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공학박사학위논문

**Hybrid 3D Printing
by Bridging Micro/Nano Processes**

**마이크로/나노 공정의 융합을 통한
나노스케일 3차원 프린팅**

2015년 8월

서울대학교 대학원

기계항공공학부

윤 해 성

마이크로/나노 공정의 융합을 통한 나노스케일 3 차원 프린팅

Hybrid 3D Printing by Bridging Micro/Nano Processes

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Abstract

Hybrid 3D Printing by Bridging Micro/Nano Processes

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The aim of this work was to develop a novel hybrid manufacturing method for nanoscale three-dimensional (3D) printing with multi-material capabilities. 3D structuring methods at the micro/nanoscale are major goals of various engineering fields, and much work has been carried out to improve the minimum feature size, geometrical complexity, and material selection. With the aim of nanoscale multi-material printing, a hybrid process was reported with an integrated nanoparticle deposition system (NPDS) and focused ion beam (FIB) system; however this process has limitations in terms of surface roughness and control over the layer thickness, as well as with the process scale, and furthermore, lack of sacrificial layers.

In this dissertation, a novel hybrid process is described, which combines aerodynamically focused nanoparticle (AFN) printing, micro-machining and focused ion beam (FIB) milling. AFN printing is based on NPDS, and micro-machining was used for local planarization. In addition to these processes, spin-coating was used to fabricate sacrificial layers. By bridging these different

micro/nanoscale processes, the resulting hybrid process can address the limitations of the individual processes.

To create the hybrid process, each process was investigated to enable compatibility. With the AFN printing system, the surface morphology of a detached substrate was observed, and the bonding mechanism between the substrate and nanoparticles was investigated. A novel printing strategy was identified to reduce the scale of the process. With the micro-machining system, different tool geometries were investigated. Complex geometries inspired by conventional-scale tools were implemented on the micro-scale, and their effects were investigated. With the FIB system, material re-deposition phenomena were investigated to reduce defects that occur during ion sputtering. A novel path-generation strategy was identified and investigated for different scanning paths.

Process capability is discussed using fabrication examples and functional applications. The novel hybrid process represents a significant advance in the state of the art, and enables far improved process scales or dimensional degree of freedom, without losing the advantages of broad choice of materials.

3D-printed micro bi-material cantilevers were fabricated as a thermal actuator. The mechanical and thermal properties of the structure were investigated using an *in-situ* measurement system, and irregular thermal phenomena were analyzed. It is expected that these *in-situ* measurements of the 3D printed microstructure will contribute to materials research.

Various 3D structures can be fabricated using the process described here from a range of metal/ceramic inorganic materials, including polymers. In particular, it is expected that the process will contribute to the area of customized nanoscale structuring, with potential applications in medical treatments. It is also expected that this work will contribute to further improvements in manufacturing technology by combining different manufacturing resources.

Keywords: 3D printing, Hybrid manufacturing, Nano manufacturing, Microstructure, Multi-material, Rapid prototyping

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Chapter 1.

Introduction

1.1. Overview

Recent progress in manufacturing techniques has enabled reductions in feature sizes and improved resolution, as well as reductions in the constraints of processing materials and geometry. In particular, with integrated electronics, micro/nanoscale structuring has been a major aspect of engineering developments [1].

3D structuring techniques have been investigated because controlled 3D structures can provide a higher density of functionality [2]. Numerous studies have been reported for direct printing and fabrication of complex patterns [3]. However, it is not straightforward to implement 3D structuring at the micro/nanoscale, mainly due to the fabrication limits. Despite the existence of direct printing techniques, which allow deposition of very small amounts of material in an effective and efficient way, it remains difficult to exploit the full potential of direct printing in the fabrication of controlled 3D structures, such as a horizontal cantilever [4].

Conventional semiconductor techniques such as photolithography have been applied to fabricate 3D structures [5]; however, these techniques are limited in terms of material selection and process scale [6]. Moreover, they typically involve multi-step processes, toxic chemicals and are expensive [7].

In this dissertation, a novel 3D printing process at the micro/nanoscale is described, with improved performance, reduced constraints, and a higher degree of freedom in terms of the geometry of the fabricated features compared with existing techniques. To achieve this, different micro/nanoscale fabrication processes were

integrated, creating a novel hybrid process.

One of major research trends for process development is integrating different processes [8]. In one existing hybrid process [9], fabrication techniques were combined, resulting in significant improvements compared with conventional fabrication techniques.

In this dissertation, aerodynamically focused nanoparticle (AFN) printing, micro-machining, focused ion beam (FIB) milling and polymer spin-coating processes are combined. By bridging these processes, 3D printing at the micro/nanoscale could be implemented using multiple materials.

First, 3D structuring technologies at the micro/nanoscale are reviewed, and an existing hybrid process integrating a nanoparticle deposition system (NPDS) and an FIB is discussed in terms of the limitations of the process scale and geometry of the features. To overcome the limitations of current systems, a new hybrid process is developed. Details of the approach are described, including scaling of the printing system, control of the surface quality, and the use of sacrificial layers to fabricate 3D structures.

The configuration of the hybrid system is described, followed by the requirements to combine different fabrication processes. Each process was investigated and modified to enable a combined process. With the AFN printing system, the printing scale needs to be narrowed, and bonding was investigated in this regard. A novel printing strategy was identified by controlling the timescale between printing and deposition. The effects of the scanning path of the FIB milling system were analyzed because the ion beam creates directional defects, mainly due to material re-deposition, and various path generation algorithms were investigated.

With the micro-machining system, different tool geometries were investigated to determine the optimal tool shape for local planarization of printed material. Finally, spin-coating was investigated, and the use of an ion beam with polymer materials was investigated to implement a sacrificial layer.

Following optimization and bridging of individual processes, the overall capability and performance of the novel hybrid process was investigated, and 3D printed micro/nanoscale structures were fabricated. We discuss the performance improvements of the novel hybrid process, and then consider the outlook of the process. With increasing demand for 3D structuring at the micro/nanoscale, it is expected that this process will contribute to hybrid manufacturing.

Bi-material cantilevers were designed and fabricated as micro thermal actuators. The mechanical and thermal behaviors were investigated using an *in-situ* measurement system. The 3D printed microstructures exhibited anomalous thermal phenomena whereby the structure contracted at a certain temperature, which is thought to be due to the low temperature sintering of the porous structure. Further investigation of the material properties is required, and it is expected that this research will contribute to new structuring methods, such as 4D printing.

3D structures were fabricated using various different metal/ceramic inorganic materials, as well as polymers. Compared with conventional technologies, the process described here is expected to contribute to customized nanoscale structuring, with potential applications in medical treatments and biomechanics. In addition, it is expected that the definition of a hybrid process will be expanded beyond cloud-based manufacturing, via distribution and bridging of individual fabrication techniques to create manufacturing-as-a-service. A brief outlook is discussed at the end of the dissertation, including a review of development trends of manufacturing technologies.

1.2. Review of 3D structuring technologies at the micro/nanoscale

Numerous studies have reported on 3D structuring at the micro/nanoscale [10]. **Figure 1** shows some selected techniques for nanoscale 3D structuring. These can be classified into four categories according to process physics: energy beam-based techniques, aerosol/liquid jet-based techniques, physical tip-based techniques, and forming/molding/self-assembly.

Energy beam-based techniques exploit the energy of a beam to implement an additive or subtractive process. During irradiation, energy is transferred to a photoresist on the substrate to define a pattern [11]. Ultraviolet (UV) light is commonly used in such processes; however, the process scale is related to the wavelength of the radiation, and features with a scale smaller than the half wavelength might be blurred [12]. Numerous techniques have been developed for smaller scales (typically less than 100 nm), including X-ray, electron and ion beams [13]. These techniques still require beam absorption materials, as well as expensive processes [14].

Aerosol/liquid jet-based techniques, as well as direct printing techniques which disperse very small quantities of material on the substrate directly, have been investigated to overcome the limitations of energy-beam based methods. Some techniques have been developed for mask- and solvent-free printing, which enable material/substrate selectivity by circumventing the limitations of heat- or energy-induced techniques [15]. Recent advances in direct patterning techniques have been reported for organic materials, functional polymers, and even tissue engineering [16].

Figure 1. Techniques for 3D micro/nanoscales structuring

However, direct patterning techniques are typically limited to relatively low-resolution systems, compared with energy beam-based technologies, typically in the range of a few tens of micrometers [17]. This is one trade-off between expensive and complex processes and ease of patterning. Moreover, direct patterning techniques are usually limited in terms of the three-dimensional structure that can be formed because the material is “printed” from a source onto the substrate [18].

Physical tip-based techniques employ a sharp tip, such as that used with an atomic force microscope (AFM). Ink molecules can be used for direct writing of a desired material, and the tip can be a tool both for additive and subtractive processes [19]. These methods combine the high resolution of lithography and ease of patterning of direct writing technologies, and have been applied to biological applications [20]. However, these techniques are not readily applicable to 3D printing, because very small amounts of material are used on the surface. Despite the process width ranging from tens to hundreds of nanometers, most processes are at very early stage of development for complex 3D structures [21].

The final category is forming/molding/self-assembly. Nanoimprinting technologies can be included in this category. Because of difficulties in fabrication of the micro/nanoscale mold, it is difficult to apply these techniques with similar flexibility and scale to conventional manufacturing techniques [22]. For some limited cases, such as single-layer polymer materials, this kind of forming technique can be used to create the desired structures [23]; however, it is limited in terms of the geometric degree of freedom.

A hybrid process reported by Prof. Ahn's group is also included in this category [9]. This process consists of additive nanoparticle printing and subtractive ion beam milling. Details of this hybrid process are given in the following section.

Table 1 lists some state-of-the art examples of 3D structuring at the micro/nanoscale. **Table 1(a)** and (b) show structures fabricated using energy beam-based technologies. These can have higher resolutions, as compared to other techniques, but have limited material selectivity. **Table 1(c)** and (d) show structures fabricated using aerosol/liquid jet-based technologies. These are examples of specific technologies for 3D structuring at the micro/nanoscale. Electrodynamic focusing was used to form the flower-like structures shown in **Table 1(c)**, and electrospinning was used to form the nanopottery structure shown in **Table 1(d)**.

Table 1(e) shows a structure fabricated using nanoscale 3D printing [9]. Using this process, small features were fabricated (a few tens of nanometers), and multiple materials could be printed. However, this 3D printing process has limitations in terms of the surface quality and geometric capabilities. Moreover, the scale of nanoparticle printing and ion beam milling must be regulated for inter-compatibility.

Table 1. State-of-the art examples of 3D structuring at the micro/nanoscales

Energy beam-based techniques
	(a) The micro-Thinker fabricated using two-photon initiated photopolymerization [24]
Aerosol/liquid jet-based techniques
	(c) Flower-like structures fabricated using electrodynamic focusing of nanoparticles [26]	(d) Nanopottery fabricated using electrospinning [27]
Forming/molding/ self-assembly, etc.
	(e) Three-dimensional structure fabricated using nanoscale 3D printing [9]

Figure 2. The virtuous circle of 3D micro/nanoscale structuring techniques

Figure 2 shows a virtuous cycle of existing technologies. As discussed above, beam-based techniques have significant constraints in terms of material selectivity. Aerosol/liquid jet-based techniques have larger process scales than beam-based techniques, and physical tip-based techniques are limited in terms of dimensional complexity. Therefore, it is desirable to develop a nanoscale 3D printing process that combines the advantages of all of these techniques.

Figure 3 shows various 3D nanoscale structuring technologies with respect to the minimum feature size and dimensional complexity. The characteristics of each process are summarized in the figure legend. Most of these techniques are subject to limitations with respect to the process physics. Energy beam based-technologies can be used to fabricate 3D features, and the minimum resolution of these technologies typically ranges from tens to hundreds of nanometers; however, energy beam-based technologies are limited in terms of material selection because the material must withstand irradiation. Aerosol/liquid jet-based techniques are typically limited in terms of the scale of the features, and physical tip-based techniques are limited in terms of geometric freedom.

Figure 3. A comparison of 3D micro/nanoscale structuring techniques with respect to the minimum feature scale and dimensional complexity

It is desirable to develop new processes with reduced feature size, improved resolution, and fewer constraints in terms of materials and dimensional complexity. In particular, associated with the demands of fabrication and assembly of micro/nanoscale components [28], combining the advantages of different fabrication techniques is highly desirable.

1.3. Existing hybrid process

Here we describe a novel hybrid process for 3D printing at the micro/nanoscale with multi-material capabilities. As shown in **Figure 2**, a novel process is required to improve the process scale and resolution, the degree of freedom in terms of geometry, and provide broader material selection. Several studies have been carried out over the past few years, and previous work is discussed in this chapter.

Figure 4 shows micro/nanoscale structuring techniques as a function of the scale and dimensional complexity. The desired area is shown in the figure; *i.e.*, small-scale, with high levels of geometric freedom and material selectivity.

Figure 4. Limitations and requirements for 3D nanoscale structuring with multi-material capabilities

1.3.1. Hybrid NPDS+FIB process

To achieve 3D printing at the micro/nanoscale with multiple materials, a hybrid process had been reported, which integrates NPDS with FIB milling [9]. NPDS can enable the deposition of thin films using accelerated aerosolized nanoparticles [29], which impact on and adhere to a substrate [30]. This technique can be used to print metal/ceramic nanoparticles in dry room-temperature conditions with relatively low vacuum conditions compared with sputtering [31]. NPDS does not require chemical binding or heat treatment; hence, it can be used with a broad range of materials, both in terms of the nanoparticles and substrate [30]. It can be used to deposit metals or ceramics on both on hard and flexible substrates. Here we used NPDS as an additive part of the hybrid process.

FIB is a widely used nanoscale fabrication system [32, 33]. Similar to NPDS, FIB can be used with many solid materials, and provides precise fabrication of features larger than a few tens of nanometers. Here FIB was used as the subtractive aspect of the hybrid process.

The hybrid process was designed with NPDS as a thin-film additive process and FIB as a subtractive profiling process. **Figure 5** shows a schematic diagram of hybrid process integrating NPDS and FIB, and **Figure 6** shows a 3D structure fabricated using the hybrid process.

Because the hybrid process consists of NPDS and FIB, the process has the advantages of processing conditions and material capabilities. First, two sub-processes can be processed in dry room-temperature conditions, and do not require any pre- or post-process. Moreover, because two processes uses physical impacts of nanoparticles and ion sputtering, respectively, they can be used with the most solid materials. At the last, fabrication is possible at the nanoscale; NPDS can deposit a thin film with a thickness of tens of nanometers, while FIB can fabricate a pattern with a scale of tens of nanometers.

Figure 5. Schematic diagram of the hybrid process, which integrates NPDS and FIB [9]

Figure 6. A 3D structure fabricated using the NPDS+FIB hybrid process [9]

Therefore, the constructed hybrid process can fabricate 3D structures with various metal/ceramic inorganic materials with a super-precision ranged at about tens of nanometers. The process meets the requirements on multi-material capabilities at the micro/nanoscale in particular.

1.3.2. Limitations of the existing hybrid process

The hybrid process described above is limited in terms of process scale and surface quality. As shown in **Figure 6**, nanoparticles were printed over the entire substrate, because NPDS has a width scale of a few hundreds of micrometers. Another limitation of the hybrid process is poor surface quality. NPDS uses dry nanoparticle aerosols, and the surface roughness can be several micrometers. This uneven surface caused by nanoparticles cannot be flattened by the FIB milling [34], because the ion beam performs conformal sputtering on the surface. Special techniques can be used with a simultaneous image processing [35], it is usually not easy to planarize the porous surface of different materials. Moreover, because there is no sacrificial layer, the hybrid process can be used to form simple 2.5D structures.

Table 2 lists the advantages and limitations of the existing NPDS+FIB process. Because NPDS is a dry room-temperature process, 3D printing can be performed without thermal treatment. Moreover, NPDS can be used to print metal/ceramic nanoparticles onto metal, ceramic or polymer substrates, and so can be applied to flexible substrates.

Because of the lack of a sacrificial layer, only 2.5D features can be fabricated, as shown in **Figure 6**. Moreover, the width and height of the NPDS layers cannot be precisely controlled. The printed layer is typically hundreds of micrometers wide. Furthermore, the surface roughness cannot be well controlled, which may be several micrometers. This is because NPDS was developed for large-area thin-film deposition, and is not suitable for additive 3D printing processes. Therefore, NPDS needs to be improved to provide control over the width and height of the features, as well as to provide undercut structures.

Table 2. Advantages and limitations of the NPDS+FIB hybrid process

Advantages	<ul style="list-style-type: none"> • Dry and room temperature process • No thermal treatment • Metal and ceramic materials can be deposited on metal, ceramic and polymer substrates • Applicable to flexible substrates • Super-precision profiling (~50 nm) using FIB
Limitations	<ul style="list-style-type: none"> • Large width scale of NPDS • Difficult to control the feature size, geometry and surface quality • Not fully exploited process potential • Poor control over the layer thickness • Not applicable to 3D features with undercut features

Figure 7 shows the process capabilities of FIB and NPDS in terms of the width and height. NPDS and FIB were not combined, and the surface was not well controlled. FIB has a much smaller scale than NPDS; hence, the hybrid process cannot perform 3D printing effectively. Micro/nanoscale structures can be fabricated by repeating each process serially; however, in this manner the potential of each process is not fully exploited.

To overcome the limitations of NPDS+FIB discussed above, control over the width scale and layer thickness should be improved, and a sacrificial layer should be implemented. To create the process synergy, two processes need to be bridged more, rather than simply repeating each process. Details of research approaches for the integration and bridging are introduced in the next section.

Figure 7. The width and height scales of FIB and NPDS as process capability

1.3.3. Details of research approaches for a novel hybrid process

Figure 8 shows a comparison of the existing NPDS+FIB hybrid process and the desired novel hybrid process with respect to the minimum feature size and the dimensional complexity. Hybrid processes have been reported with the aim of nanoscale multi-material 3D printing; however, there remain several limitations, as discussed above. A novel hybrid process with full 3D structural capability is therefore desired.

Figure 8 also shows the feature size and dimensional capability of exiting approaches. For the novel process, the printing scale needs to be reduced. As shown in **Figure 7**, NPDS has a much larger scale compared with FIB. The surface roughness of the printed structure must also be controlled, as well as the thickness of each layer. Control over each layer is important for multi-layer processes. In addition, a sacrificial layer should be implemented.

In this dissertation, various micro/nanoscale processes were integrated to construct a novel hybrid process, as shown in **Figure 8**. To scale down the printing process, NPDS was improved, and the nanoparticle bonding mechanism was investigated in detail. To control the surface roughness and implement a sacrificial layer, local planarization and polymer coating processes were developed. To integrate these processes, each fabrication step was investigated and optimized individually.

The system configuration of the resulting hybrid process is described in the following chapter, together with a discussion of the key requirements for integration, and details of the research approaches for each of the individual fabrication processes.

Figure 8. The existing NPDS+FIB hybrid process and the goals for a hybrid process in terms of the feature size and dimensional complexity

Chapter 2.

System configuration for the novel hybrid process

2.1. Process configuration overview

Following the requirements of nanoscale multi-material printing, a novel nanoscale hybrid process was established by integrating AFN printing, micro-machining, and FIB milling to overcome the drawbacks of the existing hybrid process. **Figure 9** shows the hardware systems used in the novel nanoscale 3D printing process.

Figure 9. Hardware systems of the novel nanoscale 3D printing process

An aerodynamically focused nanoparticle (AFN) printing system, or improved nanoparticle deposition system, was adopted as the primary additive process as it can print various inorganic nanoparticles on a substrate without any chemical bindings or heat treatments [36]. By adopting AFN printing rather than NPDS, printing can be controlled at smaller length scales, without losing the advantages of existing NPDS. AFN printing systems deposit nanoparticles at specific processing points, while NPDS is more appropriate for large area, thin film deposition. Details of the AFN printing system are introduced in the next section.

Alternatively, a FIB system was adopted as the primary subtractive process. FIB is a powerful direct writing tool, is compatible with most solid materials, and has high precision [37]. Although FIB can serve as an additive process, with the assistance of gas-injection, milling was mainly used in this research.

Mechanical micro-machining was chosen to assist and regulate two processes at different scales. Planarization is necessary in multi-layer processes [38], and micro-machining was adopted to improve the surface quality, and give control over the layer thickness. As hybrid systems are typically used for porous structures with metal/ceramic nanoparticles, mechanical planarization processes are suitable for inorganic materials. Mechanical machining can fully meet these requirements [39].

A uniform sacrificial polymer layer was formed by spin-coating [40]. The substrate was coated with polymer material, which was removed using solvents following the process planning. A polymer layer with a thickness from hundreds of nanometers to several micrometers was used.

A referencing technique to align the coordinate system of three different systems was investigated and implemented [41]. Since the AFN printing system had a width scale slightly larger than desired, the referencing system had to be designed such that it could be resolved after AFN printing, micro-machining, and FIB milling. It therefore consisted of multiple deep-tilted marks at different scales, which were able to be used at a range of magnifications.

By bridging different micro/nanoscale processes, nanoscale 3D printing processes were implemented. Process planning was generated based on the desired part design, and each process was repeated as needed. A sacrificial layer was coated on the substrate, and the desired shape was milled using a FIB system. After milling, nanoparticles were printed and planarized. By integrating with each other, process barriers in each process can be crossed over.

Various metal/ceramic materials could be processed at micro/nanoscale as the hybrid process used AFN printing, micro-machining, and FIB milling. Process scales of each process are able to be more controlled well, without losing the advantages of existing hybrid process. Uneven surface and layer thickness can be controlled using the micro-machining, and the width scale of nanoparticle printing can be reduced. At the last, sacrificial layers can be implemented using the spin-coating process.

2.2. Critical defects in integration

It is essential to optimize and regulate each process used in the construction of the hybrid process and system. Since each process has different characteristics and scales, an understanding of individual process physics is necessary. Bridging different processes requires a higher level of knowledge than independent use of each process. Key requirements and inevitable drawbacks of each process are shown in this chapter.

Figure 10 shows some examples of process failure. **Figure 10(a)** is an example of micro-machining failure. For the case of ductile material printing on a hard substrate, *i.e.* silver nanoparticles on silicon, nanoparticles stick and adhere more strongly to each other than to the substrate. Hence, if micro-machining is not sufficiently stabilized, printed features could be detached from the substrate. Stabilization has been a main aspect of machining processes at all scales [42, 43]. Moreover, sample detachment phenomena limit the height scale of structure.

(a) Micro-machining failure

(b) Ion beam failure (re-deposition)

Figure 10. Examples of failure and highlighting the need for optimization of FIB milling process

Even if a structure remains after micro-machining, ground features could have defects as shown in **Figure 10(a)**. Therefore, machining should be improved to effectively planarize the desired section.

Defects inevitably occur during the FIB milling process. One of the largest defects in FIB milling is caused by material re-deposition. Sputtered atoms tend to redeposit on the opposite side of the processing beam [44], causing large geometrical errors (**Figure 10(b)**). Nanoscale phenomena are influenced by ion beam parameters (ion energy and current), milling parameters (dwell time and beam overlap), and the target material [37]. Many researchers have investigated in process control and planning in order to avoid the defects in FIB milling [45, 46]. For further improvements, a novel processing strategy is required to minimize or control the defect.

The integration, optimization and investigation of each process have been studied. Improvements to the AFN printing process are required to enhance bonding between printed features and the substrate and to reduce the printing scale. Machining precision had to be enhanced to avoid defects on the ground surface, and FIB milling required optimization to minimize defects caused during ion sputtering.

In addition to investigation and optimization of each process, a sacrificial layer needs to be implemented to fabricate a freeform 3D structure. After construction of the hybrid process, design and process planning knowledge also needs to be formulated for the fabrication.

Chapter 3.

Bridging fabrication processes

3.1. Key challenges

Here, the integration of three different processes is discussed. Each process has been optimized, to overcome the defects highlighted previously. **Figure 11** shows the key challenges for successful integration.

A bonding mechanism to improve the adhesion between printed features and the substrate in the AFN process was investigated. By better understanding the process physics, printing could be better controlled, and process scales could be reduced further by controlling process parameters, rather than controlling aerosol generation or the focusing mechanism, which both require a great effort.

The tool geometry of the micro-machining system was optimized. 3D cutting edges were fabricated using FIB milling, and their geometry investigated to improve machinability. Most micro-scale tools have a simple geometry comprising single edges or plain features. In this study, 3D geometries inspired by conventional machining tools were implemented (*i.e.*, clearance and rake angle), and their performance was evaluated.

A novel FIB system path generation strategy was suggested to avoid and distribute material re-deposition effects. Most paths were inspired by conventional machining techniques, and defects could be controlled by re-ordering scanning points.

The sacrificial layer implementation was investigated. PMMA (poly(methyl methacrylate)) was used as a sacrificial layer, and the physics of ion irradiation was investigated.

As a result of these efforts, a novel hybrid process was established. Efforts in each process are discussed in more detail, and a novel polymer application is introduced. The hybrid process can be fully exploited in multi-material 3D printing at the micro/nanoscale with the application of a polymer sacrificial layer.

3.2. AFN printing system adoption

An AFN printing system has been developed for the novel hybrid process [36]. Conceptually, the AFN printing system controls the generation and focusing of an aerosol. Nanoparticles are first placed in a feeder, and pressure is generated using excitation and purging of compressed air. Through this pressure, an aerosol was generated with nanoparticles, and then focused through the nozzle.

Figure 12 shows a schematic of the AFN printing system. The focus of nanoparticles is determined by the air pressure and the nanoparticle weight/size. Computational analysis of nanoparticle printing has been well studied in a recent publication [36].

Through use of an AFN printing system, dimensions can be drastically reduced by controlling aerosol generation and focusing. Compared to NPDS, the resolution of nanoparticle printing decreased from hundreds to tens of micrometers.

AFN printing system is more appropriate for direct printing of metal/ceramic materials, while NPDS is more appropriate for thin film applications, (*i.e.*, solar cells or electrochromic windows [47, 48]). Since AFN printing system adopt a nozzle with a diameter of 300 or 500 μm , patterns are printed based on points. **Figure 13** shows silver points printed by an AFN system. The point diameter was of the order of tens of micrometers.

Printed structures still have an uneven surface, and are not yet readily applicable to 3D printing at the micro/nanoscale. Moreover, the dimensions are greater than is possible with FIB milling. It is therefore necessary to further increase the resolution to enable printing of full 3D freeform structures with any desired undercut.

Figure 12. Schematic of an AFN printing system [49]

Figure 13. Silver structures printed by an AFN printing system [50]

The bonding and focusing mechanisms were investigated to further reduce the machining scales. The bonding mechanism directly influences not only the deposition occurrence but also the adhesion strength between printed features and the substrate. To investigate the AFN bonding mechanism, the interlayer between the printed features and substrate was studied.

To investigate the interlayer, samples were first detached from the substrate by pulling with a micro tool, and the surface morphology was observed. In this study, silver nanoparticles on a silicon substrate (which are most frequently employed in the hybrid printing system) were investigated.

Figure 14. Hardware configuration for sample detachments

Figure 15. Schematic diagram of the process for detaching features

Figure 14 shows the hardware configuration for sample detachment. The substrate was mounted on a nano-stage (SLC1730, customized axes, SmarAct GmbH, Germany), and pulled with a micro tool (Daewon Precision Grinding, Korea).

A micro tool with a diameter of 30 μm was positioned perpendicular to the substrate. The nano-stage was then moved laterally to pull the target sample in a horizontal direction. **Figure 15** shows a schematic diagram of printed feature detachment.

Figure 16 shows the surface morphology of the substrate after detaching printed features. As illustrated, many nanoparticles remained at the center of the feature, while few nanoparticles remained in the outer regions (**Figure 16(a)**). The middle photos (**Figure 16(b)** and (c)) show the center area and outer area respectively. In the center region, there are also many scratches on the silicon substrate (**Figure 16(d)**). It should be noted that the size of the center area, herein referred to as the ‘focal point’, does not vary as a function of the original feature scale.

Figure 16. Surface morphology of the substrate after detaching printed features

Figure 17. Surface morphology of the substrate after detaching a printed line

Figure 18. Bonding mechanism of nanoparticle-based printing techniques [51]

For clearer investigation, the detached surface of various line structures was observed. **Figure 17** shows the surface morphology of the substrate after detaching a printed line. The width of the original silver line increased from left to right, and ranged from 30 μm to 60 μm. However, the size of the focal point did not vary, but was maintained between 30 μm and 40 μm.

The existence of a focal point is important evidence in the investigation of this bonding mechanism. **Figure 18** shows the bonding mechanisms of impact-based nanoparticle printing processes [51]. Even though the mechanism of cold spray is slightly different with a NPDS or AFN printing system, they are all based on particle impacts, and are therefore compatible. Considering the particle diameters and impact velocities investigated in former studies of NPDS and AFN printing [36, 52], it is expected that the bonding mechanism of the AFN printing system is a combination of sticking and erosion.

In particular, evidence of erosion is present on the surface, and the focal point can meet this requirement. At the start of the nanoparticle printing process, nanoparticles are focused at a certain point, with a diameter of approximately 30 μm , which is similar to the minimum scale of the AFN printing system, and also comparable to the focal point diameter. During a certain time ($\sim$ few ms to s), the nanoparticle beam scratches the substrate surface, after which particles bond to the substrate to form an interfacial layer. After bonding to the focal point region, nanoparticles then bond to existing nanoparticle structures, rather than the surface. It is thought that nanoparticles remain in the outer region, rather than in the original focal point.

With this theory, the printing strategy can be altered. In the existing printing method, nanoparticles are printed when there is sufficient aerosol flow, but the substrate can move while nanoparticles are scratching the surface. If there is motion before nanoparticles are firmly bonded in the focal point, only partial structures remain with a smaller diameter. With a moving path, particles cannot bond well as the surface is not sufficiently scratched. Hence, only the smaller structures remain in the initial focal point. For this strategy, moving feed also needs to be large enough to not make new scratches on the moving path while moving the substrate.

Figure 19 shows and compares features defined with the novel printing strategy (moving a substrate while nanoparticles are scratching the substrate), and the existing printing method (printing with a sufficient aerosol flow).

As shown in the figure, features with the novel printing strategy are half the size of those printed using the existing strategy. Using this printing method, feature scales can be significantly narrowed down without controlling the aerosol flow or focusing mechanism directly, both of which require more complex experimental equipment.

With more precise control of printing time scales, it is expected that even smaller structures can be printed. Because the bonding mechanism plays a major role in nanoparticle printing [53], understanding on the bonding mechanism is essential to control the printed features. Also it is expected that the bonding force per unit area is stronger in smaller features than larger ones, because the portion of a focal point becomes larger in smaller features. Though many studies have investigated for adhesion of microstructures [54], however it is still very difficult to measure and standardize the adhesion force [55]. Analysis on the bonding and adhesion force need to be kept investigated.

(a) Minimum feature scale by novel printing strategy (top-view)

(b) Minimum feature scale by the existing printing method (tilt-view)

Figure 19. Comparison of printing strategy effects.

(a) shows a smaller size, less than the diameter of focal point.

3.3. Micro-machining system investigation

For the local planarization, a mechanical micro-machining was adopted. **Figure 20** shows the hardware configuration of the micro-machining system. A substrate was mounted on a 4-axis nanostage (SLC1730, customized axes, SmarAct GmbH, Germany), and a high-speed spindle (D1733, Westwind Air Bearings, UK) was used for the machining.

Mechanical machining is a very traditional and classical fabrication method, and a chemical mechanical polishing (CMP) has been widely used in the fabrication of micro-electro-mechanical system (MEMS) devices [56]. Particularly in this hybrid process, micro-machining was adopted in order to cut out various metal/ceramic inorganic materials, as stated above.

Figure 20. Hardware configuration of the micro-machining system.

A tool diameter was 30 μm , which is similar size to the focal point in the AFN printing process. Two CCD cameras were used to observe the machining process. **Figure 21** shows the machining configuration during the local planarization. Because the tool diameter was determined as the size of a focal point, it was compatible with size of printed features. Before the planarization, printed features had a corn shape due to the nanoparticle focusing; however, after the planarization, structures had a flattened surface on the top of the corn.

In order to set an origin, a contact between the tool and substrate was measured using optical images and electric resistance measurement. Because setting an origin of the coordinate system largely influences the final precision of the machining system [57], precise measurement of the contact between tool and workpiece is very important. After the tool approached to the substrate enough, the electrical contact was checked at every movement step less than 20 nm, as well as with optical images. If the electric current is measured, then the height at that time was set to be a zero, hence the height of planarization can be well controlled.

Figure 21. Machining configuration during the local planarization

For the improvement of the machining system, tool geometries were investigated. Size and geometry of cutting tools widely varied with respect to their own purposes [58, 59].

Many researchers have tried to fabricate micro tools typically ranged from several tens of micrometers [60]. Micro tools were fabricated by precision mechanical grinding wheels and micro-electrodischarge machining (μ -EDM) [61], or FIB system [62, 63]. Bhavsar reviewed micro-tools fabricated using FIB milling process, and suggested a novel tool design with four cutting edges [64]. Although many of micro-cutting tools were designed and fabricated at the minimum diameter of 5 μm , most of them have simple geometries compared to conventional-sized tools-plain or single cutting edge- mainly due to the fabrication limit.

Hence, in this study, it was aimed to improve cutting tool geometries using the FIB milling. FIB is a very expensive process and is not appropriate for mass production, nevertheless it can be applied to a specific cutting of special purpose. Research on tool geometries was well introduced in a recent article [65]. The main objective of the research was to implement specific geometries of conventional machining tools in micro-machining tools. Tool geometry was one of the most important factors affecting on the final product quality [66]. In this study, with a specific purpose-local planarization of printed nanoparticle structures-FIB was used with a multi-axes manipulator in order to fabricate multiple cutting edges for implementation of clearance and rake angle.

Figure 22 shows the suggested tool geometries; no-pattern, single edge, double edge, quadruple edge, and lattice pattern. To improve the machinability, a clearance angle of 10° was implemented to each cutting edge. For the case of lattice pattern, it has both rake and clearance angles, and edge angle was 90° .

Silver nanoparticles were printed on a silicon substrate using the AFN printing system with a width of about $50\text{ }\mu\text{m}$, and with a height of about $50\text{ }\mu\text{m}$. Micro-machining set-up was the same as introduced above, and a machining height, a distance from the substrate to the tool, was set to be $30\text{ }\mu\text{m}$.

After the machining, the structure was observed using a 3D surface profiler (μSurf , NanoFocus, Germany). To evaluate the performance of cutting tools, surface roughness and height controllability were measured and analyzed.

Figure 22. Various micro-machining tools and their geometry: [65]
(a) no-pattern, (b) single edge, (c) double edge, (d) quadruple edge, and (e) lattice pattern

Figure 23. Surface profiles in terms of different tool geometries [65]

Figure 24. Surface roughness in terms of different tool geometries [65]

Figure 23 and **Figure 24** show surface profile and roughness after the micro-machining with different tool geometries. From the results, it was confirmed that the height of structure can be controlled within 1 μm . It largely depends on the step size used in setting an origin of the machining system. On the other hand, surface roughness and flatness can be controlled within 50 nm. It was confirmed that surface can be effectively flattened with micro-machining tools.

From the perspective of tool design, a tool with more edges showed the better quality. However, the no-pattern tool also showed good performances as the quadruple edge tool. It seemed rugged end face of the tool influenced on the surface, because the tungsten carbide rod was fabricated by the EDM process, which is very rough cutting at this scale. Among various tool patterns, the multiple-lattice edge tool showed the best quality.

On the other hand, tool wear after the machining was also observed. Wear is one of the most important factors in mechanical machining processes [67, 68]. **Figure 25** shows various tool geometries after the machining. In the experiment, Total 3 samples were machined per each tool, and tools showed a negligible wear. For the case of the lattice pattern tool, cutting edge at the tip was slightly worn, however, still it was applicable to further machining of printed samples.

Tool wear might be a critical problem particularly in the micro-machining [39]. Moreover, tools should cut out various metal and ceramic materials in this hybrid process. Though the printed structures have relatively low modulus and strength compared to the bulk material, wear at the tool tip edge will cause a large geometric error. In order to reduce the wear, application of lubricants can be considered. Particularly for the case of micro-machining, novel lubricants such as graphene based lubricants or solid lubricants can be effective [69, 70].

Figure 25. Various micro-machining tools geometry after the machining: [65]
 (a) no-pattern, (b) single edge, (c) double edge, (d) quadruple edge, and (e) lattice pattern

For further investigation, machining parameters can be further improved. Machining parameters such as feed rate are important factors on the final product quality [71, 72].

3.4. Analysis of material re-deposition of FIB milling

With FIB milling, scanning paths were investigated to minimize material re-deposition phenomena. Clear occurrence of material re-deposition was observed in many studies. [73] Because material re-deposition has a directional property, some researchers tried to investigate the effect of scanning paths. So far, only some simple paths, *i.e.* spiral path, were investigated [74].

In this study, a novel path generation strategy was suggested inspired by conventional mechanical machining. Research on ion beam paths was well introduced in a recent article [75].

The basic concept to minimize the material re-deposition is distribution of scanning directions. To distribute ion beam defects, balancing, distribution, and backstitch concepts were implemented, and their effects were evaluated.

The novel path generation strategy was suggested as shown in **Figure 26**. The strategy consists of three different steps; designation of process region, specification of scanning type, and specification of scanning order. First of all, the processing region is defined. Overall process region can be processed at once, or can be segmented. Then overall scanning type is determined at the second step. Processing region can be processed with transverse, rotational, radial, or parallel way algorithms with a certain free angle. Random and combination concepts also can be implemented.

After the specification of scanning type, the scanning order of processing points is determined. Processing points can be scanned serially or randomly. Backstitch and balanced algorithms could be implemented at this step, and it was expected they can contribute in distribution of the ion beam defect.

Figure 26. Path generation strategy for ion beam milling [75]

Through the novel path generation strategy, various scanning paths can be generated. For example, existing *Raster* scan path can be generated by ‘conventional (process region) – transverse (scanning type) – continuous steps (scanning order).’ Re-ordering scanning order can be applied to scanning lines and points, simultaneously.

Among various scanning paths able to be generated through the generation strategy, nine representative paths were selected and evaluated. **Table 3** shows a list of the selected nine different paths for an experimental set.

Path (a)-(c) are conventional concepts, that processing an ion beam in transverse way (*Raster* and *Serpentine*) and a rotational way (*Spiral*), respectively. Path (d)-(f) are associated with new path generation algorithms, backstitch and balanced. Backstitch algorithm is inspired from the micro-drilling [76], which repeats moving backward and forward to minimizing the effect of adjacent processing points. By

scanning far points earlier, adjacent points can be balanced. Balance algorithm is to make a balance in scanning direction. For example, the *Balanced raster path* has two *Raster* paths in the opposite direction.

Table 3. Selected nine scanning paths [75]

No.	Process region	Scanning type	Scanning order	Named as
(a)	Conventional	Transverse	Conventional (left to right, top to bottom)	<i>Raster</i>
(b)		Transverse	Conventional (left to right then right to left, repeatedly)	<i>Serpentine</i>
(c)		Rotational	Conventional (outside to inside)	<i>Spiral</i>
(d)		Transverse	Backstitch	<i>Backstitch raster</i>
(e)		Transverse	Balanced	<i>Balanced raster</i>
(f)		Rotational	Balanced	<i>Balanced spiral</i>
(g)		Border finish	Conventional (left to right, bottom to top)	<i>Border finish raster</i>
(h)		Random	(Random)	<i>Random</i>
(i)		Combination – Transverse + Rotational	Conventional (left to right, outside to inside)	<i>Raster spiral combination</i>

Path (g) is inspired from the burr-free tool path, which was applied to the path generation in planar milling [77]. This algorithm processes outer boundary first and then inner processing region. The *Random* path re-orders all processing points randomly, and the *Raster spiral combination* path is combination of the *Raster* and *Spiral* paths.

Figure 27 shows a schematic diagram of nine scanning paths for the experimental set. One line of processing points is represented as arrow in the figure. Because the time required to move the beam between different processing points (~ a few nanoseconds) is negligible compared to the beam dwelling time, overall process time does not vary a lot in terms of the beam scanning paths.

Figure 27. Schematic diagram of nine scanning paths [75]

For the experiment, same FIB column as in the hybrid process was used. Gallium ions (30 kV) were used in FIB (COBRA FIB, Orsay Physics, France). The target area was $6 \times 6 \mu\text{m}$ square consists of 6,561 processing points. Since some of the paths have to be scanned with two different paths, *i.e.* balanced or combination paths, the total number of scan was determined as 2, processing 13,122 processing points. The ion beam current was 716 pA for a probe size of 136 nm. The dwell time per point was 3 ms, which is relatively large and is able to create a large material re-deposition. Since the objective of the experimental set is to investigate the effect of novel paths, process parameters were chosen to maximize the defect.

Figure 28 and **Figure 29** show top-view and tilted-view of surface morphology of silicon substrate after milling a square. For the cases of *Raster* and *Serpentine*, pockets had a large inclined surface, and they were tilted to opposite direction of beam processing. For example, in the *Raster* path, beam processed from left to right and from bottom to top, the fabricated surface was tilted from right to left and from top to bottom. In the *Serpentine* case, because the scanning had a balance in a horizontal direction, it was only tilted in a vertical direction. The *Spiral* path showed a large defect in its diagonal direction. It is mainly due to the beam overlapping, between adjacent pixels along to the diagonal direction.

On the other hand, *Backstitch raster*, *Balanced raster*, and *Balanced spiral* showed the better surface quality compared to former ones. Particularly the *Balanced raster*, showed the smoothest surface. However the overall depth was much smaller. The *Border finish raster* did not show significant improvements compared to the *Raster* scan path. Pocket was tilted from top to bottom, because the *Border finish raster* started *Raster* path from left to right and from bottom to top after scanning the outer border line.

Figure 28. Top-view image of the structures fabricated using different paths. The scale bar is 5 μm .

Figure 29. Tilt (45°)-view image of the structures fabricated using different paths. The scale bar is 5 μm .

The *Random path* showed a rough surface, and the *Raster spiral combination* path showed a slight defect in its diagonal direction. *Random* and *Raster spiral combination* showed interesting results because the FIB sputtering was influenced by pre-processed points. For the case of the *Raster spiral combination*, after the first set (*Raster path*) scanning, the pocket was expected to have a shape similar to **Figure 28(a)**. However, after the second set (*Spiral path*) scanning, the pocket had a flat surface. This is mainly due to the effect of inclined surface; sputter rate of ion beam increases as inclined angle increases. After the first scanning, ion sputtering occurred more at inclined wall, and re-deposited atom were thought to stick back to the deeper side. This is thought to be a cause of flat surface in the *Random* and *Raster spiral combination*.

To quantify the surface morphology results, fabricated structures were measured using an atomic force microscopy (AFN, DimensionTM3100, Veeco, USA). Substrate surface was set to be 0, and only the milled structure data was used.

Figure 30 shows the maximum depth and root mean square (RMS) depth in terms of nine different paths. Among various paths, the *Serpentine* path showed the maximum depth, as well as the average depth of the pocket. *Raster*, *Spiral*, and *Border finish raster* showed slightly lower than the *Serpentine*, and other paths showed much smaller depth values.

This is intuitively because of the tilted pocket. With *Backstitch raster*, *Balanced raster*, *Balanced spiral*, and *Random* paths, the effect of material re-deposition was well distributed, and leveled similar to adjacent points. However with *Raster*, *Serpentine*, *Spiral*, and *Border finish raster*, the effect of material re-deposition was focused in one direction, hence pockets had higher depth values.

Figure 30. Maximum depth and root mean square (RMS) depth with respect to various paths

Figure 31. Standard deviation of normalized profiles with respect to various paths

On the other hand, **Figure 31** shows the standard deviation of the normalized pocket profile. This value represents the squareness of the milled pocket, because it indicates how far the measured points are from a specific level. For the normalization, the depth profile was divided by the absolute average of the profile. Normalized depth profile then varied centering on (-1).

Figure 32. Milling samples for the database; TiO₂ grooves on planarized Ag

As observed in surface morphology, *Raster*, *Serpentine*, *Spiral*, and *Border finish raster* have significantly higher values compared to the others. Among nine different paths, the *Balanced raster* showed the minimum, and was followed by the *Backstitch raster* and *Random*. Since the standard deviation represents squareness, but not roughness, the *Random* path showed a quiet small value.

Through this research, scanning paths can be generated with respect to the corresponding purposes. Path can be determined considering the higher material removal rate, or higher surface quality. Experimental results also imply that the material re-deposition can be successfully balanced just by controlling the scanning paths, not ion beam conditions, or milling conditions.

Furthermore, results of parameter study have been compiled as the database in addition to scanning paths. **Figure 32** shows experimental samples for the database. Silver was deposited on a silicon substrate, and then was planarized. On the surface, grooves were milled using the ion beam, and then were filled with titanium oxide as a protection layer. Cross sectional images were obtained by ion beam milling, and the width and depth of grooves were measured and analyzed.

(a) Effect of number of repetitions

(b) Effect of beam current

Figure 33. Effect of beam parameters on groove depth

Figure 33 shows the analyzed results-effect of beam parameters on groove geometries. Higher current and number of repetitions can deliver larger grooves as similar to the intuitions. However, the process rate is not proportional to the sputtered volume. Therefore, appropriate process parameters need to be determined with respect to required conditions. In addition to silver materials, experiments were

performed with various materials, and results have been compiled to the database.

In order to acquire precise geometry, construction of the database and empirical modeling is very important, as well as the computational analysis. Data has been collected from several sets of experiments.

3.5. Application of a sacrificial layer

Finally, a sacrificial layer was implemented. PMMA was coated on the substrate using a spin coater (ACE-200, DONG AH Trade Corp., Korea). Rotational speed of 500 and 4,000 rpm was used to coat PMMA material.

The most remarkable aspect in PMMA coating is that the chemical composition can vary by the ion beam irradiation. When the ion beam is irradiated on PMMA, energy of the ion beam influences on chemical bonding of PMMA. Then the chemical composition of ion irradiated PMMA changes, and some gaseous products are generated, as follows [78]:

For the removal of PMMA, acetone was used as etchant. However the ion irradiated PMMA remained even after the etching because of the changed chemical composition. In the most cases, remained PMMA formed a thin shell with a width typically ranged from tens to hundreds of nanometers, and the width was controllable in terms of the ion dose of beam irradiation.

In this study, this remained thin layer was applied to a mold for the nanoscale 3D structuring. Nanoparticles can be printed with a smaller scale after the ion beam milling of desired geometries in the PMMA layer, and then ion irradiated thin layer sieges nanoparticles structures; hence it can be used as mold.

Figure 34 shows a process flow chart of the suggested hybrid process with a sacrificial layer. PMMA was coated on the substrate, and then was milled using FIB. Any 3D structure can be fabricated using a multi-axes manipulator. During the ion beam milling, a thin layer remained on the border shell of the milled structure. Then

the structure was filled using the AFN printing system, and then undesired part was removed by the micro-machining. After the etching, only nanoparticle structure remained with an ion irradiated PMMA thin layer.

Figure 35 shows fabricated examples using the nanoscale hybrid printing system with a sacrificial layer. **Figure 35(a)** shows a tilted pillar PMMA shell without the nanoparticle printing, and **Figure 35(b)** shows a tilted pillar filled with silver nanoparticles. Unlike other micro/nanoscale fabrication processes, 3D structures with various undercuts can be fabricated, as well as any desired freeform on the surface.

Figure 34. Process flow chart of the hybrid process with a sacrificial layer

(a) Tilted pillar shell (45°)

(b) Tilted pillar structure (60°)

Figure 35. Fabricated examples using the developed hybrid process with a sacrificial layer

3.6. Bridging fabrication processes

Bridging procedures of three different systems were partially introduced in a recent publication [49]. With advances in process scales and surface quality, the novel hybrid system was developed. With assistance of the micro-machining process, uneven surface can be flattened, and can have better surface quality. Moreover, it helps clear FIB milling of printed structures, because FIB milling uses sputtering, which has very conformal and makes large defects when milling an uneven porous surface.

In this study, silver (Ag, <100 nm, 576832-5G, Sigma Aldrich, USA), titanium oxide (TiO₂, <25 nm, 637254-100G, Sigma Aldrich, USA), and barium titanate (BaTiO₃, <3 µm, 208108-500G, Sigma Aldrich, USA) were used as main work materials. For the AFN printing system, source pressure of 50-100 Pa was used with a chamber pressure of 0.1-1 Pa. **Table 4** shows process parameters used in the AFN printing system.

For the micro-machining, a tungsten carbide tool blank (Daewon Precision Grinding, Korea) with a diameter of 30 µm and cutting lengths of <10 µm was used. A high-speed spindle (D1733, Westwind Air Bearings, UK) was used with a four-axis nano-stage (SLC1730, customized axes, SmarAct GmbH, Germany). In this hybrid process, rotational speed of 60,000 rpm and feed of 1-5 µm/s were used. For FIB profiling, 30 kV of gallium ion by FIB (COBRA FIB, Orsay Physics, France) was used. Ion beam currents were controlled with respect to corresponding probe size.

For the integration, reference marks were patterned by FIB milling, and were processed based on scanning ion microscopy (SIM) images. Since the coordinate system of the hybrid process are aligned using images at corresponding magnifications of process views, precision of the coordinate system largely depends on the process imaging ability and pattern width. It ranges within 50 nm. Unlike

optical reference patterns used in MEMS processes, the image-based reference marks can easily have nanometer resolution in a local area. Most of all, with one reference mark, structures can be fabricated with any desired offset, unlike conventional alignment marks using an optical diffraction [79].

Table 4. Process parameters of the hybrid process

Parameters	Values
Distance between the substrate and nozzle (mm)	1.0
Source pressure (Pa)	50-100
Chamber pressure (Pa)	0.1-1
Feed rate for deposition ($\mu\text{m/s}$)	0-200
Carrier gas	Air
Powder material	Ag, TiO_2 , BaTiO_3
Substrate material	Si
Rotational speed for cutting (rpm)	60,000
Feed rate for cutting ($\mu\text{m/s}$)	1.0-5.0

(a) Process flow chart of the hybrid system

(b) Corresponding samples with process flow chart

Figure 36. Process flow chart and corresponding samples of the hybrid system [49]

As an example, some multi-material samples were shown. **Figure 36** shows the process flow chart and corresponding sample images of the developed hybrid system. For fabrication of samples in **Figure 36**, silver was printed on a silicon substrate and then was ground by micro-machining process. It was milled by FIB (SNU, denoting *Seoul National University*), and titanium oxide was printed again on the surface. After finishing process, metal/ceramic material letter could be fabricated with a scale of several μm .

Figure 37 shows another multi-material structure example. On the milled pocket on silver sample, titanium oxide was printed and planarized. On that surface, barium titanate was printed. Seeing energy-dispersive X-ray spectroscopy (EDS) image in **Figure 37**, interlayers between different materials were clearly observed.

Overall process capabilities were further discussed in detail in the next chapter with more examples.

Figure 37. Multi-material structures fabricated by the hybrid system; SIM image (left) and EDS image (right) [49]

Chapter 4.

Process capability

4.1. Process envelope

In this chapter, the process capability of various techniques is evaluated. As discussed in the Introduction, the material selectivity, process scale, and geometric degree of freedom of the developed process are evaluated. Significant performance improvements can be made by bridging different micro/nanoscale processes. The definitions of the terms ‘bridging’ and ‘hybrid’ are discussed and analyzed later in this chapter.

Figure 38. Hardware configuration of the constructed hybrid process

Table 5. Material compatibility of printing

Substrate Particle		Ceramics				Metals					Polymers				
		Si	Al ₂ O ₃	Glass	FTO-glass	AISI 304	AISI 316	Cu	Al	TiNi	PCB	PE	PP	PMMA	PET
Ceramics	TiO ₂	△		X	0	0		0	0			△	△	0	0
	Al ₂ O ₃	0	0	0	0	0		0	0						0
	MnO	0		0	0										
	ZrO	0													
	BaTiO ₃	0						0	0						0
Metals	Sn	0		0	△			0		0	0			0	0
	Ni	0			X	□	□				△	△	△	△	△
	Ti				X										
	Al												0		
	Ag	0													0

○: Film deposition

△: Powder attachment (Not film)

X: No deposition

□: Film deposition with specific condition (He carrier gas or heating)

Figure 38 shows the hardware configuration used in the constructed hybrid process; the system can additionally operate in an ‘individual’ process mode. Different vacuum conditions are used for each process. Micro-machining is performed at atmospheric pressure, while AFN printing and FIB milling are performed under a vacuum. In particular, the FIB system requires a high vacuum ($\sim 10^{-7}$ torr). Intermediate environment and cleaning processes are required between each process to remove nanoparticle debris and machining swarf.

Table 5 shows the materials available for NPDS and AFN printing. As these printing systems bond particles by force, the deposition characteristics differ with respect to the weight and size of the nanoparticles. The appropriate process parameters for each material need to be investigated. Deposition quality is largely dependent on substrate characteristics and therefore research into the compatibility between different materials is required.

Table 6 summarizes the process capability of the three techniques. By introducing a sacrificial layer, a novel hybrid process can have a range of applications broader than existing hybrid techniques [9, 49]. Moreover, this novel process presents advantages over conventional micro/nanofabrication processes, *i.e.*, beam-based direct writing or direct printing technologies.

In contrast with the previous hybrid process (NPDS+FIB), the novel hybrid system can fabricate 3D freeform structures with any desired undercut. Furthermore, the process scale can be reduced to hundreds of nanometers. The nanoparticle printing accuracy can be increased and a more uniform top surface achieved.

Typically, beam-based writing techniques such as FIB-CVD are compatible with the broadest range of materials. As the hybrid system uses high-speed printing, any inorganic material can be printed without chemical binding or heat treatment.

The hybrid process also shows advantages over MEMS (lithography+etching) techniques. Typically MEMS devices are designed and fabricated layer-by-layer, but the suggested hybrid process can fabricate any freeform structure. Also, the length scales that can be fabricated with the hybrid system are typically shorter, as a subtractive FIB system is used.

Table 6. Process capability comparison summary of different processes

Processes	Beam-based writing	Direct printing	Suggested Nanoscale 3D printing
Description	Laser direct writing, FIB-CVD, <i>etc.</i>	Inkjet printing, E-jet, <i>etc.</i>	AFN printing + FIB + micro-machining + spin-coating
Geometry	3D w/o sacrificial layer	3D w/o sacrificial layer	3D w/ sacrificial layer
Undercut capability	Limited in some cases	Limited in some cases	Fully applicable
Material	Metal/ceramic/polymer	Metal/ceramic/polymer	Metal, ceramic, polymer simultaneously
Minimum process scale	~ 50 nm	> 1 μm	~ 100 nm (additive) ~ 50 nm (profiling)
Process step requirements	High vacuum chamber	High vacuum chamber	High vacuum chamber
Application	Micro/nanoscale welding, prototyping	Micro/nanoscale patterning	Micro/nanoscale structuring, prototyping

Figure 39 shows the process scale envelopes of NPDS, AFN printing, FIB, and the proposed hybrid process. As shown in **Figure 7**, NPDS is not fully applicable to 3D printing with full utilization of FIB. However, the process scales of AFN printing systems are better suited to FIB, and micro-machining can be used to improve the surface quality. By integrating AFN printing, micro-machining, and FIB, nanoparticle printing processes can be used for 3D printing. At this stage, structures with width scales around tens of micrometers can be fabricated with 2.5-D design.

Through the use of a polymer sacrificial layer, process scales can be reduced further by appropriate use of FIB. Polymer sacrificial layers contribute not only to an improvement in the degree of geometric freedom but also to the improvement of process scales, by offering micro/nanoscale molds and supporting structures.

Figure 39. The performance of the hybrid fabrication technique with respect to individual processes

As it is without help of sacrificial layer, the minimum structure width scale is at around 30 μm . Height can range from hundreds of nanometers to hundreds of micrometers. Profiling scale is up to FIB system, typically ranged larger than 50 nm. With help of sacrificial layer, the minimum structure width can be reduced further up to 50 nm, similar to the scale of FIB milling.

As shown in **Figure 39**, FIB can now be applied at all scales, and complex 3D patterns can be fabricated with a sacrificial layer. Although each process has been improved in this dissertation, the primary focus has been on the design and implementation of the hybrid fabrication, and process planning systems.

In this dissertation, reference is made to the term ‘bridging’. The term ‘bridging’ has a definition similar to the terms ‘integrated’ or ‘hybrid’; however in this study, it represents the full utilization capabilities of each process. It is also related to the control ability of each process. In the conventional hybrid process, NPDS and FIB are processed serially, but their process scales are not fully bridged. Hence, a region of inaccurate processing exists with insufficient control. Approaches in which the hybrid process involves the integration of AFN printing, micro-machining, and FIB, are partially bridged, and structures can be fabricated with some constraints within a relatively small process envelope. Finally, by spin-coating, the processes are fully bridged, and the process scale envelope is expanded to include full utilization of the FIB milling process. Structures can be fabricated by FIB milling without undesired or uncontrolled parts.

In the next section, process capability is detailed in terms of geometric degree of freedom. Process capabilities are discussed again with the novel definition of ‘hybrid’ process.

4.2. Geometric degree of freedom

Figure 40 shows a scale comparison between NPDS, an AFN printing system, and the suggested nanoscale 3D printing system. Structures deposited by NPDS have a limited height scale, from 60 nm to several μm , and a width scale of at least 200 μm . AFN printing systems can focus an aerosol beam and, therefore, have a reduced width scale (around 30 μm) and an increased height scale. Rather than 3D printing, NPDS is more appropriate for thin film deposition, and AFN printing is more appropriate for the direct patterning of metal/ceramic nanoparticles. Both systems fabricate structures in dry room-temperature conditions, and the structures have uneven surface roughness.

Figure 40. A feature comparison of NPDS, AFN printing system, and nanoscale 3D printing system.

The suggested hybrid process can fabricate unconstrained freeform 3D structures. The top right figure shows the average width scale of the suggested system. The width profile follows the specification of FIB; hence, it can be narrowed to 50 nm, but nanoparticle structures follow the minimum diameter of the nanoparticles used. In this experiment, silver nanoparticles with an average diameter of 100 nm were used. For the case of high-aspect ratio pillars, as shown in **Figure 40**, the average pillar width was ~250 nm, and the minimum width was ~100 nm. In addition, the suggested system can fabricate 3D freeform structures as shown in the bottom right figure of **Figure 40**. The fabricated T-structure had a 5 μm undercut. The surface finish was also controlled, unlike individual NPDS or AFN printing systems.

Figure 41 shows a different freeform sample with two types of undercuts. It has a tilted central pillar, and a freeform broccoli-like structure. From this figure, it is demonstrated that the hybrid process can fabricate both undercuts and freeform structures. The left part of the structure has a negative undercut, the right part of the structure has a positive undercut, and the top surface has a freeform nanoscale clover structure. These samples are clear evidence of the advanced geometric capabilities of the hybrid process developed here.

Figure 41. 3D printed nanoscale clover with two types of undercuts

4.3. Expanding definition of ‘hybrid’ and ‘bridging’ process

In this section, the definition of a hybrid process is discussed. In addition to the process envelope, in terms of scale and geometric capability, strict classification of the suggested process is discussed, as the process lies beyond the classical definition of a ‘hybrid’ process.

Traditionally, hybrid processes have been defined as a combination of techniques acting simultaneously in a single processing area, *i.e.*, laser-assisted machining (LAM) [80, 81]. However, following recent process improvements, this definition has broadened to include configurations in which the advantages of more than two processes are integrated [82].

Figure 42. Novel definition of hybrid process

In this study, different processes were integrated but were not processed simultaneously so different processing conditions could be applied. FIB requires a highly controlled high-vacuum system, and NPDS requires a relatively low vacuum and nanoparticles. Machining can be processed under a vacuum, but was processed under atmospheric conditions. This work defines the developed process as a hybrid manufacturing process (**Figure 42**).

The three different processes share a coordinate system and substrate configuration. As the length scales are of the order of tens of nanometers, alignment between the processes needs to be strictly controlled to under 50 nm. Regardless of nanoscale structure, separated reference marks were investigated and implemented to share the same coordinate system.

In addition to sharing a coordinate system and sample set-up, the three processes all contribute to the process improvements. The AFN, micro-machining, and FIB systems contribute to additive, subtractive, assistive processes, respectively, and cannot be substituted in the fabrication of 3D nanoscale structures. By combining different processes, the process scales and degree of freedom are drastically improved.

The integrated process is therefore defined as a hybrid process. From this perspective, surface coating and heat treatment are not hybrid processes. Structure forming does not share a coordinate system and surface contribution with coating or heat treatment processes.

It is suggested that a novel definition of hybrid fabrication is essential for further improvements to the manufacture processes. Concerns about fabrication difficulty have increased, *e.g.*, the processing of difficult-to-cut material [83] or bio-material [84]. It was once thought impossible to use conventional manufacturing techniques; however, researchers have investigated solutions to the problems involved, typically using hybrid manufacturing processes [85].

The definition of a hybrid process has been broadened [86]. Following recent trends, more research in the area of integrating and bridging different manufacturing processes is necessary, *e.g.*, the standardization of data gathering and monitoring, fabrication platform, modulation, as well as investigation and optimization of each individual process are all required.

Chapter 5.

3D printed micro/nanoscale structures

5.1. Potential applications

In this chapter, some structures and functional applications are shown using the developed hybrid 3D printing processes. As stated previously, the developed system can fabricate a range of 3D freeform structures without material and geometric constraints. The process scales can be reduced further than conventional MEMS techniques.

Figure 43 shows potential applications of the developed hybrid process. Conventional MEMS techniques have been applied to several engineering fields, *e.g.*, sensors [87], actuators, and bio-applications [88, 89] (referred to as mechanobiology in the figure). Mechanical bio-sensors show high efficiency, high sensitivity, and a short response time when compared to other physical or chemical sensors [90]. However, they also have poor selectivity and complex fabrication procedures [91]. The developed hybrid process can use a broader range of materials, reduce process scales, and increase the degrees of freedom in geometry. Therefore, it is expected that mechanobiology can be implemented at cellular scales.

The novel hybrid process is suitable for a wide range of custom geometric design requirements. Micro/nanoscale structures for medical treatment typically require individual patient customization [92, 93].

Figure 43. Potential applications in customized nanoscale structure

Since the research objective was to develop a novel process with improved performance, applications are not limited in some cases. By integrating different manufacturing processes, limitations can be mitigated, and the range of potential applications increased. In this chapter, some structures with complex geometries are shown, and their functional applications discussed.

5.2. 3D printed nanoscale structures

Structures with complex geometries were fabricated, demonstrating micro/nanoscale 3D printing. **Figure 44** shows a micro statue mimicking *Christ the Redeemer* in *Rio de Janeiro*. The height of the micro statue was $\sim 10\text{ }\mu\text{m}$, and the width was $\sim 15\text{ }\mu\text{m}$. The minimum thickness was approximately 700 nm.

A substrate was coated with PMMA, and was then milled by a FIB system. Hand and arm structures were fabricated. Then silver nanoparticles were deposited using the AFN printing system, and the PMMA layer was removed. Since the ion dose of FIB milling can be controlled, the arms could be tilted at an angle to the body. The size of the statue's head was approximately 1 μm .

Figure 44. 3D printed micro-Jesus statue (made of silver)

Figure 45. Micro-rotor (made of silver)

Figure 46. Micro-rotor fabrication process

The body of the statue appeared to be porous at this scale, mainly due to the size of the nanoparticles. Moreover, the ion beam may ion charge the structure at this scale. Nevertheless, the fabricated statue demonstrates the undercut and freeform 3D capabilities of this fabrication process.

Figure 45 shows a micro-rotor. Similar to the micro statue, it was fabricated by PMMA coating, FIB milling, AFN printing, and micro-machining. Silver nanoparticles were used in structuring. When FIB milling, the sample angle was controlled by a multi-axis manipulator, hence milled pockets could have different blade angles.

Figure 46 shows the fabrication process of the micro-rotor. In **Figure 45**, yellow dot lines imply the base of the blades, and the four blades can be shown to have an undercut of 15° in different directions.

For the fabrication of inclined blades, the sample was tilted to different angles in the FIB chamber, and pockets were milled. As shown in **Figure 35**, nanoparticles could be deposited in the pocket at angles up to 60° , reducing the number of processing steps required, as more complex geometries can be fabricated at once.

Floating structures are also possible with the developed hybrid process. In **Figure 45**, a rotor is attached to the substrate to show the geometric features of four differently inclined angles; however, it could have undercuts under the blades.

Figure 47 shows a micro-rotor with floating blades. The fabrication process was similar to the former instance; however, ion beam milling was controlled so as not to touch the substrate. Though the top surface was not controlled well, as shown in **Figure 45**, the structure in **Figure 47** shows the possibility of floating rotors, thus demonstrating the possibility of moving components.

Figure 47. Micro-rotor with floating blades

5.3. Functional structures

5.3.1. 3D printed micro-electronics

In addition to 3D structuring, some functional applications were considered. 3D printed micro-electronics were fabricated as shown in **Figure 48**. **Figure 48(a)** shows printed silver lines on a silicon substrate with a width of 30 μm . Line features can be fabricated if the printing is performed at a particular feed rate, which is slow enough to allow the bonding of nanoparticles to the substrate. 3D structures were fabricated along this line using FIB milling. **Figure 48** shows a resistor and some capacitor examples. Both structures have a wall width of less than 1 μm .

Since AFN printing systems use only particle impact for adhesion, structures can be fabricated on hard, flexible, and curved substrates. Therefore, the developed process can be applied to direct printing of electronic components, which are applicable to flexible electronics.

In addition to the fabrication of a capacitor, dielectric material can be printed between separated wall structures (**Figure 49**). Barium titanate was used, which has a dielectric coefficient approximately 1,000-2,000 times that of air, and is widely used in energy storage devices [94]. Since the structure and dielectric material can be selected, the fabrication process can be freely planned.

The hybrid process developed for the fabrication of electronic components is capable of directly printing circuits with fewer constraints on materials or substrates. Various conductors, resistors, capacitors, and inductors can be fabricated. Given the material capabilities of this technique, semiconducting components or relays can be fabricated. For further applications, research into the electrical properties and robustness of components patterned on flexible substrates could be investigated.

Figure 48. 3D printed micro-electronics; resistors and capacitors (made of silver)

Figure 49. Micro-capacitor with a dielectric material (barium titanate between silver conductive material walls)

5.3.2. Bi-material cantilever

(a) Bi-material cantilever (made of silver and titanium oxide)

(b) Cross-sectional image

Figure 50. Bi-material cantilever and its cross-sectional image [49]

In the future, micro/nanoscale robots and actuators may be investigated. **Figure 50** shows a bi-material cantilever fabricated from silver and titanium oxide. For fabrication, FIB milling, AFN printing, and micro-machining were repeated two times for silver and titanium oxide, respectively. The horizontal pillar was fabricated first, and then one side edge was cut to be a cantilever. The width of the cantilever was 8 μm, and the length was 100 μm. The overhang height was 20 μm. To enable thermal actuation by heat expansion, the aspect ratio was designed to be more than 10. In **Figure 50(b)**, the interlayer between silver and titanium oxide is clearly shown.

For functional verification, the thermal expansion was tested. After heating the sample at 200 °C and then cooling, the sample was displaced as shown in **Figure 51**. However the cantilever moved in a direction opposite to expectations, and did not return to the original position. This may have been caused by porosity resulting from AFN printing. Because nanoparticles are printed without chemical binding, the structure is particularly porous. When heat is applied, the cantilever is expected to expand but not be transformed because of its hard ceramic structure. When the cantilever is cooled, the structure returns to normal, due to the slightly sintered and hardened metal structure.

To investigate the irregular behavior of this structure, the bi-material cantilever was investigated in more detail. Research on the mechanical and thermal behaviors of the bi-material cantilever are discussed in the next chapter. Nevertheless, even at this stage, fabricated examples show the promise of multi-material printing at the micro/nanoscale.

Figure 51. Thermal deflection of a bi-material cantilever

5.4. Possibility of mass production

5.4.1. Analysis of productivity and processing cost

Several structures and functional applications have been shown. In this chapter, the possibility of mass production is discussed. Since process scales can be reduced further, very small structures can be fabricated; however, large area fabrication should be considered for practical applications. As this process uses a subtractive FIB system, it can be argued that this process is not suitable for mass production, mainly due to the high process cost and low process rate. However, these problems can be reduced with process planning.

Figure 52 and **Figure 53** show the volume and time distribution of the hybrid process for the fabrication of a bi-material cantilever. Although the processing volume of FIB milling is insignificant, it accounts for a large portion of the total process time. As FIB milling uses ion sputtering to remove material [95], the ion beam probe size is much smaller than that of AFN printing. Hence, FIB is the most time-consuming process in the hybrid technique.

As the hybrid process is based on negative lithography, subtractive volumes can be minimized. Depending on the design or operators' proficiency, process planning and time can vary. The role of FIB milling should be reduced to produce the most efficient fabrication plan.

Based on an analysis of productivity and processing time, process rates and manufacturing costs were calculated. Since the processes used were developed by the authors of this study, published costs were not available. Therefore costs were estimated by comparison with similar processes.

Figure 52. Process volume distribution of the hybrid process

Figure 53. Processing time distribution of the hybrid process

Table 7 shows the cost of each process. FIB milling is widely adopted as a manufacturing service, and costs approximately 200,000 KRW/h, or 173.9 USD/h. Direct patterning AFN printing systems cost around 88,000 KRW/h, or 76.5 USD/h. Micro-machining was assumed to be similar to CMP (Chemical Mechanical Polishing) services (146,000 KRW/h, or 127.0 USD/h). Some high cost equipment was used, *e.g.*, a stage with nanometer precision. The cost of spin-coating was assumed to be 25,000 KRW/h, or 21.7 USD/h.

Table 7. Cost of each process

Process	Cost	Reference
FIB milling	200,000 KRW/hr	NNFC, National Nanofab Center [96]
	173.9 USD/hr	
AFN printing	88,000 KRW/hr	KPEC, Korea Printed Electronics Center [97]
	76.5 USD/hr	
Micro-machining	146,000 KRW/hr	CMP, NNFC, National Nanofab Center [96]
	127.0 USD/hr	
Spin-coating	25,000 KRW/hr	KPEC, Korea Printed Electronics Center [97]
	21.7 USD/hr	

The processing rate was also calculated based on cost. The fabrication cost of the bi-material cantilevers described above was calculated to be 1,455,000 KRW; it took 9.25 hours and the processing volume was $6,400 \mu\text{m}^3$. The average processing rate was $0.192 \mu\text{m}^3/\text{s}$, and the average processing cost was 157,000 KRW/h, or 136.5 USD/h.

The calculated values were compared with other technologies, particularly with FIB-CVD 3D structuring methods, which constitute a widely offered fabrication service. According to the National Nanofab Center, Korea, the processing cost is approximately 400,000 KRW/h, or 347.8 USD/h [96]. According to Igaki *et al.* [98], the processing rate of FIB-CVD can be controlled up to about $0.005 \mu\text{m}^3/\text{s}$. E-beam CVD can also be considered; however, the processing rate of E-beam CVD is lower than FIB-CVD.

Figure 54 shows a comparison of the rates and costs of five processes. Considering the calculated values, the process developed here has a relatively high processing rate and low cost. FIB-CVD deposits the entire volume of a structure, whereas the hybrid process can deposit large material volumes over a short time using AFN printing and micro-machining.

Bridging different micro/nanoscale processes contributes not only to performance improvements (*e.g.*, process scales or dimensional complexity) but also to rate and cost, by processing materials at various scales.

Figure 54. Comparison of different processes with respect to the manufacturing flexibility and cost

5.4.2. Suggestions for mass production

Suggestions for mass production are shown at the device level. **Figure 55** shows a mass production scheme. As discussed in the former section, FIB milling contributes to a large portion of the total processing time. Therefore, if this subtractive process is replaced, processing time could be significantly reduced. AFN printing and micro-machining have a larger process scale, for large area fabrication. **Figure 55** shows an example of nano imprint and the developed hybrid process. In this example, the FIB milling process was replaced with the nano imprint process, and the AFN printing and micro-machining were repeated. In this example, large area 3D structures can be printed.

Figure 55. Suggestion for mass production: nano imprinting+developed hybrid process

Difference between nano imprinting and this hybrid process is that the suggested hybrid process can fabricate 3D metal/ceramic structures as desired. Since nano imprinting uses nanoscale patterned stamps and curable polymer, it is regarded as a promising technology for mass production of nano patterns [99]. However, though large area patterns can be fabricated at the nanoscale, material is limited; material needs to be able to be deformed by mold pattern, with minimized residual layer for uniform production [100].

However, by bridging with the developed hybrid process, multi-material structuring can be implemented. FIB milling can be replaced with nano imprinting technology, and patterned space can be filled with nanoparticle printing. As shown above, even the pocket is tilted with a certain angle, nanoparticles can be filled inside the pocket. After the etching, only nanoparticle structure can remain.

One practical example is a super hydrophobic surface coated in many 3D micro patterns. **Figure 56** shows a design using a super hydrophobic surface.

If the structure is fabricated in an array, like the structure shown in **Figure 41**, then the surface could be functionalized to be super hydrophobic. The mechanical properties of the surface can be controlled by characterization. The structure can be designed for each purpose, and implemented over a large area.

Figure 56. Suggestion for a mass production example with a super hydrophobic surface

5.5. Fabrication summary and future outlook

Various fabrication examples were shown for certain practical applications. In addition, productivity and process costs were analyzed, and the possibility of mass production was discussed.

Figure 57 shows a summary of fabricated examples. All structures in the left part of the figure are shown at the same scale. A tilted pillar is made of silver and fabricated using AFN printing system. Structures with a high aspect-ratio can be fabricated using AFN printing system with a width scale of 30 μm . [50]. Then bi-material cantilever is shown with a length of 100 μm . Then ‘SNU’ letter was shown with the capacitor structures. Micro-rotor and micro-statue have much smaller size less than 30 μm . Figure at right bottom in **Figure 57** shows the tilted broccoli-shape-statue again. Freeform and two types of undercuts were implemented at nanoscale. Compared with other shapes, the developed process shows better geometric degree of freedom with multi-material capability.

For all fabricated examples, the future outlook of hybrid processes has been discussed. As shown, by adopting a hybrid process, process scales and performance can be improved. Improvements to the performance of manufacturing technologies are required, and hybrid manufacturing has been widely investigated. One of the latest trends is cloud-based manufacturing [101]. Based on well-developed infrastructure, manufacturing is used as a service.

Considering this trend toward the distribution of design and manufacturing resources, it is expected that future hybrid manufacturing systems would be cloud-based. With internet communication, hybrid processes could be connected between remote sites, and further improve upon existing process barriers (**Figure 58**).

In 20th century, industries mainly concerned about ‘design for manufacturing (DFM)’ issues, and have mainly investigated for the effective and cheap design and manufacturing techniques. However, in the future, it is expected that ‘manufacturing for design (MFD)’ will promise for the implementation of esthetic design and manufacturing with various required properties. On this stream from ‘design for manufacturing’ to ‘manufacturing for design’ paradigm change, hybrid processes will contribute to improve processes to meet various requirements from design fields.

Figure 58. Future outlook of “hybrid” manufacturing process

Chapter 6.

Thermal microactuator

6.1. Design and fabrication

As an additional example of 3D printed structures, a microactuator was designed and fabricated. Mechanical microactuators can be used as various applications such as a microelectromechanical relay, with enhanced performance rather than electrical switches made of semiconductor materials [102]. Mechanical microactuators can be driven by various sources, *e.g.*, electrostatic [103], piezoelectric [104], and magnetic [105] sources; however, in this study, a thermal actuation mechanism was selected. Thermal actuators deliver larger forces and are easier to fabricate, compared with other operational modes [106]. Additionally, because thermal microactuators do not interfere with electron beam or ion beam analysis, the thermal actuation mechanism can be incorporated into high-vacuum systems for *in-situ* investigation of the sample in question.

Figure 59. Design of a bi-material cantilever [49]

To be activated by a thermal mechanism or thermal expansion, the structure should be designed with two materials having different thermal expansion coefficients, such as a metal and a ceramic. From the perspective of multi-material selectivity in complex structures, a hybrid process can meet this requirement.

A bi-material cantilever, shown in **Figure 50** and **Figure 59**, was fabricated using different material compositions. Based on the deflection of the bi-material cantilever [107], the overall length of the cantilever was designed to be ~100 μm . Considering the bulk properties of silver and titanium oxide as the cantilever constituent materials, the deflection of the beam tip was expected to be ~2–3 μm for a temperature difference of 200 $^{\circ}\text{C}$. The deflection of the cantilever at the beam tip can be calculated as follows (**Equation 2-Equation 4**):

$$d = R(1 - \cos \theta) = \frac{1}{\kappa} \{1 - \cos(\kappa l)\} \quad \text{Equation 2}$$

where

$$\kappa = \frac{6E_1E_2(a_1 + a_2)a_1a_2\varepsilon}{E_1^2a_1^4 + 4E_1E_2a_1^3a_2 + 6E_1E_2a_1^2a_2^2 + 4E_1E_2a_1a_2^3 + E_2^2a_2^4} \quad \text{Equation 3}$$

and

$$\varepsilon = (\alpha_1 - \alpha_2)\Delta T = \Delta\alpha\Delta T \quad \text{Equation 4}$$

If we assume that the bi-material deflection of two materials with different heat expansion coefficients (α_1 and α_2 , $\alpha_1 \ll \alpha_2$) can be expressed as given in **Equation 2**, then κ can be calculated from the elastic modulus (E_1 and E_2), the width (a_1 and a_2), and the thermal expansion coefficients of the two materials. **Figure 60** shows a geometric diagram of bi-material cantilever deflection.

Figure 60. Geometric diagram of the deflection of a bi-material cantilever (top view)

Figure 61. Bi-material cantilever fabrication process

(a) Pure Ag

(b) Ag:TiO₂ = 6:4

(c) Ag:TiO₂ = 2:8

(d) Pure TiO₂

Figure 62. Cross-sectional SIM images of cantilevers with different material compositions

Figure 61 shows the fabrication process for a bi-material cantilever consisting of silver and titanium oxide. The substrate was first coated with a polymer. A cantilever-shaped pocket was milled in the polymer using a focused ion beam (FIB). The first material (silver) was printed and planarized via aerodynamically focused nanoparticle (AFN) printing. A second pocket was then milled into the silver using a FIB. The second material (titanium oxide) was printed via AFN printing. After polymer etching, the overall structure was finished in more detail, with further milling.

Figure 62 shows cross-sectional SIM images of four fabricated cantilevers: a pure Ag cantilever, a 60% Ag and 40% TiO₂ cantilever, a 20% Ag and 80% TiO₂ cantilever, and a pure TiO₂ cantilever. The cross-sectional shapes varied slightly among the cantilever samples, because ion beam milling of the polymer was not stabilized.

Nevertheless, different material compositions are evident in the images. The cross-section of silver is more porous, because the size of silver nanoparticles is much larger than those of titanium oxide. Moreover, because silver is softer and more ductile than titanium oxide, the processing rate for ion beam milling is much higher. Hence, the roughness of the cross-section is lower in silver than in titanium oxide. As such, it was expected that the four different cantilever samples would show different mechanical and thermal behaviors with respect to their material compositions.

6.2. Mechanical properties

The mechanical properties of the fabricated cantilevers were evaluated with respect to their thermal actuation mechanism. Because the structure was too small to apply conventional test methods, *e.g.*, indentation, a new *in-situ* measurement set-up was constructed, as shown in **Figure 63**. A micro-gripper (FT-G102, Femto Tools Ag, Switzerland) equipped with a microforce sensor was installed on a nano-manipulator (SLC1730, customized axes, SmarAct GmbH, Germany) to measure the gripping force. Nano-manipulators were controlled using a modular controller (MCS-6C-IDESH, SmarAct GmbH, Germany). All behaviors were observed via *in-situ* ion-beam scanning.

The right side of **Figure 63** shows the micro-gripper and cantilever structure inside the ion beam chamber. Because the force sensor was installed only on the fixing hand in the horizontal direction, the cantilever was pushed in the horizontal direction, as the gripping hand moved away from the fixing hand.

Figure 63. Hardware configuration for *in-situ* measurement of micro/nano-mechanical properties

Figure 64. Cantilever displacement as a function of the time step

Figure 65. Force as a function of cantilever displacement over three trials

The travel length was 3 μm , and the velocity was 100 nm/s. **Figure 64** shows the displacement of the cantilever with respect to the time step. To set the origin, the gripping hand approached the cantilever in the horizontal direction, until the repulsive force could no longer be measured. The travel length was determined by the thermal deflection calculated in the former section.

Figure 65 shows measured force profiles of the silver–titanium oxide cantilever with respect to its displacement over three trials. The force profile was linear and consistent over the three trials, indicating that the deformation of the cantilever was elastic. Other cantilevers with different material compositions showed similar results (**Figure 65**).

Using beam deflection theory, the elastic modulus of a beam can be calculated from the measured force profile, as follows (**Equation 5-Equation 6**) [108]:

$$\delta = \frac{FL_1^2(3L - L_1)}{6EI} \quad \text{Equation 5}$$

with

$$E = \frac{ab^3}{12} \quad \text{Equation 6}$$

where P is the force applied to the cantilever, L is the length of the cantilever, L_1 is the length from the anchor to the position where the force is applied, a is the height of the cantilever, b is the width of the cantilever, and I is the moment of inertia of the cantilever. **Figure 66** provides a geometric description of the beam deflection parameters. The maximum deflection of the tool tip can be calculated using the moment of inertia and the beam geometry.

Figure 66. Geometric notations for beam deflection theory

Figure 67 shows the calculated elastic modulus of various cantilevers, in terms of the volume fraction of titanium oxide material. The pure silver beam showed a slightly smaller elastic modulus than the pure titanium oxide beam, and beams with multi-material composition showed intermediate values. The intermediate value trend follows the rule of mixtures, a simple assumption used to estimate the macroscopic properties of composite materials [109]. Because the cantilevers consisted of two different materials, the measured mechanical properties are intermediate in value between the material properties of the individual bulk samples. In this study, the cantilever was assumed to be one material, and the elastic modulus was calculated using this simple model.

Using the rule of mixtures, the mechanical properties of the composite material can be predicted using the *Voigt* model (Equation 7) [110] and the *Reuss* model (Equation 8) [111].

$$E_c = f E_f + (1 - f) E_m \quad \text{Equation 7}$$

and

$$E_c = \left(\frac{f}{E_f} + \frac{1-f}{E_m} \right)^{-1} \quad \text{Equation 8}$$

with

$$f = \frac{V_f}{V_f + V_m} \quad \text{Equation 9}$$

where E_c , E_f , and E_m are the elastic moduli of the composite, fibers, and matrix, respectively, and V_f and V_m are the volume fraction of the fibers and matrix, respectively.

These two models provide the means to predict the properties of composite materials. The *Voigt* model assumes that the strain of the fibers is equal to the strain of the matrix material, and the *Reuss* model assumes that the stress of the fibers is equal to the stress of the matrix material.

Because the beam is pushed in the horizontal direction, and not along the direction of the beam length, these assumptions are not perfectly suited. However, as shown in **Figure 67**, our results are in good agreement with the *Voigt* and *Reuss* models; this implies that the behavior of the composite material can be effectively predicted using the measured mechanical properties of the pure-material beam.

Figure 67. Calculated elastic modulus of various bi-material cantilevers in terms of the volume fraction of TiO_2 material

On the other hand, the fabricated beams showed smaller values than those associated with the bulk properties, in which the elastic modulus of bulk silver and titanium oxide are ~ 83 GPa and ~ 283 GPa, respectively. However, measured elastic modulus was about 1.17 GPa (for silver) and 2.03 GPa (for titanium oxide), respectively. They accounted about 2.46% and 0.59% of bulk material properties, respectively.

The discrepancy was attributed to the AFN printing process, in which nanoparticles were used to form the cantilever structure. Weak mechanical properties fabricated using nanoparticle printing techniques have been a main aspect, even in field of the inkjet printing [112] or selective laser sintering processes [113]. Mechanical and electrical properties of printed structures have been widely investigated [114], as well as the properties of conventional 3D printed structure at

the macroscale.

Previous studies on the mechanical properties of structures created using a nanoparticle deposition system (NPD) showed similar results, but slightly lower values. Lee *et al.* fabricated a silver pillar using AFN printing and a FIB system [115]; compression tests revealed an elastic modulus of 0.420 GPa for the silver pillar. Choi *et al.* printed a titanium oxide film on fluorine-doped tin oxide (FTO)-glass using an NPD system, and performed indentation tests [116]; an elastic modulus of 1.70 GPa was measured in this case. These values are both smaller than the measured values shown in **Figure 67**, but are of the same order.

Weak mechanical properties can be a critical defect in practical applications; thus, numerous investigations have focused on mechanical properties in an effort to improve the performance of materials. A previous study [116] investigated the effect of laser-assisted deposition of a titanium oxide film on the elastic modulus of the film; the elastic modulus of the film improved from 1.703 to 5.134 GPa. Sintering is widely used as a post-processing treatment in nanoparticle printing [117, 118]. By applying the heat, nanoparticles stick together and contract, and then mechanical properties can be improved. The effect of thermal treatment is discussed in the next section.

6.3. Thermal behaviors

Figure 68. Hardware configuration of the *in-situ* heater system

In addition to the mechanical properties, the thermal properties of the cantilever samples were examined. For the observations, a ceramic heater was installed in the vacuum chamber. **Figure 68** shows the hardware configuration of the *in-situ* heating system. The heater was designed to be heated to 600 °C (within 1%). The heating block was mounted on a cooling block that was connected to coolant lines.

Figure 69. Temperature profile of heating/cooling cycles.

1. Room temperature state, 2. First heating run (to 300 °C), 3. First cooling run (100 °C), 4. Second heating run (300 °C), and so on.

Figure 69 shows the applied temperature profile. Because the chamber was kept under high-vacuum conditions, it took more time for cooling than heating. The maximum heating temperature was 300 °C, and the cooling temperature was set to 100 °C. Temperatures exceeding 500 °C may result in outgassing of the chamber components [0], and cooling to temperatures below 100 °C required too much time.

In the heating process, the sample was heated from room temperature to 300 °C (1 → 2), which was followed by a decrease in the sample temperature from 300 °C to 100 °C (2 → 3). After one cycle of heating and cooling, the cycles were repeated within the same temperature range from 100 °C to 300 °C (3 → 4, and so on). *In-situ* heater installation allowed the sample deflection to be observed in real time via SIM images. With respect to the temperature, states of cantilever beams were observed in real time.

(a) Room temperature (20 °C)

(b) Heating state (300 °C) – 1st cycle

(c) Cooling state (100 °C) – 1st cycle

(d) Heating state (300 °C) – 2nd cycle

Figure 70. Thermal behavior of the silver/titanium oxide composite beam

Figure 70 shows the thermal behavior of the silver/titanium oxide beam. In its initial state, the beam retained its original configuration at room temperature (20 °C). As the beam was heated, it began to bend towards the metal (**Figure 70(b)**). This behavior is counterintuitive, because the thermal expansion coefficients are generally much bigger for metals than ceramic materials.

The beam bending behavior and contraction of silver has been attributed to low-temperature sintering. Moon *et al.* investigated the thermal behavior of silver nanoparticles (size: <20 nm), and revealed that shrinkage of the silver nanoparticles occurred over the temperature range of 150–250 °C [120]. On the other hand, Auyeung *et al.* investigated the effect of laser decal transfer to micro cantilevers, and they found that mass deduction of micro cantilevers occurs after curing at 200–400 °C [121].

When the composite beam was cooled after the first heating run, the beam bent towards the metal, due to thermal contraction (**Figure 70(c)**). After one heating and cooling cycle, the beam bent back towards the ceramic when heated, as intuitively expected (**Figure 70(d)**).

The most basic conclusion from these results is that the composite structure needs at least one heating-cooling cycle before initiating thermal microactuator operation. After one cycle of heating to temperatures of at least 250 °C, the silver nanoparticles are mostly sintered and they then behave as expected. Additionally, one can conclude that the structure fabricated by the hybrid process can be deformed after fabrication using thermal treatments. Moreover, the deformation is controllable with material composition and geometry. Thus, this result suggests the plausibility of micro/nanoscale four-dimensional (4D) printing applications [122].

At the last, this *in-situ* experiments with a heater let us know how much the temperature is required to influence on the shape or mechanical properties. Data from experimental sets can be applied both to computational analysis and practical applications.

(a) Room temperature (20 °C)

(b) Heating state (300 °C) – 1st cycle

(c) Cooling state (100 °C) – 1st cycle

(d) Heating state (300 °C) – 2nd cycle

Figure 71. Thermal deflection of a pure silver beam.

(a) Room temperature (20 °C)

(b) Heating state (300 °C) – 1st cycle

(c) Cooling state (100 °C) – 1st cycle

(d) Heating state (300 °C) – 2nd cycle

Figure 72. Thermal deflection of a pure titanium oxide beam

Figure 73. Comparison of elastic modulus before and after heating

To strengthen the assumptions above, the thermal behavior of pure material beams was also examined in an attempt to elucidate the behavior of the composite beam.

Figure 71 shows the thermal behavior of a pure silver beam. The same temperature profile was applied. As expected, the silver material contracted when heated for the first time (first cycle) (**Figure 71(b)**), and then contracted more when cooled (**Figure 71(c)**). After one cycle of heating and cooling, however, the pure silver beam showed conventional thermal expansion properties (**Figure 71(d)**).

Figure 72 shows the thermal behavior of the pure titanium oxide beam. The pure titanium oxide beam deflected slightly when heated, but then showed negligible deflection during cooling and subsequent heating for a second time.

The mechanical properties were measured again after the heating experiments. **Figure 73** shows the elastic modulus before and after heating. Even after heating, the pure silver beam showed a smaller elastic modulus value than the titanium oxide beam, and the composite beam showed an intermediate value, in accordance with the rule of mixtures. The remarkable point here is the increase in the elastic modulus, particularly with respect to titanium oxide.

It is thought to be the strengthening effect in silver came out as losing volume of the cantilever. However, more detail investigation is essential for further analysis. Mechanical properties of printed structures have been main interests in various engineering applications [123].

It is expected that *in-situ* observation of thermal behaviors would contribute significantly to material research in the area of nanoparticles or micro/nanoscale structures, *e.g.*, the minimum temperature of laser-assisted nanoparticle printing.

Chapter 7.

Summary and conclusion

The purpose of this study was to develop a novel, nanoscale 3D structuring method that combines the advantages of different fabrication technologies. Particularly with respect to direct beam writing and patterning methods, the aim was to develop a 3D printing process with multi-material capabilities and nanoscale resolution.

To this end, an integrated NPDS/FIB hybrid process had been proposed. However, the suggested process has several drawbacks in terms of surface roughness and controllability, as well as a lack of sacrificial layers and irregular processing scales.

Hence, in this dissertation, a novel hybrid process is suggested that integrates an AFN printing system, micro-machining, an FIB system, and polymer spin-coating processes. Each process was investigated separately and as an integral component of the hybrid process.

For the AFN printing system, the surface morphology of the sample-detached substrate was observed, and the bonding mechanism was investigated. Based on an examination of the bonding mechanism, a novel printing strategy was suggested for small feature printing that narrows the printing scale. For the micro-machining system, different tool geometries were investigated and evaluated. From the experimental results, a specific lattice pattern was implemented for the micro-tool. A novel path generation strategy was suggested and evaluated for the FIB system, in terms of its processing performance.

After integrating and bridging these different processes, the process capabilities were evaluated using several fabrication examples. Nanoscale multi-material 3D printing was implemented, and several functional printing examples were demonstrated. Through the development of a novel printing system, it is expected that the system would contribute significantly to customized nanoscale structuring techniques.

As a functional application, bi-material cantilevers were fabricated as thermal microactuators. Due to the small size of the fabricated structures, an *in-situ* measurement set-up was constructed to investigate the mechanical and thermal behaviors. During the measurement, cantilevers showed irregular thermal behavior. Contraction of the cantilevers at certain temperatures was attributed to low-temperature sintering.

This dissertation contributes to material research from many perspectives. Meaningful results and discussions were derived from the research. First, nanoscale 3D printing was implemented with multi-material capabilities. The developed process can be used to fabricate 3D structures of varying complexity (*e.g.*, undercuts or freeform structures), using metal, ceramic, and polymer materials. Features can be fabricated on hard, flexible, or even curved substrates, without heat treatment. Various structures were demonstrated in this dissertation.

Second, the process of ‘bridging’ different fabrication methods extended beyond the existing limitations of individual processes. Each process was investigated and improved, in an attempt to optimize the proposed hybrid, nanoscale 3D printing process.

From this investigation, thermal microactuators were fabricated and evaluated. The thermal actuation mechanism has remarkable benefits regarding *in-situ* observation of changes in the material, because other microactuation mechanisms are influenced by electron- or ion-beam scanning. Moreover, the developed process using thermal microactuators fully meets the requirements for conventional

technologies, with applicability to a wide selection of inorganic materials.

Because the characteristics of printed microstructures differ from those of conventional bulk structures, *in-situ* investigation of the mechanical and thermal behaviors is expected to contribute to improving material properties and advancing micro/nanoscale applications. In particular, the thermal behavior of microstructures can be used to develop new fabrication/assembly techniques, such as 4D printing.

Moreover, by bridging different fabrication processes, the processing capabilities can be enhanced significantly beyond that of the individual processes. Thus, bridging requires higher processing knowledge than the sum of the knowledge required for the single process operations individually, given that the hybrid process creates synergy in process performance, processing rate, and even in processing costs.

The demand for manufacturing-as-a-service has prompted the bridging and integration of different manufacturing processes for improved performance and efficiency. Thus, manufacturing technologies are expected to be applied with a wider definition of hybrid processes in the future.

Appendix

Web-based CAD/CAM service

In addition to process integration, computer-aided design/manufacturing (CAD/CAM) software was also implemented. **Figure 74** shows a schematic diagram of the proposed CAD/CAM system. Because the process consists of four different processes, process planning can differ depending on the designer and/or the operator's proficiency. Hence, in the CAD/CAM S/W, the designer was responsible for the design process.

First of all, users design the part based on pre-determined fabrication sets. Using the designed part, process planning can be generated following the design tree. Generated process planning can also be adjusted by the process operators. During the design stage, design for manufacturing rules are automatically checked using the existing database. **Table 8** shows selected DFM rules for the CAD/CAM S/W. It is designed to offer advices on material compatibilities and process parameters.

To assist with the design and manufacturing of the developed process, a CAD/CAM system was designed and implemented as a web-based software. S/W was implemented with the help of Prof. Kunwoo Lee's Lab, and was implemented on the Web: <http://hccl.snu.ac.kr/webcad>.

Figure 75 shows the user interface of the Web-based CAD/CAM system. Using user interfaces (UIs), the NPDS (or AFN printing) and FIB system can be processed with pre-determined part graphics. The geometrical configuration and process planning can be exported and transferred to the process operators. Several examples shown in this dissertations are offered.

Figure 74. S/W schematic of the developed CAD/CAM system [124]

Table 8. Selected DFM rules for the CAD/CAM software [124]

DFM rules	Contents
Material compatibility	Check compatibility of the bottom and current layer material
	Check height limitations of the micro-machining
Process knowledge	Check printing scale of the NPDS processes
	Check limitations of the aspect ratio of the FIB milling process

Figure 75. User interface (UI) of the Web-based CAD/CAM system

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요 약

본 연구에서는 새로운 나노스케일 3차원 프린팅 공정, 특히 다종재료를 $1\ \mu\text{m}$ 이하의 정밀도로 인쇄할 수 있는 공정을 개발하였다. 기존의 마이크로/나노스케일 3차원 공정들은 재료의 선택성, 공정의 정밀도, 기하의 자유도 측면에서 다소 한계를 가졌으며, 이러한 한계를 극복하고자 나노입자적층시스템(nanoparticle deposition system, NPDS)과 집속이온빔(focused ion beam, FIB)의 융합공정이 제안된 바 있다. 그러나 기 공정은 희생층의 부재, 공정 크기의 부적합 등과 더불어 특히 적층된 층의 두께와 표면에 제어되지 않는다는 단점을 가지고 있었다.

따라서 본 논문에서는 AFN (aerodynamically focused nanoparticle) printing 시스템, 평탄화를 위한 마이크로 가공(micro-machining) 시스템, 집속이온빔(FIB) 시스템, 그리고 희생층을 위한 스핀 코팅(spin-coating) 시스템을 융합함으로써 새로운 공정을 제안하였으며, 서로 다른 공정을 융합함으로써 기존 공정이 가지고 있던 한계를 해결할 수 있었다.

공정 융합을 위하여, 우선 각각의 공정에서 이론과 실험을 통하여 최적화가 진행되었다. AFN printing 공정에서는 인쇄된 시편을 탈착 후 기판 표면을 관찰함으로써 적층 메커니즘을 분석하였고, 그 결과로부터 보다 작은 구조물의 적층을 위한 새로운 인쇄 기법이 제안되었다. 마이크로 가공 공정에서는 다양한 형상의 마이크로 공구가 설계, 제작되었으며, 특히 적층된 구조물의 평탄화에 미치는 영향을 분석하였다. 집속이온빔 공정에서는 재료 재증착 현상을 최소화 하기 위하여 새로운 경로 생성 전략이 제안되었고, 정밀도에 미치는 영향을 분석하였다.

마이크로/나노스케일에서 금속(Ag, Sn 등)과 세라믹 재료(BaTiO_3 , TiO_2 등)를 이용한 다양한 예시를 제작함으로써, 공정 능력을 평가하였다. 기타 마이크로/나노스케일 공정들과 비교하였을 때, 새롭게 개발된 공정은 기존 공정의 장점을 잃지 않으면서 재료의 정밀도, 기하의 자유도 등에서 명확하게 발전된 성능을 보여주었다.

실질적인 응용안으로서 금속/세라믹 재료로 구성된 외팔보를 열 구동기 용도로 제작하였으며, 기계적/열적 물성을 평가하였다. 3차원 프린팅 공정을 통하여 제작된 마이크로 외팔보는 일반적인 재료와 다른 열적 특성을 보여주었으며, 분석 결과는 앞으로 마이크로 구조물의 기계적/열적 특성 연구에 많이 기여할 것으로 기대된다.

본 연구에서는 다양한 금속/세라믹/폴리머 재료를 이용할 수 있는 나노스케일 3차원 프린팅 공정을 개발하고 그 응용안을 보였으며, 특히 서로 다른 공정들을 융합함으로써 전혀 새로운 공정 능력을 개발할 수 있음을 보였다. 개발된 시스템은 특히 의료분야와 같이 특정화 된 형상을 필요로 하는 나노 생산 분야에 크게 기여할 것으로 기대되며, 아울러 융합을 통한 새로운 공정의 개발 과정과 결과는 미래 제조 고려 설계 (design for manufacturing, DFM)에서 설계 제조 고려(manufacturing for design, MFD)로의 생산 관점 변화에 기여할 것으로 기대된다.

주요어 : 3차원 프린팅, 나노 공정, 다종 재료, 마이크로 구조, 융합 공정, 쾌속 조형

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