01	0,01	0,001-x*1000	Lithography, layers, nano analytic
tactile	SFM	1	1	0,1 X 0,1	biol., polym. probes
optical	Ultra objective	>1	>1		see AEM
quantum	STM	0,01	0,01	100 X 10	ultra fine layer analysis
optical	SNOM	10-20	10-20		e.g. LIGA masks
acoustical	SNAM	100-1000	10		smooth probes:textile hard probes:elect. parts
capacity	SCM	7	1		semiconductor surface
thermal	SThM	50	50		semiconductor elements
interference	White light interferometry	100	0,3-3	0,0016-0,5 x0,0016-0,5	not reflecting surface profilometry
interference	Holographic Interferometry	100	200-300		micro form, position in the plane
triangulation	Stripe projection	200	200	40x40	Micro profile, roughness of non-reflecting surface
activ focus	Confocal Laser Scanning	500	250-300		Micro profile, roughness
passiv focus	local sharpeness	100	12		3D surface profile
electromagn.	AEM	0,2	0,2		3D Micro structur analysis
optical-tacile	Auto focus+ touch sensor	<50	<50	400x400x200	2,5D Micro form, position

Tab. 1: Overview on actual measuring processes and their main field of application

Summary

Comparing the current state of the technical knowledge in micro production, no big differences can be found in the companies and institutions visited in the different countries. Visible are rather country-specific, often traditional focuses in the application and in research of micro production processes. In the USA, the industrial sectors automation and handling technology mostly benefit from the micro production technology due to the strong MEMS development and the support of the semiconductor technology. In contrast to that it is more strongly attempted in Japan to build up and establish a production technology for miniaturized products by long-term research, focused on the non-semiconductor-based conventional manufacturing processes and a miniaturized machine technology. In Switzerland, micro production technology is mostly applied in precision engineering due to the extensive experience in the manufacturing of miniaturized products in the watch industry. This has led to a continuous development and advancing of the necessary mechanical production technologies. In Germany, there is vast knowledge of the semiconductor-based micro-technological processes, the conventional manufacturing processes, the size-adapted machine technology and the further development of conventional machine technology. A focus cannot be identified at the moment so that it is possible to use the potentials of the various approaches equally in the micro production technology in the future. In the opinion of all study participants, a transfer of these technologies into the development of actual products offers good possibilities of pursuing micro production especially in wage-intensive industrial countries in an economically efficient way.

In general, the participating companies and research institutions reckon with a continuous development in the field of miniaturized systems and micro production technology. Revolutionary technical developments and market developments, however, are not seen in the near future. The weakness of economic activity of the world market is often considered to be the biggest market-impeding factor. The majority of the study participants thinks that an advancing of manufacturing technologies and product developments is necessary especially in times of weak markets in order to have a good starting position on the market after an economic recovery.

References

[1] Hesselbach, J. et al.: "mikroPRO – Untersuchung zum internationalen Stand der Mikroproduktionstechnik", Vulkan Verlag, 2002.

[2] Bierhals, R. et al.: "Wirtschaftliche Potentiale der Miniaturisierung aus industrieller Sicht", Abschlussbericht zur Studie des Wirtschaftsministeriums Baden-Württemberg, Karlsruhe, 1999.

[3] Alschweig, E. et al.: "Skalierte Strukturen – Konventionelle Verfahren in der Präzisions- und Mikrobearbeitung", Tagungsband: Aachener Werkzeugmaschinen-Kolloquium. Shaker Verlag Aachen, S. 269-305, 2002.

[4] Weck, M.; Fischer, S.: "Ultraprecision milling of complex surface geometries", Proceedings of 13. Annual Meeting, ASPE, pp. 31-34, 1998.

[5] Weule, H.; Hüntrup, V.; Tritschler, H.: "Microcutting of Steel to Meet New Requirements in Miniaturisation", Annals of the CIRP Vol. 50/1, 2001.

[6] Hoffmeister, H.-W.; Wenda, A.: "Novel grinding tools for machining precision micro parts of hard and brittle materials", Proc. of the 15th annual meeting of the ASPE, USA, pp. 152-155, 2000.

[7] Klocke, F.; Bilsing, A.; von Bodenhausen, J.: "Fertigungstechnische Aspekte in der Mikrosystemtechnik", MAV Konradin Verlag, Leinenfeld, S. 46-48, 2002.

[8] Moriwaki, T.; Shamoto, E.: "Ultraprecision diamond turning of stainless steel by applying ultrasonic vibration"; Annals of the CIRP, Vol. 40/01, pp. 559-562, 1991.

[9] Brinksmeier, E.; Gläbe, R.: "Elliptical Vibration Cutting of Steel with Diamond Tools", Proc. of the 14th Annual ASPE Meeting, USA, pp. 163 – 166, 1999.

[10] Wechsung, R. et al.: "Market analysis for microsystem an interim report from the NEXUS TASK FORCE", Proc. of Micro System Technologies 98, Potsdam, 1998.

[11] Spennemann, A.: "Eine neue Maschinen- und Verfahrenstechnik zum Spritzgießen von Mikrobauteilen", IKV-Berichte aus der Kunststoffverarbeitung, zugleich Dissertation, Aachen, 2000.

[12] Weule, H.; Stengel, G.; Buchholz, C.: "Variation of Geometry and Size for Optimized Demoulding, Separation and Handling of Moulded Micro Parts within an Automated PIM-Process", Proc. of 3rd international conference of euspen, 2002.

[13] Geiger, M. et al.: "Microforming", Annals of CIRP, Vol. 50/2, 2001.

[14] Joo, B.Y. et al.: "Development of Micro Punching System", Annals of CIRP, Vol. 50/1, 2001.

[15] Hesselbach, J.: "Montage miniaturisierter Bauteile", Fertigungstechnisches Kolloquium Stuttgart 2000 (FTK2000), Springer-Verlag, S. 198-217, 2000.

[16] Koelemeijer Chollet, S.; Jacot, J.: "Cost Efficient Assembly of Microsystems", mst-News, Januar 99, pp. 30-33, 1999.

[17] Pfeifer, T.; Freudenberg, R.; Dussler, G.; Bröcher, B.: "Quality control and process observation for the micro assembly process", Z. Measurement – Journal of the International Measurement Confederation, Band 30, Heft 1, pp.1-18, 2001.

[18] Roth, H.: "Klein und gewitzt, Grundlagen der Mikro- und Nanofokus- Röntgeninspektion", Inspect 1/2002, GIT Verlag Darmstadt, S. 54-57, 2002.