# RSC Advances

ROYAL SOCIETY OF CHEMISTRY

www.rsc.org/advances

# 3D printed tactile pattern formation on paper with thermal reflow method

Wonjin Jo, Do Hyun Kim, Jeong Sim Lee, Heon Ju Lee, Myoung-Woon Moon*

Institute for Multidisciplinary Convergence of Matter, Korea Institute of Science and Technology, 136-791 Seoul, Republic of Korea

*** Corresponding Author**
Myoung-Woon Moon
Institute for Multidisciplinary Convergence of Matter, Korea Institute of Science and Technology,
136-791 Seoul, Republic of Korea
Phone: +82-02-958-5487
Fax: +82-02-958-5451
E-mail: mwmoon@kist.re.kr

## Abstract

Three-dimensional (3D) printing is an effective technique for creating variable tactile patterns such as braille on the planer cellulose paper for visually impaired persons. In this study, we fabricated printed tactile patterns in a size controllable manner with a fused deposition modeling 3D printer. It was demonstrated that the printed dots was adjusted with the size, thickness, shape as well as interfacial adhesion strength. After the polymeric tactile patterns were formed, the thermal reflow process was conducted on a hot plate as a post-processing step, showing significant improvement in surface smoothness due to the surface tension effect. Furthermore, the interfacial adhesion strength of the printed pattern on cellulose paper was enhanced by tightly bonding on the paper through uniformly reflowing filament melted into cellulose networks after thermal reflow. Compared to punched patterns formed on paper, the printed dots maintained their original shape without any damage caused to the pattern surfaces before or after the tribology test. Therefore, 3D printed tactile pattern with several advantages might be useful in helping visually impaired persons to enhance their sense of touch or to practice tactile recognition.

## Introduction

Tactile patterns have been developed for the location-based guidance and communication of human interaction such as in elevators, paving blocks, paper, and even plastic credit cards. In particular, braille tactile patterns have been considered the written sound for visually impaired people. The braille system was invented by *Louis Braille* using embossed six-dot arrays [1]. By modifying the raised-dot system for soldiers to write and read messages in the dark at night, the six-dot braille method was developed and implemented using a mechanical braille system by the formation of braille dot patterns embossed on paper or an aluminum plate. The six-dot cells are arranged as two columns of three positions, where the combination of raised dots in any of the six positions represents specific letters or numbers. The standard parameters for braille size vary among braille-producing countries, i.e., each dot is 1.5 mm in diameter and 0.6-0.9 mm in height in the USA.

However, it has been considered that it is too difficult to generate braille letters of a desired size or shape for each individual or produce tactile maps with multi-layer thicknesses using mechanical braille devices such as embossers. In particular, for the newly blind or blind children to learn braille, larger or variously sized braille or tactile patterns are desired. The dots are created by punching them on paper, meaning that braille is written back to front and only one font size is available with no difference between titles or texts in paragraph. Therefore, conventional braille devices are limited in the size and thickness of the tactile patterns they produce and even in drawing patterns for certain figures. New techniques have been adopted for the supplementation or replacement of mechanical braille devices [2, 3]. For instance, a direct ink-jet printer using certain materials such as ceramics is utilized to write raised letters or braille dots more efficiently on a hard surface [4]. In addition, direct ink-jet printer can be applied to ceramic wares such as kitchen and washroom wall tiles for navigation in the home or outside. However, it is not easy for the visually impaired to access or own such printing devices because of their higher price and massive size.

Recently, 3D printing has emerged as an additive manufacturing technology for creating sophisticated and custom-made devices or objects with low-cost materials, which can be employed for various applications in both the scientific and engineering fields, such as tissue and scaffold engineering [5-7], microfluidics [8], chemical synthesis [9], architectures, and electronics [10]. Furthermore, this technique is highly promising for forming 3D configurations on desired surfaces, such as braille cells on cellulose paper. The 3D printer enables the generation of unique tactile patterns with defined shapes and sizes from computer-aided design files. Among the several types of printing methods, such as fused deposition modeling (FDM) [11], powder bed and inkjet head [12], selective laser sintering [13], and stereolithography [14], the FDM method has been known to produce relatively hard and thermally stable structures. Even though its spatial resolutions, i.e., a *z*-axis resolution within the range of 100 to 400 microns and an xy-axis resolution within a few hundred microns, are larger than those for other types of printing methods, which can cause undesired surface roughness, the system and materials used in FDM are cost-effective and do not require chemical post-processing steps.

In this work, we fabricated tactile patterns on cellulose paper using a FDM 3D printer by controlling the width or diameter and thickness of the patterns (Fig. 1a). The tactile patterns, 3D raised-dot braille cells, were fabricated on a flat sheet of paper by direct writing using the 3D printer as shown in Fig. 1b. In addition, the 3D printed patterns were further developed through a thermal reflow process to improve their surface adhesion on the paper surface. It was also observed that the rough surfaces of the as-printed tactile patterns due to their relatively low spatial resolution became smooth after thermal reflow via hot-plate annealing. The mechanical durability of the patterns was explored by performing tribology tests to monitor the wear and frictional behavior of the tactile patterns before and after the thermal reflow process, which were compared with that of punched patterns formed on paper using a conventional braille device.

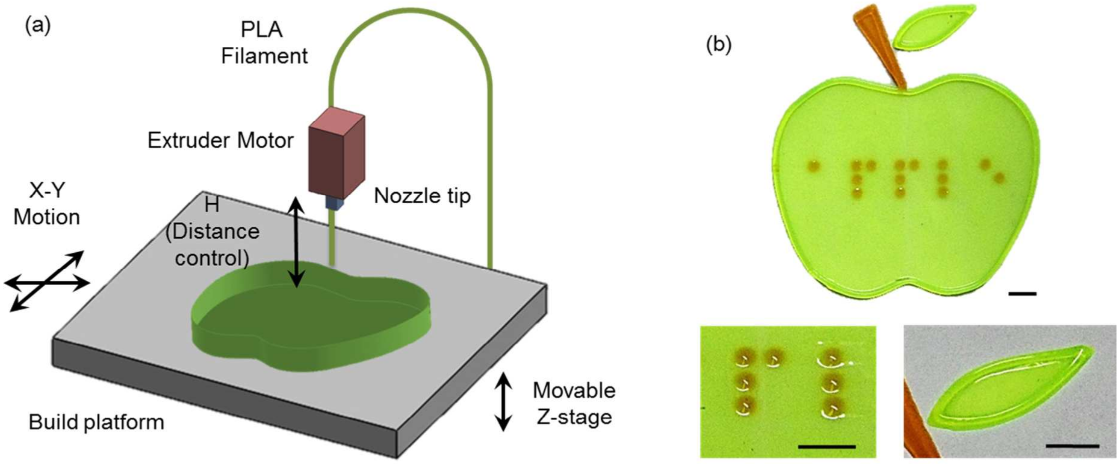


**Figure 1.** (a) A schematic diagram of the FDM system. (b) A graphic type of tactile braille pattern meaning apple printed by the FDM 3D printer. The scale bars are 5 mm.

## 1. Experimental methods

### 1.1. Three-dimensional printing procedures

A commercially available FDM 3D printer (3DISON, ROCKIT, Rep. Korea) was used in all printing experiments. The driven system of the standard FDM printer basically extrudes a thermoplastic filament material through a nozzle directly onto the build platform [11]. The filament was heated and extruded following the programmed path and hardened immediately within 1.8 sec as it touched the substrate [15]. Simple tactile patterns were drawn with computer-aided design software and imported into 3D printing software (CreatorK, ROCKIT, Rep. Korea) to create 2D sliced layers with a programmed slicing algorithm [16]. The nozzle was first moved in the horizontal direction to form the first layer and then moved in the vertical direction for the formation of the next layer. For the braille formation, a sheet of A4 paper composed primarily of cellulose with a density of 80 g/m$^2$ was prepared as the build platform. Parts were built layer by layer, with a layer thickness of 0.3-0.4 mm. The material used in this process was a polylactic acid (PLA) filament as a thermoplastic polymer, which is one of most popular and biocompatible filaments used in the FDM method. After the tactile patterns were formed, the thermal reflow process was employed to thermally anneal the printed patterns on the paper above the PLA filament temperature. Thermal reflow was performed within 1 min at 160 ºC on a hot plate in air.

### 1.2. Characterization

The tactile patterns printed on cellulose paper and the interfaces between the deposited tactile patterns and the paper were observed using a scanning electron microscope (SEM) (Nova NanoSEM 200, FEI). Before SEM observation, an 8-nm-thick Pt film was coated on the substrates to prevent electron charging of the pattern deposited on the paper surface. An electron-accelerating voltage of SEM was 10 kV. The 3D images of the printed patterns were reconstructed using 3D measurement software (Mex 5.1. Alicona) with the acquired SEM images, which were obtained at three different angles, -10º, 0º, and 10º. The cross-sectional line profiles were generated directly on the 3D reconstructed SEM images with the same software. A path was defined on the image and the corresponding line profile was achieved automatically. The frictional behaviors of the patterns were investigated using a homemade ball-on-disc-type wear rig. Steel ball bearing (AISI 52100) with diameter of 6 mm was set to slide over the paper featuring the tactile pattern at a linear speed of 100 mm/s with a rotating radius of 20 mm and a normal load of 5 N, which is relatively higher than the typical pressure exerted by the human finger, 1 N, due to the consideration of a safety factor to account for a certain impact or high friction. The maximum sliding distance used in the tribology test was fixed at 12.5 m, completed over 100 laps. The tribology tests were performed at room temperature with a fixed relative humidity (RH) level of 20-30%.

## 2. Results and discussion

Tactile patterns of different thicknesses along the *z*-axis and width in *xy*-plane were printed on a sheet of paper to study the viability of the FDM printing technique for printing braille patterns. In principle, a mechanical braille printer is only set to produce a standard sized braille dot measuring 1.5 mm × 1.5 mm × 0.7 mm (in USA braille system), which makes it difficult to distinguish between different types of text, such as large titles, body titles, or body text, or to highlight important keywords in a book. In addition, it is known that using large braille or tactile patterns is more effective than using standard-size patterns to teach the newly blind or young blind children braille [17]. The FDM 3D printing method could control the thickness of the tactile patterns on paper by layer-by-layer printing. The thickness was increased with the increase in layer number from 1 to 3 as shown in Fig. 2a, where the thickness was linearly dependent on the deposited layer number. Each layer was printed to be approximately 0.4 mm in thickness.

The printed tactile patterns were prepared with large or small type in proportion to the printing height (H), which was defined as the distance between the nozzle tip and paper surface (Fig. 1a). As shown in Fig. 2b, the width of the patterns increased as the printing height decreased, i.e., when the nozzle tip was close to the paper surface. As the printing height was reduced from 0.32 to 0.14 mm, the extruded filament tended to print larger patterns measuring 1.52 to 2.06 mm, respectively, because of the increase in the driving force of extruding the filament onto the surface. With the combination of both thickness and width control afforded by the 3D printer, braille cells with different heights and diameters could be generated, as presented in Fig. 2c. ‘Size 1’ composed of two layers was fabricated in the standard braille size, whereas ‘Size 2’ composed of four layers was twice as large as the standard size. These results indicate that the FDM printer method can be applied to produce the braille in various sizes and shapes.

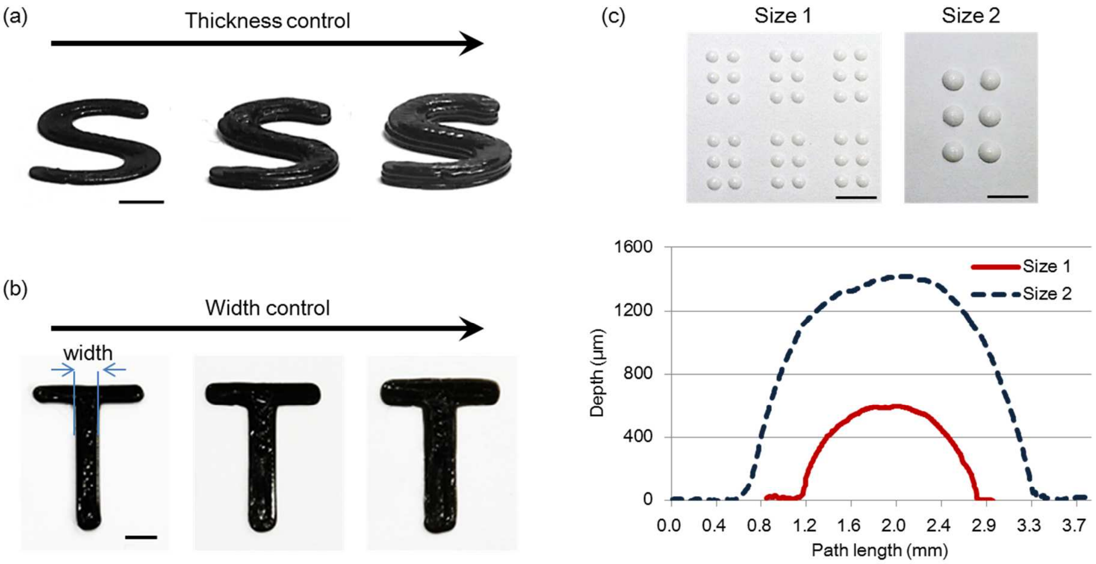


**Figure 2.** The letters 'S' and 'T' formed with (a) various thicknesses using one, two, and three layers from left to right and (b) the various widths of tactile patterns formed by controlling the printer height from 0.32 mm (left) to 0.14 mm (right), respectively. (c) Braille cells with different heights and diameters were generated, resulting in different cross-sectional line profiles. The scale bars are 2 mm for (a) and (b) and 5 mm for (c).

It is known that the FDM printing technique produces undesired surface roughness in micro- or nanoscale because parts are deposited layer by layer to a thickness of a few hundred micrometers. Therefore, a distinct border line between layers at the outer surface (indicated with red arrows) was clearly observed, as shown in the top view of the SEM image in Fig. 3a. In addition, a layer was created by extruding the filament in a laydown pattern; the layer was covered with adjacent lines of filament and often led to ribbing or movement among path lines as indicated by the white dotted arrow in Fig. 3a. In order to render the surface roughness to be smooth, the thermal reflow technique was applied to the pristine tactile patterns formed on paper sheets. Once the temperature approaches the glass transition temperature ($T_g$) of the PLA filament, the viscosity of the polymer is significantly reduced [18]. Above $T_g$, the PLA polymer is melted and reflowed such that a smoother surface is created by surface tension [19]. Upon heating, the molecular chains of the thermoplastic polymer become tangled with each other, which can then be loosened and the thermoplastic material reshaped[20]. Therefore, as extra heat propagates into the layers of the heat-expandable PLA polymer, the rough surface becomes a smooth hemispherical profile. In our study, the optimal temperature for PLA to reflow was above 160 ºC. As shown in Figs. 3a-c, a smooth configuration was achieved by applying a reflow temperature at 160 ºC with a reflow duration of at least 1 min. The paper material was observably durable at this temperature because the ignition temperature of normal cellulose-based paper is 233 ºC [21]. Cross-sectional line mapping confirmed that the transition to a surface smoothness could be controlled by the reflow time. The thermal reflow effect was clearly observed on the top surface of the printed braille dot, demonstrating that the plateau region on the top surface of the tactile pattern (Fig. 3a) was extensively improved to form a smooth, round surface (Fig. 3c). In addition, the border lines (indicated by the red arrow) between printed layers disappeared by reshaping the PLA polymer over the applied reflow time.

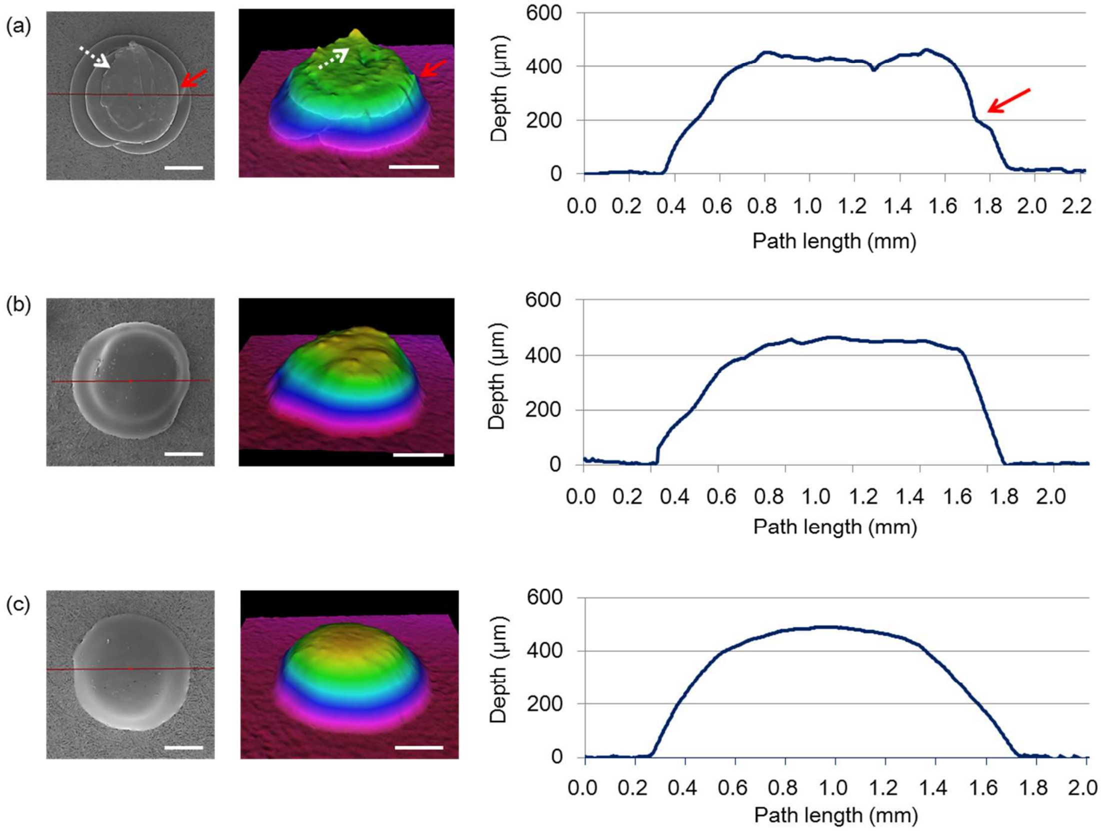


**Figure 3.** Thermal reflow study with a braille dot according to the reflow duration. The pristine rough surface of dot (a) underwent roughness reduction for 30 sec (b) and ultimately formed a smooth hemispherical profile at 160 ºC within 1 min (c). The change in surface smoothness was confirmed by SEM, 3D reconstructed images, and a cross-sectional line profile (through red lines in left SEM images) from left to right. The border line and movement path line are marked as red and white dotted arrows, respectively, in Fig. 1(a). The scale bars are 500 µm.

After thermal reflow, not only was the surface roughness of the printed patterns smoothed but the interfacial adhesion of the PLA filament of the braille dot printed on paper was also significantly improved. The as-printed PLA dots were partially attached to the cellulose fibers composing the sheet of paper due to the rapid solidification of the extruded filament. In addition, gaps were formed in the unconnected areas at the interface between the PLA dot and the paper (see Fig. 4a). Due to the randomized cellulose fibers on the paper, imperfect bonding could support the braille patterns only on the fibers of the top surface of the paper. Therefore, when an external force such as that exerted by a finger is applied on the printed patterns, the interfacial adhesion may not be strong enough to hold the patterns. However, the thermal reflow process allowed the melted PLA to infiltrate the pores between cellulose fiber networks and fill the empty gaps completely, as shown in Fig. 4b, which indicates that the interfacial bonding force between the printed braille dots and the paper surface was enhanced.

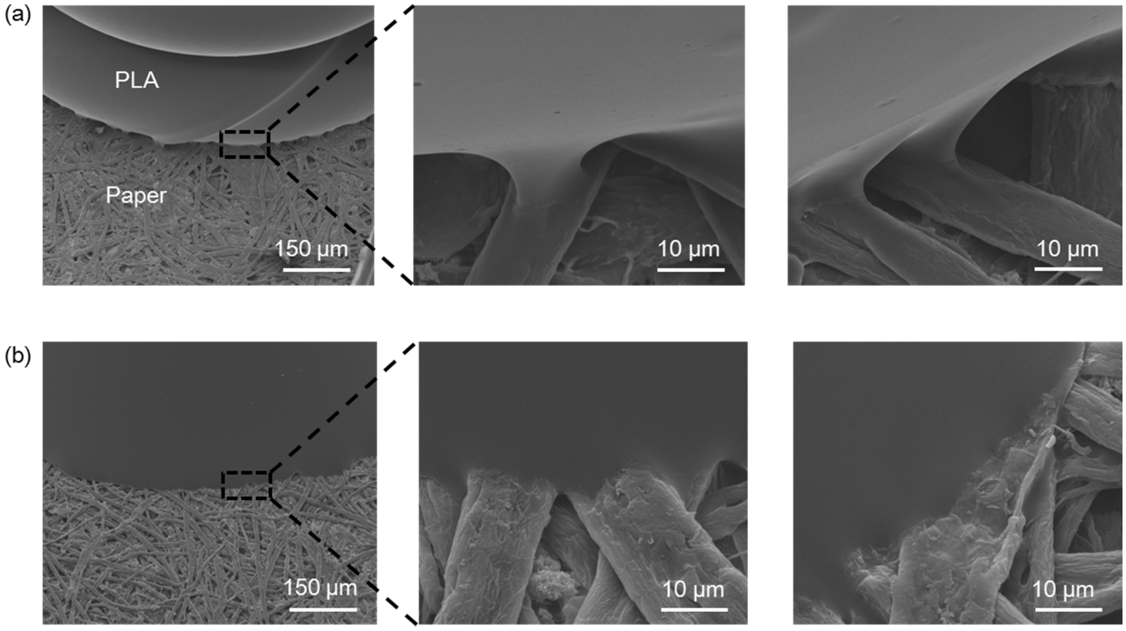


**Figure 4.** SEM images of the interfaces between the tactile pattern and the cellulose fibers of a sheet of paper (a) before and (b) after thermal reflow. The regions indicated in dotted rectangles (left) in (a) and (b) were magnified (right).

The enhancement of the mechanical stability and adhesion strength of the printed patterns was further investigated by tribology testing. The paper surfaces with braille cells were tested before and after the thermal reflow treatment in ambient air. In the case of the as-printed tactile patterns, under an applied force of 5 N with a sliding speed of 100 mm/sec, many braille dots located on the wear track were debonded from the surface as the steel ball bearing slid over them, as shown in Fig. 5a. Because the as-printed braille dots were bonded partially from the cellulose, the size of the contact points was too small to tightly hold the entire large pattern. Therefore, the dot patterns on the wear track were readily pulled out during the tribology test. The weak bonding strength was confirmed by the observation that any residue, such as traces of peeling, did not remain both on the detached spot on the wear track and the bottom of the detached braille dot (Figs. 6a-d). The detailed observation in Figs. 6c-d presents that overall cellulose networks were well connected without torn cellulose fibers at the edge of detached spot on the paper. This is consistent with the results from Fig. 6b showing pressed dents (indicated with a white arrow) formed by cellulose. This is due to the strong contact between the braille dot and the paper by the combined weight of braille dot and pressure pressing down towards the paper. It demonstrates that the braille dot sit on the paper by strong contact rather than tight connection. This result indicated that the as-printed braille dots could be easily detached by frequent touching by a visually impaired person.

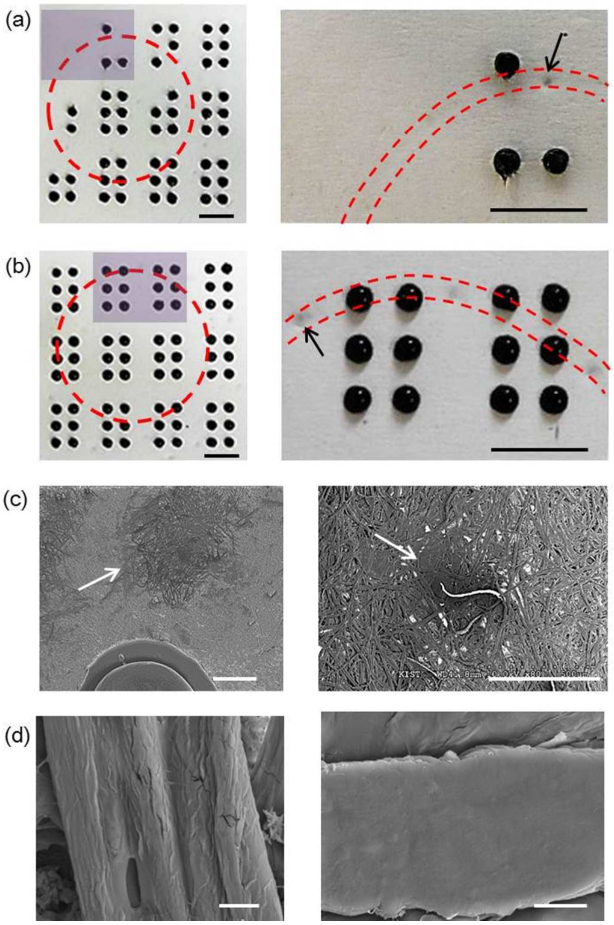


**Figure 5.** Braille patterns (a) before and (b) after the tribology test. Due to the thermal reflow process, the adhesion of tactile pattern was significantly improved. The red dotted circle and black arrow show the trace of the ball movement and the wear mark. (c) SEM images present the damage caused to the cellulose paper by the sliding ball. (d) The distinctive morphology of the pristine cellulose surface (left) was not recognized after the tribology test (right). The scale bars are ((a-b) 5 mm, (c) 500 µm, and (d) 5 µm.

However, after the thermal reflow process, the adhesion strength of the braille dots was increased significantly; indeed, none of the braille cells showed adhesive failure after the tribology test, as indicated in Fig. 5b. Therefore, it is clear that the debonding behavior was greatly dependent on the interfacial adhesion strength between the braille dot and the underlying paper. Microscopic examination of the wear tracks showed that the cellulose paper suffered from severe adhesive wear (Fig. 5c). The surface deformation on the paper occurred along the ball movement path, as indicated in black. Moreover, several deep and rough wear marks were observed due to the strong impact of the sliding ball over the 3D braille dots. Close observation of the area by SEM (Fig. 5d) indicated that, despite the heavy load of the ball on the paper, which crushed the cellulose surface, all braille cells remained intact without any damage on the same wear track. The adhesion enhancement could be attributed to the interdiffusion of melted PLA between cellulose fibers on the paper surface. Upon heating, the loosened PLA molecules can easily move through the randomly tangled cellulose networks since the PLA behaves as a classic flexible-chain polymer [22]. It has been observed that physical bonding by the PLA polymer is affected by elevated temperature via heat dissipation during the thermal reflow process [23]. Under such conditions, the initial interconnecting phase could be thickened and widened due to the thermally activated reactive diffusion of the entire PLA filament in the printed braille dot within 1 min at 160 ºC. To compare the detached area with that of the pristine dot, we intentionally tore a braille dot after thermal reflow process and observed it by SEM. It was revealed that the pristine dot without thermal reflow process had pressed dents by fibers on its bottom surface while no damage was found on its counter surface of cellulose paper, indicating weak adhesion between the polymer dot and cellulose fibers as shown in Figs 6a-d. However, imaging confirmed that presence of cellulose residue on the detached area (Figs. 6e-f), which indicates that the PLA and cellulose were strongly bonded together and that the cellulose itself was torn from the paper (Figs. 6g-h). Therefore, the results demonstrate that high adhesion strength with improved durability was obtained due to the effects of thermal reflow.

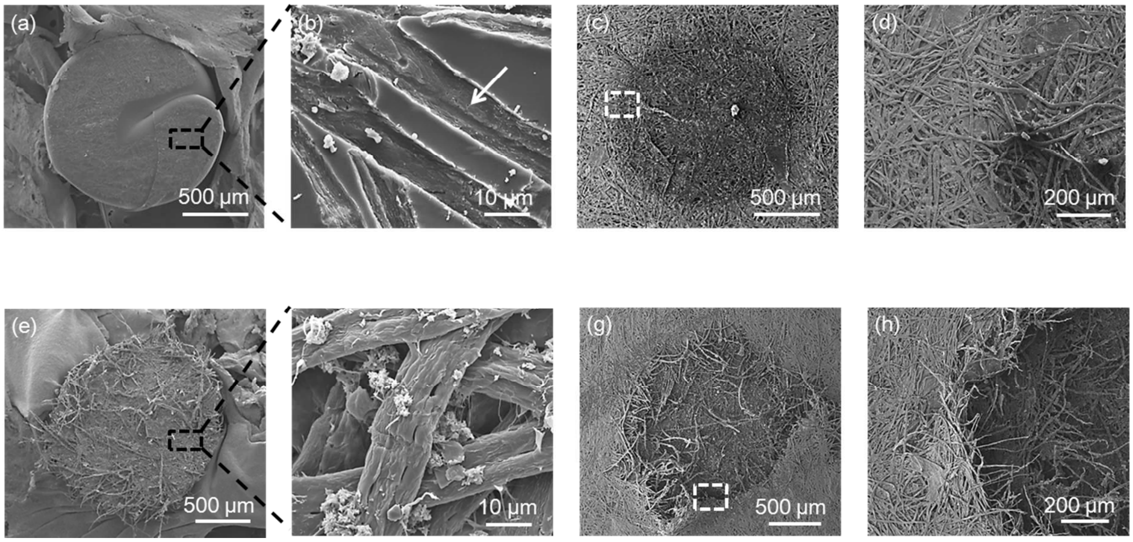


**Figure 6.** SEM images of (a, b) the bottom surface of a detached braille dot and (c,d) its counter surface of cellulose paper before thermal reflow process. A white arrow indicates a pressed dent on dot surface. SEM images of (e,f) a detached dot and (g-h) paper surface after thermal reflow process.

(d) and (h) were taken at the edge of the detached region by magnifying the indicated dotted boxes in (c) and (g), respectively.

The most commonly used braille printing devices create raised dots by punching them on paper; thus, it produces an indentation on the reverse side of a sheet of paper. Therefore, the durability of the shapes formed may be weak under certain pressure. It is confirmed that the braille dot (Fig. 7a) formed on a sheet of cellulose paper by an embosser, a common mechanical braille device, was easily pushed and crushed (Fig. 7b) by a 5 N external force because of the lack support presented by the empty backspace of the paper. The original raised height of the braille cell created by the mechanical braille device was reduced considerably after the tribology test, as indicated by the cross-sectional profile (Fig. 7c). The reduced braille dot morphology may lead to the misreading of letters or numbers, which in turn may confuse visually impaired people in recognizing the meaning of certain braille cells. On the other hand, the patterns formed by the FDM 3D printing method combined with the thermal reflow process maintained their original shape without any damage caused to the pattern surfaces before or after the tribology test, as shown in Figs. 7d-f. Braille is an important tool for exchanging information among the visually impaired and has been extensively used to transfer textural information only. Therefore, precise recognition is the most important factor for braille readers. In this regard, the results are meaningful and promising and indicate that this technique compensates for defects such as distortion or normal wear that may occur in typical braille patterns created using other devices.

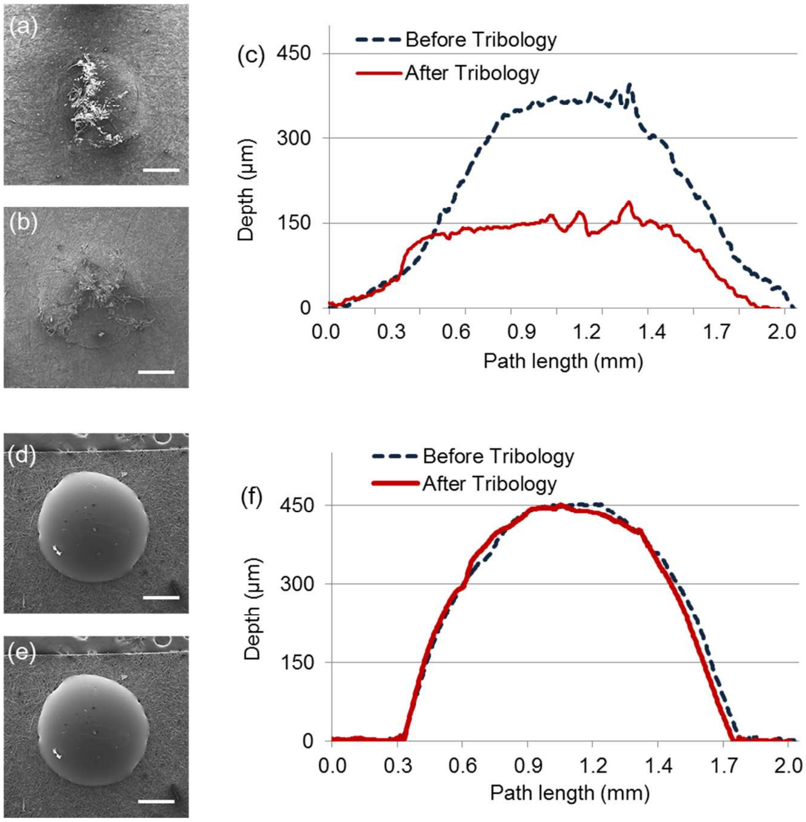


**Figure 7.** SEM images of a braille dot created by an embosser (a) before and (b) after tribology testing. (c) The cross-sectional line mapping shows that the braille dot was crushed by a 5-N external force. Unlike that created by the mechanical braille device, the braille dot printed by the FDM printer remained intact, as confirmed by SEM images ((d) before and (e) after tribology test) and (f) line mapping. The scale bars are 0.5 mm.

## 3. Conclusion

A new method for generating tactile patterns for visually impaired persons by 3D FDM printing was introduced, offering a simple and effective additive manufacturing technology. This method was demonstrated to have several practically useful and powerful properties fulfilling the requirements of tactile pattern fabrication. First, it was possible to easily control the width and thickness of tactile braille patterns of various diameters or raised heights. The 3D printing technique could also be used to draw features on paper, which may help visually impaired people to understand the real shapes of figures. Second, the roughly textured patterns were rendered smooth by the thermal reflow method. It was demonstrated that tactile surfaces with a plateau region on their top surfaces and a rough boarder line between printed layers were extensively improved to form smooth, round surfaces. Third, thermal reflow also significantly enhanced the interfacial adhesion strength of printed patterns, and it allowed the tactile patterns to remain intact against an external friction force. Therefore, the new approach for producing raised or 3D tactile patterns using a 3D FDM printer can provide versatile and cost-effective communication methods that may be easier for visually impaired people to learn braille or various patterns. Our methods will broad applications such as the development of tactual maps and patterning the surfaces of everyday objects such as computer keyboards or even direction boards.

## Acknowledgement

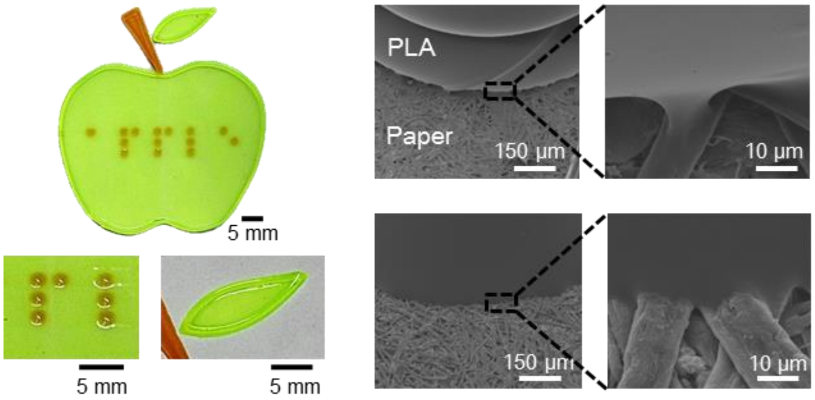
This work was supported by the KIST internal projects.

## Reference

1. J. Jiménez, J. Olea, J. Torres, I. Alonso, D. Harder and K. Fischer, *Surv Ophthalmol*, 2009, **54**, 142-149.
2. K. Itoh, K. Oda, Y. Sudoh and H. Osada, *Technol Disabil*, 1999, **11**, 161-167.
3. Y. Zhang, S. Yang and J. R. G. Evans, *J Am Ceram Soc*, 2004, **87**, 2301-2304.
4. D. McCallum, K. Ahmed, S. Jehoel, S. Dinar and D. Sheldon, *J Eng Design*, 2005, **16**, 525-544.
5. V. Mironov, T. Boland, T. Trusk, G. Forgacs and R. R. Markwald, *Trends Biotechnol*, 2003, **21**, 157-161.
6. B. Leukers, H. Gülkan, S. Irsen, S. Milz, C. Tille, M. Schieker and H. Seitz, *J Mater Sci-Mater Med*, 2005, **16**, 1121-1124.
7. H. Seitz, W. Rieder, S. Irsen, B. Leukers and C. Tille, *J Biomed Mater Res B*, 2005, **74B**, 782-788.
8. P. J. Kitson, M. H. Rosnes, V. Sans, V. Dragone and L. Cronin, *Lab Chip*, 2012, **12**, 3267-3271.
9. M. D. Symes, P. J. Kitson, J. Yan, C. J. Richmond, G. J. T. Cooper, R. W. Bowman, T. Vilbrandt and L. Cronin, *Nat Chem*, 2012, **4**, 349-354.
10. S. J. Leigh, R. J. Bradley, C. P. Purssell, D. R. Billson and D. A. Hutchins, *PLoS ONE*, 2012, **7**, e49365.
11. D. W. Hutmacher, T. Schantz, I. Zein, K. W. Ng, S. H. Teoh and K. C. Tan, *J Biomed Mater Res*, 2001, **55**, 203-216.
12. A. Butscher, M. Bohner, S. Hofmann, L. Gauckler and R. Müller, *Acta Biomater*, 2011, **7**, 907-920.
13. H. K. Seung, P. Heng, P. G. Costas, K. L. Christine, M. J. F. Jean and P. Dimos, *Nanotechnology*, 2007, **18**, 345202.
14. F. P. W. Melchels, J. Feijen and D. W. Grijpma, *Biomaterials*, 2010, **31**, 6121-6130.
15. D. W. Hutmacher, M. Sittinger and M. V. Risbud, *Trends Biotechnol*, 2004, **22**, 354-362.
16. P. M. Pandey, N. V. Reddy and S. G. Dhande, *Rapid prototyping J*, 2003, **9**, 274-288.

17. S. Hara, R. Kawamitsu, K. Kusunoki, H. Sato and M. Fujiyoshi, *Computers Helping People with Special Needs,* Lecture Notes in Computer Science, 2002, **2398**, Springer Berlin Heidelberg, 594-601.
18. A. Emadi, H. Wu, S. Grabarnik, G. d. Graaf and R. F. Wolffenbuttel, *J Micromech Microeng*, 2009, **19**, 074014.
19. Y. Hsiharng, C. Ching-Kong, W. Mau-Kuo and L. Che-Ping, *J Micromech Microeng*, 2004, **14**, 1197-1204.
20. I. Gibson and D. Shi, *Rapid Prototyping J*, 1997, **3**, 129-136.
21. J. Borch, M. B. Lyne, R. E. Mark and C. Habeger, *Handbook of physical testing of paper,* 2001, **2**, CRC Press, 406.
22. D.E. Henton, P. Gruber, J. Lunt and J. Randall, *Polylactic acid technology,* Natural fibres, biopolymers and biocomposites, 2005, CRC Press, 528-568.
23. C. D. Breach and F. Wulff, *Microelectron Reliab*, 2004, **44**, 973-981.

# A table of contents entry



The combination of 3D FDM printing method and thermal reflow technique was applied to fabricate tactile patterns for visually impaired people. The size controllable 3D tactile patterns were significantly improved in surface smoothness and adhesion strength on papers.