50 nm Scale Alignment Method for Hybrid Manufacturing Processes for Full 3D Structuring

Ki-Hwan Jang¹ · Hae-Sung Yoon³ · Hyun-Taek Lee^{1,4} · Eunseob Kim¹ · Sung-Hoon Ahn^{1,2}

Received: 4 June 2019 / Revised: 23 August 2020 / Accepted: 30 August 2020 / Published online: 26 October 2020
© The Author(s) 2020

Abstract

In micro-/nano-scale, multi-material three-dimensional (3D), structuring has been a major research area for making various applications. To overcome dimensional and material limitations, several hybrid processes have been proposed. The hybrid processes were performed in the same or different numerically controlled stages. If the stages differed, the substrate was moved and locked to the stage before fabrication. During the locking, alignment error occurred. This error became problematic because this significantly compromised the quality of final structures. Here, an alignment method for a hybrid process consisted of a focused ion beam milling, aerodynamically focused nanoparticle printing, and micro-machining was developed. Two sets of collinear marks were placed at the edges of the substrate. Rotational and translational errors were calculated and compensated using the marks. Processes having different scales were bridged through this alignment method. Various materials were utilized, and accuracy was less than 50 nm when the length of the substrate was less than 13 mm. The alignment method was employed to fabricate a V-shaped structure and step-shaped structure using polymer, ceramic, and metal.

Keywords Alignment method · Hybrid process · Focused ion beam · AFN printing · 3D structuring

Abbreviations

MEMS/NEMS	Micro-/nano-electromechanical system
FIB	Focused ion beam
AFN printing	Aerodynamically focused nanoparticles printing
SIM image	Scanning ion microscopy image

1 Introduction

For functional and feasible applications, micro-/nano-scale multi-material three-dimensional (3D) structuring has been mainly studied in recent years. Micro-/nano-scale structuring has long been implemented using technologies such

as micro-/nano-scale electromechanical systems (MEMS/NEMS), photolithography, and imprinting [1]. The feature size has decreased over time, and structures on scales of tens of nanometers can now be fabricated [2]. However, such structures are of low aspect ratio and limited functionality because the fabrication process is a layer-by-layer technique. Recently, several studies have reported complex full 3D structuring on micro-/nano-scales [3, 4] using two-photon lithography [5], FIB-chemical vapor deposition, and electrospinning. However, structure functionalities are limited because only a single, or a few, materials are used. Many studies have sought to create complex, multi-material, full 3D structures [6, 7]. MEMS/NEMS fabrication processes that do not exhibit unexpected chemical reactions during masking and etching, and hybrid processes (the use of two or more processes simultaneously or sequentially) have been explored. Novel nanoscale fabrication methods have also been suggested [8, 9]. These consist of AFN printing, micro-machining, and FIB milling processes. AFN printing was originally developed using nano-particle deposition [10, 11], and focused particles can make 10 μm order of primary structures with low precision [12]. The mechanical micro-machining process flattens surfaces of the deposition layers. FIB milling with the aid of a five-axis stage generates patterns in 3D shapes. Such processes repeat to fabricate full

✉ Sung-Hoon Ahn
ahnsh@snu.ac.kr

¹ Department of Mechanical and Aerospace Engineering, Seoul National University, Seoul, Korea

² Institute of Advanced Machines and Design, Seoul National University, Seoul, Korea

³ School of Aerospace and Mechanical Engineering, Korea Aerospace University, Seoul, Korea

⁴ Department of Mechanical Engineering, Inha University, Incheon, Korea

3D structures. It has advantages of saving time and money compared to conventional MEMS/NEMS processes. In addition, various materials can be utilized in the process [13, 14] because of their flexibility of materials. However, alignment issues are arisen due to multiple set-up [15]. Those processes proceed in different locations; structures are delivered between processes, and rotational and translational errors are inevitable. The alignment of FIB milling in the chamber is essential as this determined the final structural accuracy. Both rotational and transitional errors have to be considered during repeat FIB milling. Alignment issues are not confined to this hybrid method; all methods featuring processing in different locations exhibit the same alignment issue.

Certain obstacles have to be overcome when seeking to achieve precise alignment. Firstly, the regions around the processing areas are fully or partially covered during AFN printing. The width scale of such printing is from tens to hundreds of micrometers, thus usually much larger than the width scale of a FIB. Therefore, the marks in the processing area are covered during AFN printing, and marks located outside of the processing area are impossible to be detected in FIB imaging. Secondly, alignment during tilting is essential. A five-axis stage tilts the sample when we fabricate complex 3D structures via FIB milling. Lastly, the marks have to be versatile in terms of materials. The marks have to be fabricated using FIB milling to maintain this versatility.

One of the most popular conventional alignment methods is using alignment marks with additional imaging tools. In the past, optical marks were often placed on sample surfaces [16, 17]; most were based on Moiré patterns, had high complexity [18, 19] and were aligned using imaging tools prior to patterning/lithography; the stage did not move. If such methods are applied to hybrid processes, additional imaging tools (e.g., an optical microscope) were required. Also, the alignment in tilted states was impossible; the marks were compressed and useless in tilted states. Another popular method is the origin positioning before processing [20, 21]. A stage is placed at the origin, and alignment employed the origin marks based on hardware settings or location sensor data. After alignment, the stage is moved to the fabrication field, using the compensated inputs. Here, a rotational error and a translational error are affected by stage resolution, precision, and process repeatability. Therefore, errors are relatively large during processes other than FIB milling; the method was inappropriate for hybrid processes. Sensors such as laser vibrometer and capacitor sensors are applied for precise positioning in general [22], but utilizing sensors is hard to apply to hybrid processes where multi-stage and multi-deposition is inevitable.

In this paper, a novel alignment method was developed for hybrid processes. The alignment marks were linear shape and located edges of the substrate. The dimension of the marks was set considering imaging tools in processes. This

method bridged processes in different scales and maintained the versatility of layer materials. Also, the alignment in the tilted state was possible, and achieved alignment precision was less than 50 nm. V-shaped structure and step-shaped structure were fabricated using this alignment method in order to prove the abilities of the alignment method, bridging processes having different scales, the flexibility of materials, and alignment in the tilted state.

2 Novel Alignment Method

2.1 Design of Alignment Marks

Alignment marks were designed and placed for multi-scale processes; FIB milling, AFN printing, and micro-machining. The alignment was required in advance of the FIB milling, AFN printing, and micro-machining processes because each process proceeded on different stages in different places. As imaging methods of alignment, FIB imaging was utilized for FIB milling, and optical imaging was used for AFN printing and micro-machining. The linear shape was chosen to have a length longer than 50 μm , 200 nm width, and 1 μm depth—the dimension of marks was proper for both imaging methods, FIB imaging, and optical imaging. FIB imaging had 2.5 nm resolution. The optical imaging in AFN printing had a resolution for imaging 30 μm of focal point printing radius [9]. The optical imaging in micro-machining had a resolution for imaging 30 μm of tool diameter [9]. As a polished silicon substrate was adopted for the hybrid process, the fabricated marks were distinctively shown among the clean raw-surface area. Compared to FIB imaging, the optical microscope had hundreds of times lower resolution; however, the AFN printing and micro-machining had thousands of times bigger step size of about ten micrometers. Hence, the resolution of the optical microscope was good enough to guarantee the AFN printing and machining of desired regions.

Four linear marks were placed at the edges of substrates fabricated via FIB milling (Fig. 1). Marks x_1 and x_2 were

Fig. 1 Schematic diagram of marks and origin point

laid on line l_x and Marks y_1 and y_2 on the line l_y . The lines l_x and l_y were parallel to the y and x -axes of the stage, respectively, and ran vertically. Origin was the cross point of lines l_x and l_y . Therefore, the origin, mark x_1 , and mark x_2 had the same x -axis coordinate and the origin, mark y_1 , and mark y_2 the same y -axis coordinate. The intervals between collinear marks varied by the dimension of the substrate as the marks were at the edges of the substrates. Generally, the substrates are of the millimeter scale. The intervals are more significant than the length of an AFN-printed layer, which ranges from tens to hundreds of micrometers. The marks remain after AFN printing. Even though FIB milling, AFN printing, and micro-machining had a different scale of features, they consisted of a hybrid system by utilizing the same marks.

2.2 Fabrication of Alignment Mark

Since all marks were fabricated using FIB milling, marks were able to be made on various materials, including polymers, ceramics, and metals. The fabrication of marks maintained the material flexibility of the novel hybrid process. To fabricate marks x_1 and x_2 , proper place at the top edge was chosen, and mark x_1 was fabricated. After

Fig. 2 A aligned mark

Fig. 3 Alignment process for AFN printing and micro-machining

fabrication of mark x_1 , the y -axis of the stage was actuated to move to the bottom edge and mark x_2 was fabricated. Because only y -axis actuation occurred, marks x_1 and x_2 had the same x -axis coordinate. Marks y_1 and y_2 were fabricated in the same way with x -axis actuation. Process time for marks fabrication relied on materials, but less than 90 s were required (Fig. 2).

2.3 Alignment Process

The alignment processes for AFN printing and micro-machining are shown in Fig. 3. The substrate was locked at each stage of the process. During locking, rotational error and translational error were imparted. The rotational error was corrected first. Lines l_x and l_y were thus not parallel to the y and x stage axes. Marks x_1 and x_2 had different x -axis coordinates because of the rotational error. The rotational error was calculated using the difference. First, mark x_2 was captured. A virtual and vertical line that was passing the center of the imaging field was displayed over the in situ image. The center of mark x_2 was located on the line, and the y -axis linear travel was actuated. During the actuation, the x -axis coordinate of the stage was kept in the x -axis coordinate of mark x_2 and thus, the virtual line had the same x -axis coordinate. If the rotational error was negligible, mark x_1 also had the same x -axis coordinate and lay on the vertical line of the imaging field. The delta x , the distance between the center of mark x_1 and the vertical line was measured. When the delta x was bigger than half of the field of view, the delta x was measured using position information provided by the stage. On the other hand, when the delta x was shorter than half of the field of view, the delta x was calculated precisely by measuring the distance from the virtual and vertical line to the mark. The delta x meant the x -axis coordinate difference of mark x_1 and x_2 . The interval of marks was determined previously, during fabrication. Therefore, the rotational error was calculated and compensated (Eq. 1). The rotational error was corrected by iterating of compensation until the delta x reached zero.

$$\theta_e = \sin^{-1} \left(\frac{\Delta x}{L} \right) \quad (1)$$

where L : Interval between collinear marks x_1 and x_2 , Δx : x -axis coordinate difference between marks x_1 and x_2 , θ_e : rotational error.

After removing rotational error, the stage of AFN printing, and micro-machining read the coordinates of the marks. The stage was then operated based on these coordinates. Scales of the processes were around tens of micrometers, and more significant than the precision of stage. The translational error of the stage never exceeded this scale. Therefore, there was no alignment problem even if the translational error occurred during x and y axes actuation.

The alignment process for FIB milling is shown in Fig. 4. The alignment process of removing rotational error was proceeded in the same way (Eq. 1). For 3D structuring, FIB milling in tilting state was required. The alignment in the tilting state proceeded in the same way. In the tilting state, the aspect ratio of the observed image was changed. Because marks had a linear shape, only their length or thickness was affected by tilting. Although the observed interval was changed, the real value was already determined during the marks fabrication. The x -axis coordinate difference between marks was kept the same regardless of tilting. Therefore, compensating the rotational error in the tilting state was able to be proceeded using the same alignment process.

Additionally, the alignment process of identification and alignment using the origin were required; high-precision alignment was essential because the resolution of FIB milling was about 50 nm. After removal of rotational error, new patterns were placed via FIB milling on lines l_x and l_y to identify the origin. Mark x_1 was aligned, and the y -axis of the stage was actuated to reach the origin. Even though the translational error of the y -axis was imparted, the same x -axis coordinate with marks x_1 and x_2 was held during actuation. The x -axis coordinate was the same as the coordinate of origin. Therefore, a linear pattern parallel to the y -axis was made on the same x -axis coordinate. This pattern

became part of line l_x because it had the same x -axis coordinate with the marks and origin. The other pattern vertical with the previous pattern was fabricated in the same way with marks y_1 and y_2 , and actuation of the x -axis of the stage. The origin was laid on the intersection of the patterns; origin was identified (Fig. 4). The patterns were of length, width, and depth about 5 μm , about 150 nm, and 750 nm, respectively. The length was set longer than the translational error. The patterns were fabricated using FIB milling, and less than 30 s were required to fabricate the patterns.

The flow chart of the hybrid process, including the alignment method, is shown in Fig. 5. First, the collinear marks were fabricated using one axis actuation (Marks x_1 and x_2 , Marks y_1 and y_2) and FIB milling. The substrate was placed and locked in a stage of AFN printing/micro-machining. A rotational error was compensated, and the AFN printing/micro-machining process proceeded. The substrate was located to the stage for FIB and locked. The rotational error was compensated using collinear marks and one axis actuation. Two linear patterns having the same x -axis and y -axis coordinate with the origin, respectively, were fabricated. Origin was found as the intersection of the two linear patterns. Based on the origin, FIB milling was conducted. By iterating the hybrid processes, a 3D structure was fabricated.

The two-step alignment for FIB milling was adopted to achieve the alignment accuracy of about tens of nanometers by reducing the translational error. Without the two-step alignment, the linear positioning accuracy of stage mainly affected the translational error. A single travel of the FIB stage (UST-5100-SNU; E. Fjeld Company Inc., USA) occurred a sub-micrometer translational error. To overcome the linear positioning accuracy of the stage, the two linear patterns were fabricated while maintaining the single axis coordinate the same. The straightness errors of the axes (CRW3; IKO International Inc., USA) of the FIB stage mainly affected the translational error of the two linear patterns. The straightness errors were less than 2 μm per every 1 m. In the case of substrate having 10 mm, the straightness errors were smaller than 20 nm. Through this

Fig. 4 Alignment process for FIB milling

Fig. 5 Fabrication flow chart of hybrid processes

two-step alignment, the translational error was reduced from sub-micrometer to tens of nanometers.

2.4 Alignment Error

The alignment error of this alignment process was estimated. Alignment error in AFN printing and micro-machining made a negligible effect on the precision of features of the hybrid process. AFN printing and micro-machining had a process scale larger than tens of micrometers, while FIB milling has a resolution around 50 nm. Based on calculations and experiments, the rotational and translational errors of FIB milling were determined, as shown below. As the resolution of FIB imaging (COBRA FIB; Orsay Physics, France) was limited to 2.5 nm, and the stage axes had straightness errors, minimal rotational and translational errors remained after correction. The rotational error reflected the FIB imaging resolution. In the case of a 10 mm length substrate, the interval between collinear marks was 10 mm. Because the FIB has 2.5 nm of imaging resolution, any remaining gaps were less than 2.5 nm, and residual rotational error was thus less than 0.25 μ rad. A sub-micrometer translational error

occurred by the linear positioning accuracy of stage ranged within 0.1% of the length of substrate. The additional rotational error caused during the compensation process was within 0.00025 μ rad and it was negligible.

Translational error during alignment was attributable to straightness errors of the stage axes and the resolution of FIB imaging. When patterning a line, the stage moved on only one axis because the FIB cannot image collinear marks simultaneously. Both the linear shapes patterns and lines l_x and l_y were ideally identified. However, pattern translational error was caused by the straightness errors of the axes (CRW3; IKO International Inc., USA) of the FIB stage (UST-5100-SNU; E. Fjeld Company Inc., USA) (Fig. 6); the errors were up to 2 μ m per every 1 m and the pattern translational error caused by a single axis was thus calculated using Eq. 2. As both the x and y axes featured independent translational errors, the total translational error was calculated using Eq. 3.

$$\delta_1 = L \times e_s \quad (2)$$

Fig. 6 Alignment translational error caused by straightness error of axes

Fig. 7 Alignment error occurred by FIB imaging

$$\delta_2 = \sqrt{2} \times \delta_1 = \sqrt{2} \times L \times e_s \quad (3)$$

where δ_1 : Translational error of patterns in one axis , δ_2 : Translational error of found origin, L : The interval between collinear marks , e_s : Straightness error of axis ($2 \mu\text{m}$ per every 1 m , 2×10^{-6}).

The second significant error was caused during the FIB milling for linear shape patterns and FIB imaging. Linear shape patterns were proceeded using FIB milling. The intersection of patterns identified the origin. Based on the origin, the substrate was aligned using FIB imaging. During these processes, FIB milling having 50 nm precision and FIB imaging having 2.5 nm made alignment error. Therefore, the alignment error caused by FIB milling and imaging was experimentally found. Fabrication of linear patterns and alignment of the origin using patterns were iterated. After alignment, the errors were measured, and the experiment was repeated ten times. The alignment error attributable to the resolution of FIB milling and imaging (Fig. 7) was 13.3 nm. As the two factors, straightness error and resolution of FIB, causing alignment error were independent, the total alignment error was calculated

using Eq. 4. The error was under 50 nm when the substrate length was less than 13 mm.

$$\delta = \sqrt{2} \times L \times e_s + 13.3 \text{ nm} \quad (4)$$

where δ : Total alignment error (aim: less than 50 nm).

3 Results

As discussed in the previous section, the stage was designed to have a straightness error of about $2 \mu\text{m/m}$. Considering the adopted substrates had a size of 10 mm, theoretical straightness error might range up to 20 nm. Therefore, x -coordinate was kept in a range of 20 nm error during y -axis linear travel. The two marks were patterned using linear travels of a single axis. Through the marks, the origin was found, and the positioning error ranged up to 20 nm per each coordinate. Four align marks could still work pretty much well with AFN printing and micro-machining processes, but these new marks could increase alignment accuracy particularly in the FIB process.

To verify the utility and practicality of the proposed method, two featured structures were fabricated using the method. First, a V-shaped structure was created using multi-materials via 3D structuring in the tilted state. Two pockets were crossed at designated heights. Second, a step-shaped structure was fabricated in a layer-by-layer manner. Earlier, the spin coating was incorporated with other processes. Hybrid manufacture used a FIB milling with Ga^+ , an AFN printing [12], a micro-machining [23] with rotational speed (60,000 rpm), and spin coating (ACE-200; DONG AH, Korea).

3.1 Alignment During the Preparation of V-Shaped Structures

V-shaped structures were fabricated using the hybrid method and the proposed alignment tool. Two adjacent V-shaped structures were created in a polymethylmethacrylate (PMMA) (182265-500G; Sigma-Aldrich, USA) layer and filled with silver nanoparticles ($< 100 \text{ nm}$, 576832-5G;

Sigma-Aldrich, USA) and titanium dioxide nanoparticles (< 25 nm, 637254-100G; Sigma Aldrich, USA). The process parameters were described in a recent publication [8]. FIB milling was performed at two different tilts to create the V-shaped structures (Fig. 8). The aligning process was performed before milling to control the location of the cross points. The height of the structure was 3 μm ; The V-shaped structure width was 1 μm , and the tilt angles were 45 and -45° . In total, 120 and 10 s were spent to align and FIB-mill each structure, respectively. The heights of cross points were precisely controlled. The heights were 0 nm, 500 nm,

and 1 μm above the substrate. The V-shaped structures were chosen to calculate the height of cross points more precisely by easily estimating a centreline from their linearly increasing shape when compared to other shapes with the right angle (Fig. 9).

3.2 Alignment During the Preparation of a Step-Shaped Structure

A step-shaped structure was fabricated. The structure had two layers having 1.2 μm thickness, each with V-shaped

Fig. 8 Fabrication flow chart of V-shaped structure

Fig. 9 V-shaped structures (scanning ion microscopy (SIM) image, 30° tilted view)

pockets in different positions. The angle of the sidewall of the pocket was measured as 9 degrees through the experimental results of PMMA milling. The pocket width and the gap between pockets were designed as 1 μm and 200 nm, respectively, for aligning the right side surface of the pockets, so the right side of pockets could be aligned with a continuous surface, while the left side was step-shaped. The materials used were PMMA, silver, and titanium dioxide. The fabrication flow chart is shown in Fig. 10. All processes were repeated in a layer-by-layer manner. Before each iteration, the proposed alignment method was applied to control pocket location via FIB milling. Totals of 120 and 1 s were spent for alignment and FIB milling, respectively (Fig. 11).

4 Discussion

The proposed method has several advantages—first, the method bridges multi-scale processes. The dimension of the marks is designed for different scale imaging tools, FIB imaging, and optical imaging. Also, the alignment marks are located at the edge of the substrate to prevent being damaged during the AFN printing. Because the alignment marks are designed for multi-scale processes and various processes which have different characteristics, this alignment

method is able to be utilized in hybrid processes. Secondly, the method has high flexibility of materials. All marks are fabricated using FIB milling, and FIB imaging and optical imaging are utilized. Because FIB milling, FIB imaging, and optical imaging methods are able to be used with various materials such as polymers, ceramics, and metals, the alignment method could also be used. Thirdly, alignment in tilted states is possible. All marks have a linear shape, and only their lengths change during tilted states. Rotation error compensation and origin identification of origin are able to proceed in tilted states. Lastly, 50 nm scale alignment error is proved by combining calculation results and experimental results. Alignment for FIB milling has 50 nm scale in the case of a substrate shorter than 13 mm.

The two structures, V-shaped and step-shaped, emphasized the utility and potential of the proposed alignment method. As alignment is able to be utilized in tilted states, the hybrid full-3D structures can be fabricated using minimal resources in the absence of design limitations. A tilted pocket was manufactured via FIB milling; this is much simpler than the iterated layer-by-layer process. This simplicity not only can save time and cost but also can keep the surfaces of the structures smooth. The tilted pockets exhibited continuous, and not stepped, surfaces. Tilted pockets fabricated using the conventional MEMS method layer-by-layer

Fig. 10 Fabrication flow chart of step-shaped structure

Fig. 11 Step-shaped structure (SIM image, 30° tilted view)

method had stepped surfaces. Thus, the application of the proposed alignment method to hybrid processes overcomes traditional design limitations. Furthermore, the fabrication of a step-shaped structure shows the advantage of the maskless patterning using FIB. During the step-shaped structure fabrication process, the patterns used for each layer were different, and indeed arbitrary, as FIB milling was employed. Traditionally, each pattern requires an individual mask, increasing costs, and imposing design limitations. Also, the structures show that the proposed alignment method will facilitate many hybrid manufacturing processes.

5 Conclusions

A novel alignment method for hybrid manufacturing, including FIB milling, AFN printing, and micro-machining was described and structures were fabricated using this method. Two pairs of collinear marks were placed at the edges; the origin was identified as the intersection of the two linear patterns fabricated using the marks. The final alignment error reflected errors in axis straightness values and the resolution of FIB milling and imaging. When the area of the printing was less than 13 mm, the last alignment error was less than 50 nm. The proposed alignment method shows the ability to bridge processes on a different scale. Bridging among the FIB milling, AFN printing, and micro-machining process was demonstrated in this paper. The method has the flexibility of materials because it is based on FIB milling, FIB imaging, and optical imaging. The method was worked in tilted states because alignment marks were linear shape. A V-shaped structure and step-shaped structure were fabricated using this alignment method to prove the abilities to bridge processes, the flexibility of materials, and alignment in tilted states.

Through the proposed method, the fabrication of various full 3D structures was achieved. Various hybrid processes were required to overcome the limitations of traditional methods—hybrid processes required methods bridging the multiple processes. The proposed method can be used to combine numerous manufacturing processes fabricating full 3D structures for various applications. However, the alignment quality and versatility of the proposed method requires improvement in terms of mark design and image-based alignment program.

Acknowledgements This research was supported by the National Research Foundation of Korea (NRF) Grant funded by the Korea

Government (MEST) (No. NRF-2018R1A2A1A13078704) and the Basic Research Lab Program through the National Research Foundation of Korea (NRF) funded by the MSIT (2018R1A4A1059976). This work was supported by Inha University Research Grant. The English in this document has been checked by at least two professional editors, both native speakers of English. For a certificate, please see: <http://www.textcheck.com/certificate/PWQA1t>.

Open Access This article is licensed under a Creative Commons Attribution 4.0 International License, which permits use, sharing, adaptation, distribution and reproduction in any medium or format, as long as you give appropriate credit to the original author(s) and the source, provide a link to the Creative Commons licence, and indicate if changes were made. The images or other third party material in this article are included in the article's Creative Commons licence, unless indicated otherwise in a credit line to the material. If material is not included in the article's Creative Commons licence and your intended use is not permitted by statutory regulation or exceeds the permitted use, you will need to obtain permission directly from the copyright holder. To view a copy of this licence, visit <http://creativecommons.org/licenses/by/4.0/>.

References

1. Rajurkar, K. P., Levy, G., Malshe, A., Sundaram, M., McGeough, J., Hu, X., et al. (2006). Micro and nano machining by electro-physical and chemical processes. *CIRP Annals*, 55(2), 643–666.
2. Radosavljevic, M., Dewey, G., Basu, D., Boardman, J., Chu-Kung, B., & Fastenau, J., et al. (2011). Electrostatics improvement in 3-D tri-gate over ultra-thin body planar InGaAs quantum well field effect transistors with high-K gate dielectric and scaled gate-to-drain/gate-to-source separation. In *2011 international electron devices meeting, 2011* (pp. 33.31. 31–33.31. 34): IEEE
3. Vaezi, M., Seitz, H., & Yang, S. (2013). A review on 3D micro-additive manufacturing technologies. *International Journal of Advanced Manufacturing Technology*, 67(5–8), 1721–1754.
4. Shahzad, K., Deckers, J., Kruth, J.-P., & Vleugels, J. (2013). Additive manufacturing of alumina parts by indirect selective laser sintering and post processing. *Journal of Materials Processing Technology*, 213(9), 1484–1494.
5. Power, M., Thompson, A. J., Anastasova, S., & Yang, G. Z. (2018). A monolithic force-sensitive 3D microgripper fabricated on the tip of an optical fiber using 2-photon polymerization. *Small (Weinheim an der Bergstrasse, Germany)*, 14(16), 1703964.
6. Lauwers, B., Klocke, F., Klink, A., Tekkaya, A. E., Neugebauer, R., & McIntosh, D. (2014). Hybrid processes in manufacturing. *CIRP Annals*, 63(2), 561–583.
7. Van Camp, D., Bouquet, J., Qian, J., Vleugels, J., & Lauwers, B. (2018). Investigation on hybrid mechano-electrochemical milling of Ti6Al4V. *Procedia CIRP*, 68, 156–161.
8. Yoon, H.-S., Jang, K.-H., Kim, E., Lee, H.-T., & Ahn, S.-H. (2017). Hybrid 3D printing by bridging micro-/nano- processes. *Journal of Micromechanics and Microengineering*, 27(6), 065006.
9. Ahn, S.-H., Yoon, H.-S., Jang, K.-H., Kim, E.-S., Lee, H.-T., Lee, G.-Y., et al. (2015). Nanoscale 3D printing process using aerodynamically focused nanoparticle (AFN) printing, micro-machining, and focused ion beam (FIB). *CIRP Annals*, 64(1), 523–526.
10. Kim, K., Choi, D., Kim, H., Lee, M., Chu, W., Ahn, S. H., et al. (2018). Investigation of varying particle sizes of dry-deposited

WO₃ particles in relation to performance of electrochromic cell. *International Journal of Precision Engineering and Manufacturing-Green Technology*, 5(3), 409–414.

11. Kim, H., Kim, K., Choi, D., Lee, M., Chu, W. S., Ahn, S. H., et al. (2018). Microstructural control of the electrochromic and ion storage layers on the performance of an electrochromic device fabricated by the kinetic spray technique. *International Journal of Precision Engineering and Manufacturing-Green Technology*, 5(2), 231–238.
12. Lee, G.-Y., Park, J.-I., Kim, C.-S., Yoon, H.-S., Yang, J., & Ahn, S.-H. (2014). Aerodynamically focused nanoparticle (AFN) printing: novel direct printing technique of solvent-free and inorganic nanoparticles. *ACS Applied Materials & Interfaces*, 6(19), 16466–16471.
13. Lee, H. T., Lee, K. I., Jang, K. H., & Ahn, S. H. (2019). Shape memory alloy-based microscale bending actuator fabricated by a focused ion beam chemical vapor deposition (FIB-CVD) gap-filling process. *International Journal of Precision Engineering and Manufacturing*, 21, 491–498.
14. Kim, C.-S., Ahn, S.-H., & Jang, D.-Y. (2012). Developments in micro-/nano-scale fabrication by focused ion beams. *Vacuum*, 86(8), 1014–1035.
15. Jang, K.-H., Lee, H.-T., Kim, C.-S., Chu, W.-S., & Ahn, S.-H. (2014). Alignment algorithm for nano-scale three-dimensional printing system. *Journal of the Korean Society for Precision Engineering*, 31(12), 1101–1106.
16. Chen, D. C. (2012). Portable alignment device for an off-axis parabolic mirror optical axis adjustment. *International Journal of Precision Engineering and Manufacturing*, 13(1), 33–37. <https://doi.org/10.1007/s12541-012-0005-7>.
17. Chen, D.-C. (2013). Optical axis alignment for three-aspherical mirrors system using five parallel laser beams and moiré method. *International Journal of Precision Engineering and Manufacturing*, 14(3), 381–386.
18. Rajshekhar, G., & Rastogi, P. (2012). Fringe analysis: premise and perspectives. *Optics and Lasers in Engineering*, 8(50), 3–10.
19. Wang, C., & Suga, T. (2009). A novel moiré fringe assisted method for nanoprecision alignment in wafer bonding. In *2009 59th electronic components and technology conference*, IEEE (pp. 872–878).
20. Bang, Y.-B., Lee, K.-M., & Oh, S. (2005). 5-axis micro milling machine for machining micro parts. *The International Journal of Advanced Manufacturing Technology*, 25(9–10), 888–894.
21. Lee, K.-I., Lee, J.-C., & Yang, S.-H. (2018). Optimal on-machine measurement of position-independent geometric errors for rotary axes in five-axis machines with a universal head. *International Journal of Precision Engineering and Manufacturing*, 19(4), 545–551. <https://doi.org/10.1007/s12541-018-0066-3>.
22. Huang, S.-C., & Dao, T.-P. (2016). Design and computational optimization of a flexure-based XY positioning platform using FEA-based response surface methodology. *International Journal of Precision Engineering and Manufacturing*, 17(8), 1035–1048. <https://doi.org/10.1007/s12541-016-0126-5>.
23. Bilegt, E., Yoon, H.-S., Lee, H.-T., Kim, E.-S., Kim, C.-S., & Ahn, S.-H. (2016). Design and evaluation of micro-cutting tools for local planarization. *International Journal of Precision Engineering and Manufacturing*, 17(10), 1267–1273.

Publisher's Note Springer Nature remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.

Ki-Hwan Jang He received his Ph.D. in 2020 in the Department of Mechanical and Aerospace Engineering from Seoul National University, Korea. His main research interests are hybrid manufacturing, micro-/nano-fabrication, 3D/4D printing, smart materials, and micro-robotics.

Hae-Sung Yoon He is an assistant professor in the School of Aerospace and Mechanical Engineering at Korea Aerospace University (KAU). He received his B.S. in 2010, and Ph.D. in 2015 (M.S. integrated) all in Mechanical and Aerospace Engineering from Seoul National University, Korea. His main research interests are in hybrid/smart manufacturing, sustainable manufacturing, ultra-precision machining, micro-/nano-fabrication, 3D/4D printing, manufacturing for design, and smart materials.

Hyun-Taek Lee He received his Ph.D. in 2017 in Mechanical and Aerospace Engineering from Seoul National University, Korea. He is currently an assistant professor at Inha University. His research interests are smart materials, micro-/nano-fabrication, micro-robotics, biomedical devices, and design for manufacturing.

Eunseob Kim He received his M.S. in 2016 in Mechanical and Aerospace Engineering from Seoul National University. He is currently a Ph.D. student in the School of Mechanical Engineering at Purdue University. His research interests are micro-/nano-fabrication and smart manufacturing.

Sung-Hoon Ahn He received his Ph.D. degree from Stanford University in 1997. He has been affiliated with UC Berkeley, Gyeongsang National University, University of Washington, and Hyundai WIA Corp. He is currently a full professor in the Department of Mechanical and Aerospace Engineering at Seoul National University. His research interests include smart factory, green manufacturing, soft robotics, 3D printing, composite materials, micro-/nano-fabrication, renewable energy, and appropriate technology.