Hybrid Manufacturing in Micro/Nano Scale: A Review

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In this paper, a total of 57 micro and nano scale hybrid manufacturing processes are reviewed. These processes are categorized in terms of process timing and process type. Process timing is one of the most important aspects of manufacturing, and three different process schemes – concurrent, main/assistive (M/S) separate, and main/main (M/M) separate – are considered. The process type is categorized as either geometrically additive or subtractive, and all hybrid processes are categorized into combinations of additive, subtractive, and assistive process. Features and advantages are described for each of these classifications. Machining is found to be the most common process for both micro and nano-scale hybrid manufacturing. Of micro scale hybrid manufacturing schemes, 74.4% use assistive processes as a secondary process because the main purpose of most micro scale hybrid manufacturing is to improve the quality of the process. In nano scale manufacturing, 61.5% of hybrid manufacturing schemes employ assistive processes, since these processes typically focus on the fabrication of parts that are difficult to fabricate using a single, existing process. Based on a summary of published work, future trends in hybrid manufacturing at the micro and nano scale are suggested.

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1. Introduction

With the continuing development of technology and growing demands from consumers, increasingly stringent requirements have been placed on manufacturing processes. Improving productivity is becoming ever more important, as is energy consumption and environmental impact. Various manufacturing processes, including machining, additive manufacturing, forming, joining, and welding, are commonly used in the manufacturing industry.¹ However, these processes have some drawbacks that cannot be eliminated owing to technological constraints. For example, machining provides restricted accessibility to the workpiece, owing to the shape of the tool, which limits the shapes that can be fabricated. Additive manufacturing, on the other hand, leads to poor surface quality due to the “stair-step” effect.²

To overcome these limitations, two or more manufacturing processes may be combined to form a hybrid manufacturing process, exploiting the advantages of a given process overcoming the limitations of another.³ Zhu *et al.* reviewed hybrid manufacturing or combined hybrid process in 2013.⁴ In this review, hybrid processes were classified into hybrid manufacturing, which includes additive and subtractive processes,

subtractive and joining processes, additive and transformative processes, and subtractive and transformative processes, and into sub-hybrid manufacturing, which includes additive manufacturing, subtractive manufacturing, and transformative manufacturing. This classification, therefore, considers geometrical issues.

Research into hybrid manufacturing has gained importance both in industry and academia. Over the past two decades, many hybrid processes have been developed to exploit the synergistic effects that two or more different processes may bring. In addition, miniaturization and improving precision have become increasingly important. Using recently developed manufacturing processes, such as lithography processes for microelectromechanical systems (MEMS), inkjet printing, laser cutting, micro electrical discharge machining (EDM), and electrochemical machining (ECM), a diverse range of fabrication techniques have become possible at the micro and nano scale.

In this review, micro and nano scale hybrid manufacturing processes are classified on the basis of two different factors. First, micro scale hybrid systems and nano scale hybrid systems are categorized by feature size. Second, hybrid manufacturing processes are classified according to the process timing and geometry. Then, these hybrid

Fig. 1 A breakdown of the micro/nano scale manufacturing processes reviewed in this paper

processes are described according to concept, features, and relative advantages. Finally, future trends in hybrid processing at the micro and nano scale are discussed.

In this paper, a total 57 of micro and nano scale manufacturing processes are discussed, including 44 micro scale hybrid processes and 13 at the nano scale. MEMS processes are not discussed in this review as we consider them to constitute a separate fabrication process for specific applications. Fig. 1 shows a breakdown of the manufacturing processes discussed here, and hybrid processes consist of combinations of these, giving a total of 118 combined processes. These 57 processes constitute hybrid manufacturing, which consists of two different processes; there are also four hybrid manufacturing processes in which a combination of three different manufacturing processes are used. Note that some processes are not used for manufacturing but for assistive process.

As can be seen from Fig. 1, machining is the most frequently used process in hybrid manufacturing, and deposition and drilling are also commonly used. Adhesion, sintering, annealing, vibration, heating, and chemical treatment, are typically assistive processes in hybrid manufacturing.

2. What is “Hybrid Manufacturing”?

2.1 Classifications

There are a number of definitions of hybrid manufacturing⁴⁻¹⁵ including the combination of different manufacturing processes,¹⁶ two or more different material removal processes,¹⁷ different forms of energy or forms of energy used in different ways at the same time or on the same zone of impact,¹⁸ a combination of processes having a big influence on the process characteristics,¹⁹ the combination of effects that are conventionally caused by separate processes in one single process,^{19,20} and processes created resulting in one or more significant process effects, such as significant force reductions.¹⁹ In 2010, College International Pour la Recherche en Productique (CIRP) suggested two different definitions for hybrid manufacturing processes.⁴ One is ‘open’, which “combines two or more established manufacturing processes into a new combined set-up” and the other is ‘narrow’, in which “different processing principles are used on the same processing zone”.

Fig. 2 Schematic diagram showing hybrid manufacturing by ‘timing’

2.2 Hybrid Manufacturing Processes

In this paper, hybrid manufacturing processes are characterized by process ‘timing’ and by the fabrication ‘type’.

2.2.1 Timing in Hybrid Manufacturing

In manufacturing, ‘timing’ is one of the most important factors. In this review, different processes are considered according to the manufacturing timing. As shown in Fig. 2, three hybrid processes can be defined by the process time. In a concurrent hybrid process, two or more manufacturing processes occur at the same time. In an M/S sequence process, a secondary process is carried before or after the main manufacturing process. In an M/M sequence process, two or more main manufacturing processes are carried out at different times.

2.2.2 Type in Hybrid Manufacturing

Fig. 3 lists the 14 types of manufacturing process considered in this paper, which are categorized into three types: additive, subtractive, and assistive processes. Machining and grinding may be both subtractive and assistive. We define main manufacturing processes as those used to make changes in the geometry, and secondary manufacturing processes as those that maintain the geometry but modify the surface of the workpiece.

Additive and subtractive manufacturing processes are two major fabrication methods from a geometrical point of view. Transformative process that does not change volumes, but change shapes was not considered independently but included in this review as assistive processes.

Fig. 3 Classification of manufacturing processes by 'type'

Most rapid prototyping (RP) or 3D printing technologies are additive processes, whereas machining is one of the most common subtractive processes. Assistive manufacturing processes, including sintering, chemical treatment, annealing, vibration, and heating do not alter the geometry. However, these processes change or transform the properties of the workpiece in order to apply other manufacturing processes.

2.3 Hybrid Manufacturing in Different Scales

Fig. 4 shows a breakdown of the processes at the micro and nano scale in hybrid manufacturing. At the micro scale, 64% of processes are subtractive or additive. Although machining is the most commonly used process at the nano scale, deposition is significantly more common than with micro scale processes. Tables 1 and 2 list the processes discussed in this paper, and categorizes them as described above. Two or more additive, subtractive, or assistive process combine to form a hybrid manufacturing process.

3. Micro Scale Processes

In this section, details of hybrid manufacturing processes at the micro scale are described in terms of the timing and type. As shown in Fig. 5, additive/subtractive hybrid processes are the least common (9.1%). The most frequently used hybrid process was a subtractive/assistive process (56.8%), where these techniques were typically performed concurrently. Approximately 47.7% of total hybrid manufacturing processes at the micro scale involved carrying out manufacturing processes separately.

3.1 Concurrent Hybrid Manufacturing

Three different hybrid manufacturing techniques use concurrent processes: additive/assistive, subtractive/assistive, and subtractive/subtractive.

Fig. 4 Manufacturing processes used in micro/nano scale hybrid manufacturing

Fig. 5 Combinations of manufacturing processes used in micro scale hybrid manufacturing

3.1.1 Additive/Assistive

The major manufacturing processes in this class are deposition and sintering. Inkjet printing is a deposition process by which the deposited materials are sintered using a laser, as shown in Fig. 6. Groups at the University of California, Berkeley, Korea University, and ETH Zurich, have reported pulsed-laser based curing of printed nano particle inks.²¹⁻²⁵ The main purpose of these hybrid systems is low temperature fabrication of passive and active electrical components, including conducting elements, capacitors, and field effect transistors, on flexible substrates. By using laser sintering instead of substrate heating, it is possible to fabricate these electrical components at low temperatures.

The Korea Advanced Institute of Science and Technology (KAIST) developed a laser direct patterning process via the photo-thermochemical reaction of CuO nanoparticles.²⁶ The single-step fabrication of copper electrodes by laser-induced reduction of copper oxide is simple and cost-effective, and makes it possible to fabricate flexible electronics on a polymer substrate. Seoul National University developed a laser-assisted nano particle deposition system (LaNPDS), as shown in Fig. 7.^{27,81} This system has several advantages, in that it is a room temperature process, is suitable for numerous materials including metals and ceramics, a high deposition rate can be used, no chemical processes are required, and no post-processing is necessary. Dye sensitized solar cells (DSSCs) have been fabricated using TiO₂ nanoparticles, where a laser was used to improve the surface properties and photovoltaic efficiency.^{27,81}

Table 1 Hybrid manufacturing processes at the micro scale

Timing	Type	1st Process	2nd Process	Affiliation	Publish Year	Paper No.
Concurrent	Additive/ Assistive	Deposition	Sintering	University of California, Berkeley, USA	2005	21
				ETH Zurich, Switzerland		
				University of California, Berkeley, USA	2007	23
		Heating		ETH Zurich, Switzerland		
				Korea University, Korea	2011	26
				Korea Advanced Institute of Science and Technology, Korea	2012	27
	Subtractive/ Assistive	Drilling	Machining	Glasgow Caledonian University, UK	2004	28
				Glasgow Caledonian University, UK	2006	29
				The University of Edinburgh, UK		
				Glasgow Caledonian University, UK	2011	30
				Philips Dap BV, The Netherlands		
				University of Edinburgh, UK	2009	31
		Machining	Chemical treatment	Nanjing University of Aeronautics and Astronautics, China		
				University of Manchester Institute of Science and Technology, UK	2004	32
				ETH Zurich, Switzerland		
				AGIE AG, Switzerland	2001	33
				AGATHON AG, Switzerland		
				University of applied science St. Gallen, Switzerland		
	Subtractive/ Subtractive	Machining	Heating	Georgia Institute of Technology, USA	2009	34
				The Timken Company, USA		
				Purdue University, USA	2006	35
				University of Nebraska, USA	2008	36
				Korea Institute of Machinery and Materials, Korea	2012	37
				Korea Advanced Institute of Science and Technology, Korea	2012	38
		Vibration		Korea Institute of Machinery and Materials, Korea		
				University of Science and Technology, Korea	2012	39
				Pusan National University, Korea		
				Seoul National University, Korea	2008	40
				Wonkwang University, Korea		
				Nanjing University of Aeronautics and Astronautics	2003	41
M/S Sequence	Additive/ Assistive	Deposition	Sintering	Yonsei University, Korea	2009	42
				Nanjing University of Aeronautics and Astronautics, China	2009	43
				Yonsei University, Korea	2002	44
				National Central University, Taiwan	2006	45
				Politecnico di Torino, Italy		
				Microla Optoelectronics, Italy	2011	46
	Subtractive/ Subtractive	Machining	Chemical treatment	Politronica Inkjet Printing S.r.l., Italy		
				Hanyang University, Korea	2010	47
				Korea Institute of Industrial Technology, Korea		
				National Yunlin University of Science and Technology, Taiwan	2003	48
				Pusan National University, Korea	2002	49
				Korea Institute of Machinery and Materials, Korea		
M/M Sequence	Additive/ Subtractive	Deposition	Machining	Nanyang Tech University, Singapore	1999	50
				Dalian University of Tech, China	2009	51
				Harbin Institute of Technology, Harbin	1995	52
					2000	53
				Singapore Institute of Manufacturing Technology, Singapore		
				National University of Singapore, Singapore	2003	54
	Subtractive/ Assistive	Machining	Adhesion	Singapore, Ibaraki University, Japan		
				National Central University, Taiwan	2002	55
				Tsinghua University, China	2011	56
				Seoul National University, Korea	2010	57
				Soongsil University, Korea		
				Seoul National University, Korea	2012	58
M/M Sequence	Additive/ Subtractive	Deposition	Machining	Stanford University, USA	2008	59
				Carnegie Mellon University, USA		
				University of Pisa, Italy	1996	60
				Stanford University		
				Seoul National University, Korea	2007	61
	Subtractive/ Subtractive	Machining	Drilling	INUS Technology, Inc., Korea	2002	62
				Seoul National University, Korea		
				National University of Singapore, Singapore	2007	63
				Technische Universitat Dortmund, Germany	2011	64
				University of Manchester, UK	2010	65
				University of Manchester, UK		
M/M Sequence	Subtractive/ Subtractive	Machining	Drilling	GFH-mbH, Germany	2006	66
				DELPHI Technical Centre Gillinghamk, UK		
				Nanjing University of Aeronautics and Astronautics	2010	67

Table 2 Hybrid manufacturing processes at the nano scale

Timing	Type	1st Process	2nd Process	3rd Process	Affiliation	Publish Year	Paper No.
Concurrent	Additive/Assistive	Deposition	Heating Sintering		Massachusetts Institute of Technology, USA	1994	68
					Korea Advanced Institute of Science and Technology, Korea	2011	69
	Additive/Assistive	Deposition	Machining	Sintering	University of California, Berkeley, USA	2005	70
					Korea University, Korea, ETH Zurich, Switzerland		
M/S Sequence	Subtractive/Assistive	Machining	Electric filed		University of California, Berkeley, USA	2003	71
					Korea University, Korea, ETH Zurich, Switzerland		
	Additive/Assistive	Deposition	Lithography		The Australian National University, Australia	2013	72
					Swinburne University of Technology, Australia		
			Sintering		Korea Advanced Institute of Science and Technology, Korea	2011	73
					University of California, Berkeley, USA		
	Additive/Subtractive	Deposition	Machining		Seoul National University	2011	74
					Korea Advanced Institute of Science and Technology, Korea	2011	75
M/M Sequence					Hannam University, Korea		
	Additive/Assistive	Deposition	Machining	Etching	SII Nano Technology Inc., Japan, Seiko Instruments Inc., Japan	2005	76
					University of Hyogo, Japan, CREST JST, Japan		
					NEC Fundamental and Environmental Research Laboratories, Japan	2006	77
					University of Tsukuba, Japan, SII Nanotechnology Inc., Japan		
						2012	78
					KTH Royal Institute of Technology, Sweden		
						2010	79
	Subtractive/Subtractive	Machining	Machining		Toyo University, Japan, Hiraide Precision Co., Ltd., Japan		
					Nagano Prefecture General Industrial Technology Center, Japan		
					Carl Zeiss Microscopy, Germany	2012	80
					Fraunhofer Institute for Non-Destructive Testing, Germany

Fig. 6 Hybrid system including inkjet printing systems and pulsed laser systems together (modified and redrawn from references 21 and 22 schematics include lens, mirrors, laser source, CCDs, etc. for pulsed laser system and vacuum, pressure system, CCDs, etc. for inkjet system were omitted in the figure)

3.1.2 Subtractive/Assistive

Electrochemical machining (ECM), electrical discharge machining (EDM), laser machining, and mechanical machining are subtractive manufacturing process, and mechanical machining, chemical treatment, grinding, laser heating, or vibration may be used as assistive manufacturing process.^{28-39,82-91} The University of Edinburgh, Glasgow Caledonian University, and Philips Dap BV reported hybrid systems that combine focused laser beams for drilling and a jet electrolyte for machining together, as shown in Fig. 8.^{28-30,82} The main purpose of this hybrid processes is to improve of the precision and machining efficiency. Using this process, an improvement in precision of 38-65% compare with laser only process was reported, and the volumetric removal rate was increased by 54%. Nanjing University of Aeronautics and Astronautics developed a similar hybrid process, and reported an increase in the cutting rate of 50-70%.^{31,83}

The University of Manchester Institute of Science and Technology

Fig. 7 A schematic diagram of laser interaction with deposited nanoparticles and the substrate (modified and redrawn from reference 27)

used chemical treatment instead of a jet electrolyte.³² By combining laser process in an electrolyte solution, the material removal rate was increased by up to 300% compared with no chemical treatment.

At ETH Zurich, AGIE AG, AGATHON AG, and The University of Applied Science St. Gallen have reported EDM machining and ECM grinding, with an improvement in precision of 25%.^{33,84}

Laser assisted machining is another subtractive/assistive process, which was originally developed to fabricate materials with poor machinability. By applying a heat source, machining of materials with poor machinability can be facilitated, while achieving a number of improvements in the quality of the surface. Georgia Institute of Technology and the Timken Company developed a laser assisted milling machine, which was able to increase the cutting rate by 200%.^{34,85} Purdue University reported a laser heating system for

the electrolyte to have consistent spark discharge during drilling. As in the Fig. 12, gas tool immersing depth is increased which resulting enhancement in drilling depth.

3.1.3 Subtractive/Subtractive

An example of subtractive/subtractive hybrid processes is that of using EDM together with ECM or etching to perform material removal. Nanjing University of Aeronautics and Astronautics used electric discharge and anodic etching together in a high speed wire electrical discharge machining (HSWEDM) machine and reported an increase of 200-600% in the cutting rate.⁴³ Using this system, 5- μ m-long wedge-type micro-grooves and square-type micro-structures were fabricated for use as micro-molds. By combining micro-EDM and high-frequency dither grinding, it is possible to improve the precision by 40%.⁴⁴ Through this system wedge-type micro-grooves and square-type micro-structure of 5 m length were fabricated which can be used to micro-molds. On the other hand, by combining micro-EDM and high-frequency dither grinding, it was possible to have an improvement in precision by 40%.⁴⁵

3.2 M/S Sequence Hybrid Manufacturing

Different combinations of additive, subtractive, and assistive processes are described in this section.

3.2.1 Additive/Assistive

These hybrid systems are similar to the concept and purpose of the hybrid process described in section 3.1.1. Inkjet printing can be used as additive process, followed by diode pumped solid state (DPSS) laser sintering or annealing of the deposited materials.^{46,47} Groups at the Politecnico di Torino, Microla Optoelectronics, and Politrónica Inkjet Printing S.r.l, reported a hybrid manufacturing process that reduced the conductivity of fabricated electronic parts by 67%. National Yunlin University of Science and Technology reported a hybrid system that used micro-EDM as a subtractive process and laser assembly as an assistive process. By applying this hybrid system, the process applicability was enhanced and assembled component setting and inspection problems were reduced.^{48,92,93} Pusan National University and KIMM co-worked to develop chemical mechanical micro-machining process.⁴⁹ The system use chemical solution which reacts on the substrate and restricts the plastic deformation. The chemically reacted layer results in lower machining force, tool wear reduction and high form accuracy. Both brittle and ductile material were tested by this process and showed improvements in surface quality.

3.2.2 Subtractive/Assistive

In these hybrid systems, vibration is a commonly used assistive process. First, drilling is typically performed using EDM, and ultrasonic vibration is then used to increase the aspect ratio, allowing conductive hard and brittle materials to be machined, resulting in high efficiency and surface integrity.⁵⁰⁻⁵⁵

Fig. 13 shows two schematic diagrams of ultrasonic vibration-EDM systems. Nanyang Technical University reported an increase in the aspect ratio of 232 Dalian University of Technology reported an increase in the volumetric removal rate of 250% and an increase in the aspect ratio of 125% compared with no vibration.⁵¹ Harbin Institute of

Fig. 13 Ultrasonic vibration-EDM systems (modified and redrawn from references 51, 54)

Technology reported improvements in the precision of 247% and in the volumetric removal rate of 287% using these techniques.^{52,53} The Singapore Institute of Manufacturing Technology, National University of Singapore, and Ibaraki University reported an increase in the cutting rate of 6000% compared with an EDM only process.⁵⁴

Three different hybrid systems were developed based on EDM processes as a main machining process. Either ECM or a pulsed laser was used as an assistive process. Tsinghua University reported a hybrid system that combines micro electro discharge servo scanning machining (EDSSM) with micro electrochemical scanning machining (ECSM) in sequence to fabricate 3D micro mold and structures;⁵⁶ the system showed efficiency improvement in fabrication of a cuboid of 44.4%, a spherical cap of 55%, and a 1/8 ball of 44.7% compared with micro EDSSM only.

Seoul National University and Soongsil University reported a system that combines nanosecond pulsed laser ablation and micro EDM together, as shown in Figs. 14 and 15.⁵⁷ This system uses variable depth layers, which can improve the machining efficiency, and a reduction in the machining time of 75% was achieved compared with conventional EDM milling, and of 90% compared with a conventional drilling process. Furthermore, no distortion in the tool or features was reported. Tool wear was reduced by 12% compared with a conventional EDM process.

Seoul National University and Soongsil University developed a hybrid process consisting of micro electrochemical discharge machining (ECDM) and micro grinding using polycrystalline diamond (PCD) tools.⁵⁸ Three-dimensional (3D) structures were machined in glass, with a high quality surface. The machining time of the hybrid process was less than 30% that of a conventional grinding process.

Fig. 14 The concept of laser ablation and EDM in micro hybrid machining system (modified and redrawn from reference 57)

Fig. 15 Comparison of constant (top) and variable depth (bottom) layer-by-layer processes (modified and redrawn from reference 57)

3.3. M/M Sequence Hybrid Manufacturing

These hybrid manufacturing systems consist only of additive and/or subtractive processes, without an assistive process.

3.3.1 Additive/Subtractive

The combination of additive and subtractive processes has synergistic effects for the fabrication of functional parts, and parts with complicated shapes. Stanford University and Carnegie Mellon University reported a hybrid system called shape deposition manufacturing (SDM), as shown in Fig. 16, which is based on additive/subtractive processes.^{59,94-97} The University of Pisa and Stanford University reported a hierarchical adhesive patch structure where the compliance and directionality of anisotropic structures could be controlled with no clumping or matting.⁶⁰

Seoul National University developed a nano composite deposition system (NCDS) by integrating deposition and micro-machining processes.⁶¹ As shown in Fig. 16, the process is similar to SDM, but micro machining and deposition are carried out in a single stage to solve the problem of referencing, and the materials used in this system included nano composites as well as conventional polymers. As shown in Fig. 17 (a), three different deposition and machining tools move across the workpiece to carry out processes, and

Fig. 16 The process cycle of SDM with additive and subtractive process (modified and redrawn from reference 60)

Fig. 17 (a) Schematic diagram of the NCDS. (b) Fabrication example of the hybrid process. (c) Fabricated stapes (a copy of the smallest bone in the human body)

translation in the x - and y -axes is independent of that in the z -axis. Nano composite polymer-based materials were used, and functional nanoparticles, including multi-walled carbon nanotubes (MWCNTs), and hydroxyapatite, were mixed using high-shear mixing. Combinations of the matrix and nano composite additives are listed in Table 3. The reported error in the fabricated parts was only 0.17%, which compares favorably with that of deposition only (23.32%) and casting (14.55%). In addition, the tensile strength was evaluated for

Table 3 Various polymer resins used as the matrix and functional nanoparticles used as additives

Particle	Polymer Acrylated Polyurethane	PLGA, PCL Biodegradable Material	Aqueous Polyurethane	Epoxy
None	Structure	Biodegradable Material	Support	Structure
MWCNT	EM Shielding	-	-	-
Hydroxyapatite	Artificial Bone, Structure	Degradation Control	-	-
5-fluorouracil (5-FU)	-	Drug Delivery System	-	-
Nano Clay	Structure	-	Support	-
Graphite	-	-	-	Bipolar Plate

Fig. 18 The process cycle of the ECLIPSE-RP hybrid system (modified and redrawn from reference 62)

parts fabricated using acrylated polyurethane (3.2 MPa), polymer with 5 wt% MWCNT (3.67 MPa), and polymer with 40 wt% hydroxyapatite (13.53 MPa).^{61,98-101}

ECLIPSE-RP is a rapid prototyping (RP) system combining adhesion and high-accuracy from computerized numeric control (CNC) machining for the main process cycle, which was accompanied by additional machining processes, that was developed by Seoul National University and INUS Technology, Inc. as shown in Fig. 18.⁶² Through the case study, precision and cutting rate was improved about 200% and 470% respectively. Additionally cost reduction was achieved by 84% compare to one of rapid prototyping system called stereolithography (SLA). To develop Ni-Fe micro-pillar array, National University of Singapore established a template-assisted electrodeposition (Fig. 19).⁶³

3.3.2 Subtractive/Subtractive

These hybrid systems typically employ drilling in combination with either drilling or machining. Technische Universität Dortmund developed a drilling system, which combines laser pre-drilling and single-lip deep hole drilling to shorten the process chain and reduce tool wear.⁶⁴ Sequential laser and mechanical drilling was reported to

Fig. 19 A schematic diagram showing the hybrid process sequence of laser micro-machining and electrodeposition (modified and redrawn from reference 63)

Fig. 20 Combinations of manufacturing processes used in nano scale hybrid manufacturing

enhance tool life by approximately 250%.⁶⁵ Sequential laser and EDM micro-drilling, was reported to reduce the drilling time by 70% and the cost by 42%, as well as to increase the production capacity by 90%.⁶⁶ Micro-pin arrays with high-density and high-hardness were fabricated by combining mechanical peck-drilling and reverse-EDM.⁶⁷ This method provides a rapid and efficient process to form micro-pin arrays.

4. Hybrid Manufacturing in Nano scale

As shown in Fig. 20, most of nano scale hybrid manufacturing systems combine machining and deposition. A total of 30.7% of hybrid systems at the nano scale employ a third process and 69.2% perform hybrid process separately.

4.1 Concurrent Hybrid Manufacturing

We review six systems that implement different processes concurrently. Most hybrid processes discussed in this section are based on deposition, and either heating, sintering, or lithography was employed as an assistive process.

Fig. 21 A schematic diagram of laser assisted FIB-induced deposition (modified and redrawn from reference 68)

Fig. 22 A schematic diagram of an organometallic ink and laser direct curing hybrid system (modified and redrawn from references 69 and 102)

4.1.1 Additive/Assistive

A laser source was used for localized heating during focused ion beam (FIB)-induced deposition, which enhanced the precision of the deposited structure, as shown in Fig. 21. Using this system, a line width of 800 nm was achieved.⁶⁸

KAIST developed a hybrid system to fabricate microelectrodes using organometallic ink and laser direct curing, as shown in Fig. 22.^{69,102} A broad range of substrate materials may be used with this hybrid system, which is suitable for the fabrication of flexible electronics with (low thermal budget) polymer substrates.

4.1.2 Additive/Subtractive/Assistive

Similar to micro scale inkjet systems, these systems use sintering as an additive process. In contrast to micro scale hybrid manufacturing systems, these systems also have a subtractive process. The University of California, Berkeley, Korea University, and ETH Zurich reported the fabrication of electrical components on a flexible substrate.⁷⁰ Three different process, drop on demand (DOD) printing, Nd:YAG pulsed laser ablation, and Ar laser curing were used as additive, subtractive, and assistive process. A small resistivity of $5.4 \times 10^{-8} \Omega\text{m}$ could be obtained without polymer substrate deformation using an $8 \mu\text{m} \times 1000 \mu\text{m} \times 40 \text{ nm}$ polyimide film.

Fig. 23 Schematic diagram of an electric-field assisted femtosecond laser nano machining experimental setup (modified and redrawn from reference 71)

Fig. 24 A schematic diagram of the hybrid 3D nanofabrication process (modified and redrawn from reference 72)

4.1.3 Subtractive/Assistive

Prior to the development of the hybrid system described in section (4.1.2), Grigoropoulos reported an electric-field assisted nano machining system using femtosecond laser, as shown in Fig. 23.⁷¹ Using this system, a high spatial resolution of approximately 10 nm was achieved, which, at that time, was not possible using standard nano machining techniques.

4.2 M/S Sequence Hybrid Manufacturing

Two processes in this section are described, which combine deposition and lithography or sintering.

4.2.1 Additive/Assistive

The Australian National University and Swinburne University of Technology developed a hybrid system, which consisted of direct laser writing (DLW) and multistep electron-beam lithography (EBL).⁷² Using this system, shown in Fig. 24, it was possible to fabricate sub-100-nm feature sizes. First, a glass substrate is pre-patterned via DLW, then a DLW-photo resist structure is sputter coated with indium tin oxide (ITO),

Fig. 25 Schematic diagram of femtosecond laser assisted solution deposition nanofabrication process (modified and redrawn from reference 73)

and the electron-beam resist (PMMA) is spin-coated onto the structure. The PMMA is then patterned using EBL and, following development, gold is deposited using evaporation, and then lift-off is carried out. Using this process, gap nano antennas were fabricated with a center-to-center distance of 200 nm, a width of 60 ± 5 nm and a gap of 100 ± 15 nm.

KAIST and University of California, Berkeley, developed a femtosecond laser assisted solution deposition nanofabrication system, as shown in Fig. 25.⁷³ Direct femtosecond laser sintering of solution-deposited metal nanoparticles has the advantage that it is simple, direct, and high-resolution patterning can be used, unlike vacuum deposition and MEMS.

4.3. M/M Sequence Hybrid Manufacturing

Approximately 44.4% of the nano scale hybrid manufacturing systems discussed in this paper employ at least two main processes separately.

4.3.1 Additive/Subtractive

Seoul National University reported a called 3D nano printing system (3DNPS), which combined a nanoparticle deposition system (NPDS) and FIB to overcome the limited manufacturing precision, limited product geometry, unintentional chemical reactions, thermal damage, and limited availability of materials of nanoparticle deposition techniques, as shown in Figs. 26 and 27.^{74,103} This system combines the advantages of NPDS and FIB, as described in Table 4. The system described in Ref.,⁷⁴ can achieve feature sizes of 300 nm and the process can be carried out at room temperature without any binder, solution, or post-processing. By integrating a micromechanical grinding tool with 5- μ m system into 3DNPS, the localized surface deposited using NPDS was planarized and ready to be fabricated by FIB.

Multi-layer deposition, profile cutting, and repeatability of additive and subtractive processes were demonstrated.

KAIST and Hanam University developed a hybrid system by combining (additive) two-photon induced photocuring and (subtractive) selective laser ablation in a single femtosecond laser optical scanning system, as shown in Fig. 28.⁷⁵ Improved precision high-resolution patterning, compared with two-photon stereolithography, was achieved in a high-mechanical-sensitivity structure.

4.3.2 Additive/Subtractive/Assistive

Most assistive processes discussed in this section employ etching together with deposition and machining to achieve 3D free-from patterning and nano scale features.⁷⁶⁻⁷⁸ As a second process, heating was typically applied in addition to lithography and deposition. SII Nano Technology Inc. and Seiko Instruments Inc. developed a hybrid

Fig. 26 Process plan for the hybrid manufacturing process of NPS (modified and redrawn from reference 74)

Fig. 27 Fabricated nano structure with multi-material ((a) nano pocket machining while multi-layer deposition, (b) schematic diagram of 3D nano structure, and (c) dimension of fabricated structure)

Table 4 Advantages of nano printing systems

Advantages of System	
NPDS 104-109	- Room temperature processing condition,
	- Use of various available materials Including metals and ceramics
	- Relatively high deposition rate (25 - 1,000 μ m/sec)
	- Dry processing, requiring no binder and no solution
FIB 110-113	- Direct writing
	- Ultra-precision processing
	- Room temperature processing condition
	- Use of all solid materials

process to form 3D structures using gas assisted etching and FIB together with a precision wheel stage, as shown in Fig. 29.⁷⁶ The etching and wheel stages make this either a nano-milling machine or a nano-lathe in a vacuum environment, respectively. The advantage of this system is in realizing a greater variety of mechanical parts, which cannot be fabricated using existing MEMS technology.

A 3D rotor was fabricated using a combination of FIB and chemical vapor deposition (CVD), developed by The University of Hyogo, CREST JST, NEC Fundamental and Environmental Research Lab.,

Fig. 28 Schematic diagram showing ablation-assisted two-photon stereolithography process (modified and redrawn from reference 75)

Fig. 29 A schematic diagram illustrating the basic concept of 3D carbon deposition. (modified and redrawn from reference 76)

Fig. 30 An example of the FIB-CVD process used to form nano-sheet (modified and redrawn from reference 77)

University of Tsukuba, and SII Nanotechnology Inc., as shown in Fig. 30.⁷⁷ Diameter, wing-thickness, and wing-width of rotor were 5.5 μm , 0.57 μm , and 1.2 μm , respectively.

KTH Royal Institute of Technology and FEI Electron Optics reported a hybrid process, which combines FIB writing, CVD, and potassium hydroxide (KOH) wet etching, as shown in Fig. 31.⁷⁸ A suspended Si beam was fabricated with sub-micrometer dimensions using this system, and lines were fabricated with nanometer scale features using 2- and 3- layer processes.

4.3.3 Subtractive/Subtractive

Features must be fabricated with ultra-fine surfaces for applications including optical devices and micro-optical lenses. Similar to other subtractive/subtractive hybrid processes, shape machining is carried out before a final machining step. In this hybrid process, by combining laser writing and FIB, the process time can be significantly reduced

Fig. 31 A schematic diagram of a layer-by-layer fabrication process using FIB, CVD, and KOH etching (modified and redrawn from reference 78)

Fig. 32 A schematic diagram of machining using FIB (Modified and redrawn from reference 79)

while allowing enhanced precision, accuracy, and efficiency.

Toyo University, Hiraide Precision Co., Ltd., and Nagano Prefecture General Industrial Technology Center developed a laser-FIB machine, as shown in Fig. 32.^{79,114} A micro-optical lens press mold die that was 3.2 μm in diameter and 0.43- μm -deep was fabricated using a femtosecond laser and FIB. The surface roughness was decreased by approximately 1000%.

Carl Zeiss Microscopy developed a hybrid system that uses a combination of pulsed laser ablation and FIB milling.^{80,115} The laser system is mainly used to remove material of the order of several 10 mm^3 within minutes, and is attached to a load-lock chamber. This process is followed by FIB preparation and SEM analysis, which can be carried out in the same instrument. This reduces the preparation time of samples by 2000% compared with a single FIB process.

5. Discussion and Future Prediction

Throughout this review, hybrid processes at the micro- and nano scale were discussed and classified. The main purposes of hybrid processes are to overcome the limitation of single processes, to improve the quality of the finished product, in particular surface roughness and precision, and to improve the cutting rate and material

Fig. 33 Comparison of surface roughness and aspect ratio of single and hybrid processes (y-axis is log scale and numbers indicate references in this paper)

Fig. 34 A possible hybrid manufacturing process in future trends

removal rate, as well as to reduce tool wear, process cost, material costs and the total energy consumption. Surface roughness (R_a) value of micro scale hybrid manufacturing is decreased compare to single process (Fig. 33) and aspect ratio is increased by using hybrid manufacturing. These are good examples to show the advantages of hybrid processes.

In nano scale hybrid manufacturing process, there are not much of papers are existed related to improvement of quality of product but most of paper described new fabrication method which can overcome current limitations such as material, geometry, application, etc.

Most hybrid processes were developed to achieve specific goals. In other words, the desired product was designed first, and then different processes were combined to fabricate the product. Research into hybrid manufacturing processes for micro- or nano scale general fabrication machines that are suitable for multiple products or structures are under progress. Since features are becoming smaller and components are

becoming more complicated, more complicated hybrid processes are expected to be required.

A model process for future hybrid manufacturing is illustrated in Fig. 34. Such a system should be able to accommodate the following characteristics:

- Three-dimensional features.
- Multiple workpiece materials.
- Multi-functional, i.e., structural, mechanical, electrical, magnetic, optical, and/or bio-functionalities should be possible.
- Tunable materials for improving properties of materials.
- Ultra precision.

6. Conclusions

We have reviewed hybrid manufacturing processes at the micro and nano scale. These schemes were classified according to both the process timing and process type.

Machining is the most frequently used micro scale hybrid process. Most nano scale hybrid fabrication schemes are based on additive processes and, thus, deposition is more important in nano scale fabrication than in micro scale fabrication. In micro scale hybrid manufacturing processes, 74.4% used assistive processes with additive or subtractive processes as main processes. This is because the main purpose of most micro scale hybrid manufacturing processes is to improve the quality of the product. In contrast, only 61.5% of nano scale hybrid manufacturing schemes use assistive processes, as these methods typically focus on the fabrication of products that cannot be fabricated using a single process.

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