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To the Editors

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I would like to thank the reviewer for penetrating comments and suggestions.

The paper has been carefully examined and thoroughly revised in response to the questions raised. Modified parts of the paper for the reviewer's comments are written in red on the marked up manuscript.

I take this opportunity to thank you for your thoughtful handling of this paper and the referee for the review. I will be looking forward to hearing from you in due course.

Thank you for your consideration. I look forward to hearing from you.

Sincerely,

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TITLE:

Study of a Dot-patterning Process on Flexible Materials using Impact Print-Type Hot Embossing Technology

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KEYWORDS:

impact header, hot embossing, imprinting, impact embossing, fine pattern, engrave pattern

SUMMARY:

Impact print-type hot embossing technology uses an impact header to engrave dot patterns on flexible materials in real time. This technology has a control system for controlling the on-off motion and position of the impact header to create dot patterns with various widths and depths on different polymer films.

ABSTRACT:

Here we present our study on an impact print-type hot embossing process which can create dot patterns with various designs, widths, and depths in real time on polymer film. In addition, we implemented a control system for the on-off motion and position of the impact header to engrave different dot patterns. We performed dot patterning on various polymer films, such as polyester (PET) film, polymethyl methacrylate (PMMA) film, and polyvinyl chloride (PVC) film. The dot patterns were measured using a confocal microscope, and we confirmed that the impact print-type hot embossing process produces fewer errors during the dot patterning process. As a result, the impact print-type hot embossing process is found to be suitable for engraving dot patterns on different types of polymer films. In addition, unlike the conventional hot embossing process, this process does not use an embossing stamp. Therefore, the process is simple and can create dot patterns in real time, presenting unique advantages for mass production and small-quantity batch production.

INTRODUCTION:

Researchers are actively attempting to miniaturize existing devices and displays and increase the flexibility of these devices[1,2]. To reduce the width and depth of electrical channels to the micro or nano scale, high-precision technology is necessary. In addition, to increase the flexibility of these devices, the patterns of the electrical channels must be located on a flexible material, such as a polymer film[3,4]. To meet these conditions, the study of ultrafine microprocessing technology is actively underway.

Ultrafine microfabrication technology has an advantage in that possible patterning materials include not only highly rigid materials such as iron or plastic but also soft materials such as polymer films. Due to these advantages, this technology is widely used as a core process in various fields, such as communications, chemistry, optics, aerospace, semiconductor, and sensors[5-7]. In the ultrafine microprocessing field, LIGA (lithography, electroplating, and molding) or micromachining methods are used[8]. However, these conventional methods are associated with several problems. LIGA methods require a considerable amount of time and several process steps to create ultrafine patterns and incur a high cost as well because they need many different types of equipment during the processes. In addition, LIGA methods use chemicals that can pollute the environment.

To address this issue, hot embossing process technology has been spotlighted among ultrafine microprocess technologies. Hot embossing is a technology that creates a pattern on a heated polymer film using a micro- or nanoscale embossing mold. Conventional hot embossing technology is divided into the plate type and roll-to-roll type depending on the shape of the mold. The two types of hot embossing technology are different in terms of the shape of the mold, but these two processes are similar in that the embossing mold presses the polymer film onto a heated plate to engrave a pattern onto the polymer film. To engrave the pattern using the hot embossing process, it is necessary to heat the polymer film above the glass transition temperature and to apply an adequate amount of pressure (~30–50 MPa)[9]. In addition, the width and depth of the pattern change depending on the temperature of the heated plate, the material, and the shape of the embossing mold. Moreover, the cooling method after the patterning process affects the shape of the pattern on the polymer film.

In the conventional hot embossing process, embossing stamps or rollers can be embossed with the desired pattern, and the embossing mold can be used to print the same pattern onto polymer film surfaces continuously. This feature makes this process suitable not only for mass production but also for fabricating devices with soft materials, such as polymer films[10-14]. However, the conventional hot embossing method can only create the single pattern engraved in the embossing mold. Therefore, when the user wants to make a new pattern or modify the pattern, they must make a new mold to modify the imprinting pattern. For this reason, conventional hot embossing is costly and time-consuming when creating new patterns or replacing existing designs.

Earlier work introduced the impact-type hot embossing process for producing dot patterns with various widths and depths in real time[15]. Unlike the conventional hot embossing process, the impact print-type hot embossing method uses an impact header to create patterns on the polymer film. This technology moves the impact header to the desired position with a precision positioning system. A control signal is applied to print patterns at a desired width and depth and at an arbitrary position. The structure of the impact header consists of a mover, a spring, a coil winding, and a core (see **Figure 1A**)[15]. Earlier work confirmed through an analysis and experiment that such an impact header can produce the proper force for hot embossing[16]. The protocol of this paper covers the design of the hardware for the impact-type hot embossing process and the control environment for process control. In addition, we analyze the dot patterns on PET film, PMMA film, and PVC film, all of which are processed with the proposed protocol to verify that the impact print-type hot embossing process can create dot patterns with various widths and depths in real time. The results of these experiments are presented below in the results section, confirming that the embossing process can suitably produce ultrafine patterns.

PROTOCOL:

1. Fabrication of the impact print-type hot embossing process

1.1. Make model 1 and combine it with an X-stage (see **Figure 1**).

NOTE: It is recommended that Model 1 be made of aluminum to avoid heat being conducted onto the X-stage. Moreover, it is recommended that the length of Model 1 be the distance between the surface of the heat plate and the lowest height of the bearing plate of the Z-stage as the design of Model 1 varies with the size of the heat plate.

1.2. Combine the X-stage and Z-stage and assemble the Z-stage and Model 2.

NOTE: Ensure that Model 2 is made of a metal that can endure the heat from the heat plate (e.g., aluminum). Fixing Model 2 to the Z-stage tightly will ensure the capability of the Z-stage to hold the weight of Model 2 and the impact header.

1.3. Combine Model 2 and the impact header and place the heat plate below Model 1.

NOTE: Joining the impact header with the lowest position on Model 2 will ensure that the mover reaches the surface of the heat plate. It is recommended to install the heat plate after raising the Z-stage maximally to avoid any contact of the impact head with the surface of the heat plate. Use suitable software to control the stage.

1.4. Convert the STL files of the film holder (**Supplementary File 1** and **Supplementary File 2**) to GCODE files using suitable software to print the film holder with a three-dimensional (3D) printer.

NOTE: The software may vary with the 3D printer used, and some environments may support 3D printer environments without GCODE conversion.

1.5. Use the 3D printer to print the film holder with the GCODE file.

NOTE: Using a filament (e.g., Z-HIPS) is recommended because less contraction will occur when printing large parts, such as the film holder.

1.6. Install two film holders onto the end of the heat plate and fix the polymer film onto the film holder, as shown in **Figure 1**. To ensure that the polymer film is flat on the heat plate, pull the polymer film as much as possible using motion 1 of the film holder (see **Figure 1B**). To move the polymer film to the side, move the film holder via motion 2 (see **Figure 1B**).

NOTE: To fix the polymer film onto the film holder, it is recommended to use a screw. Glue is insufficient to affix the polymer film onto the film holder, and it is best for the detachment of the polymer film after the patterning experiment.

2. Fabrication of the control circuit

NOTE: This process describes the process of constructing the control circuit of the impact header and the X–Z stage.

2.1. Connect the control device that sends the signals (see **Table of Materials**) to the impact header to control it.

2.2. After connecting the control device to the impact header, input -3 V and +10 V as control signals into the impact header.

NOTE: If a +10 V control signal is sent to the impact header (see **Figure 1**), the mover (impact head) goes down and enters the turn-on state. In this state, the mover hits the polymeric film and engraves the pattern on the polymer film.

2.2.1. Raise the mover to engrave the next pattern after engraving a pattern using the mover of the impact header. To raise the mover (impact head), apply the -3 V control signal.

NOTE: A negative voltage is input to the impact header to prevent the mover from becoming magnetized by the inner remnant flux of the impact header.

2.3. If the control device cannot supply a sufficient control signal, use a high-power operation amplifier (e.g., OP-AMP) which amplifies the ~0 V–5 V control signal to ~-3 V–+10 V, as shown in **Figure 2**, to control the impact header.

2.3.1. First, prepare a dual-channel DC power supply (see **Table of Materials**). After this step, connect four nodes to provide common ground (GND) nodes to all channels: a positive voltage terminal (V1+) and a ground (GND) terminal for channel 1 and a negative voltage terminal (V2-) and ground (GND) for channel 2. An overall connection diagram is shown in **Figure 2**.

NOTE: According to the step described in 2.3.1, positive and negative voltage with different absolute values can be supplied to the operational amplifier (OP-AMP).

2.3.2. Connect the negative voltage terminal of channel 1 (V1-) of the power supply to the negative power supply voltage terminal (Vs-) of the OP-AMP, as indicated by the blue line in **Figure 2**. Subsequently, input 3 V Vcc voltage to channel 1.

NOTE: According to step 2.3.1, the 3 V Vcc voltage is supplied as -3 V negative voltage to the negative power supply voltage terminal (Vs-) of the OP-AMP.

2.3.3. Connect the positive voltage terminal of channel 2 (V2+) of the power supply to the positive power supply voltage terminal (Vs+) of the OP-AMP, as indicated by the red line in **Figure 2**. Subsequently, input 10 V Vcc voltage to channel 2.

NOTE: According to step 2.3.1, the 10 V Vcc voltage is supplied as +10 V positive voltage to the positive power supply voltage terminal (Vs+) of the OP-AMP.

2.3.4. Connect the +output channel of a control device (Vcon+) to the positive input channel (Vin+) of the OP-AMP, as shown by the green line in **Figure 2**.

2.3.5. Connect the -output channel of a control device (Vcon-) to the ground (GND) of channel 2 of the power supply, as shown by the black line in **Figure 2**.

NOTE: When connecting the (Vcon-) to the ground (GND), it is possible to connect it to one of the terminals connected during step 2.3.1 in addition to the GND of channel 2.

2.3.6. Prepare electric resistance of 1 kΩ and 10 kΩ values in each case and connect them between the red line and black line, as shown in **Figure 2**.

2.3.7. Connect the terminal between 1 kΩ and 10 kΩ to the negative input channel of the OP-AMP (Vin-), as shown by the purple line in **Figure 2**.

2.3.8. Pull out the lines from the output channel of the OP-AMP (Vout) and one of the electrical terminals described in step 2.3.1. Connect the lines to the impact header, as shown by the orange line in **Figure 2**.

2.3.9. Regarding the power supply, set the voltages of channel 1–3 Vcc and channel 2–10 Vcc. Subsequently, generate control signals of ~0 V–5 V from the control device.

NOTE: The generated ~0 V–5 V control signals will be amplified by the OP-AMP to ~-3 V–+10 V, which is necessary to control the impact header as described in steps 2.2.1 and 2.2.2.

3. Experiment design

NOTE: This section describes the processes of controlling the impact-type hot embossing device and engraving dot patterns onto the polymer film.

3.1. Install a stage-control program (e.g., Micromove) to control the X-stage and Z-stage using a control computer (PC).

3.2. Install DAQ driver software to detect the control device on the control PC that controls the impact header and install an operating program (e.g., MATLAB) to control the control device.

3.3. After installing the software, construct the hardware environment as shown in **Figure 3A** to conduct the patterning experiment.

3.3.1. Install the X stage, Z stage, impact header, film holder, and heat plate as shown in **Figure 3A** to construct the hardware environment.

3.3.2. Fix the polymer film onto the film holder and adjust the position of the polymer film using motions 1 and 2 (see **Figure 1B**) to fix the film flatly.

NOTE: To keep the film flat while adjusting direction 2, the locations of the two film holders should be parallel. To make the film flat on the heat plate, it is recommended to adjust the film holder by lowering the position according to direction 1, as shown in **Figure 1B**.

3.3.3. After fixing the polymer film, adjust the temperature of the heat plate to heat the film above the glass transition temperature.

NOTE: Each type of film has its own glass transition temperature. Therefore, it is recommended to adjust the temperature of the heat plate to its own glass transition temperature after checking the material properties of the film in the corresponding datasheet.

3.4. After setting the hardware, put the control circuit together as shown in **Figure 3B** to control the stage and the impact header.

3.4.1. Prepare the PC, control board, power supply, and OP-AMP to construct the control environment as shown in **Figure 3B**. Connect the devices as shown in **Figure 2** and then connect the computer to the control board.

3.4.2. Enter the 3 Vcc and 10 Vcc values into an OP-AMP through channels 1 and 2 of the power supply respectively, as described in step 2.3.9.

3.5. Control the stage and impact header using the control computer.

3.5.1. Adjust the initial position of impact header by controlling X and Z stages using the stage control program.

NOTE: While adjusting the initial position of the impact header, ensure that there is no collision between the impact header and the heat plate. If the position of the Z-stage is too low, the mover will collide with the heat plate, damaging both the mover and the heat plate. If there is damage to both devices, it will hinder the creation of fine patterns on a polymeric material.

3.5.2. Using the operating program, generate a 5 V control signal from the control device. According to steps 2.3.1–2.3.9, the OP-AMP will amplify the 5 V control signal to +10 V, turn the impact header on, and engrave the patterns on the polymer film.

3.5.3. Now generate a 0 V control signal from the control device using the operating program. According to steps 2.3.1–2.3.9, the OP-AMP will amplify the 0 V control signal to -3 V and turn the impact header off.

NOTE: The mover of the impact header will be raised, waiting to engrave the new pattern.

3.5.4. Move the X-stage into position to engrave the next pattern.

3.5.5. Engrave patterns 3x on the polymer film by repeating steps 3.5.1–3.5.4 sequentially.

3.5.6. Lower the Z-stage 10 µm from the initial position and execute step 3.5.5, counting the number of Z-stage moves. When the number of Z-stage movements exceeds three, move the X-stage to the initial position and raise the impact header maximally by moving the Z-stage.

NOTE: Changing the height of the Z-stage will ensure adjustments in the depth and width of the dot pattern.

3.6. Detach the polymer film from the film holder and measure the width and depth of each pattern using a confocal microscope (see **Table of Materials**), as shown in **Figure 4A**.

3.6.1. Before starting the measurement process, select the magnification value of the microscope and use the direct observation mode initially to adjust the scanning position of the polymer film. After adjusting the position by means of direct observation, fix the polymer film and change the scanning mode to the laser scanning mode.

NOTE: When using the confocal microscope, using an acrylic panel is recommended to fix the sample, as shown in **Figure 4B**.

3.6.2. Using the laser scanning mode, measure the depth and width of the dot pattern.

3.7. Repeat steps 3.3.2–3.6.2 after changing the type of film.

NOTE: Considering the glass transition temperature of each type of film, set the temperature of the heat plate before placing each film on the heat plate. In this study, the glass transition temperature of PVC film is 100 ˚C; for PMMA film it is 95 ˚C, and for PET film it is 75 ˚C.

REPRESENTATIVE RESULTS:

The impact print-type hot embossing process is a process that can be used to engrave dot patterns onto a polymer film in real time, as shown in **Figure 1**. This process can resolve the issues of the high cost and long times for pattern replacement associated with the existing hot embossing process. A control circuit was constructed, as shown in **Figure 2** (see steps 2.3–2.3.9), using the DAQ, OP-AMP, and power supply to carve patterns on various types of polymer films by the implementation of the impact header during the on-off operation. The implemented impact print-type hot embossing process is shown in **Figure 3**.

In previous studies of impact print-type hot embossing, only experiments on PMMA films were validated, while no other polymer films were tested. In order to verify that impact print-type hot embossing can engrave patterns on other polymer films in real time, experiments were carried out using PMMA film, PVC film, and PET film. The height of the impact header was reduced by 10 µm for every three points using a Z-stage, and we tested whether nine dots could form a dot pattern with various heights on the three types of films. Using the equipment shown in **Figure 3**, a dot pattern was created on the three polymer films, and a confocal microscope was used to observe the pattern (see step 3.6).

The dot pattern is shown in **Figure 4B**. As shown in **Figure 4B**, nine points were utilized, and the size of the pattern increased from Sample 1 (S1) to Sample 3 (S3) because the height of the Z-stage moved down by 10 µm. In this case, two-dimensional (2D) images by the confocal microscope of the three polymer films are shown in **Figure 5**. The 2D image in **Figure 5** shows the S1 portion of each pattern. **Figure 5A** shows a PET film sample 50 µm thick, **Figure 5B** shows a PMMA film sample 175 µm thick, and **Figure 5C** shows a PVC film sample 300 µm thick. **Figure 6** shows 2D micrographs of one dot pattern and 3D micrographs of S1 using the laser scanning mode (LSM) of the confocal microscope. As shown in **Figure 6**, we could measure the pattern width and depth of each dot pattern, and the pattern was clearly observable through the 2D image of one dot.

The width and depth results of the nine dot patterns on the three polymer films using the 3D function of the confocal microscope are shown in **Table 1**. The PET film is thinner than the other polymer films. Therefore, we created the sample carefully so that the impact header did not touch the heat plate when the Z-stage was adjusted. For PET, in S1 the average values of the pattern width and depth were 110.6 µm and 10.3 µm respectively, with corresponding errors of ~-5.6–6.2% and ~-3.3–1.7%. For S2, after the height of the Z-stage was decreased by 10 µm, the average values for the pattern width and depth changed to 155.2 µm and 17.0 µm respectively, with corresponding errors of ~-5.2–2.8% and ~-3.0–2.0%. For S3, after the height of the Z-stage was decreased by another 10 µm, the average values for the pattern width and depth changed to 170.8 µm and 25.7 µm respectively, with corresponding errors of ~-2.8–4.2% and ~-2.7–2.3%.

For PMMA, in S1 the average values of the pattern width and depth were 240.2 µm and 112.2 µm respectively, with corresponding errors of ~-1.2–1.3% and ~-4.1–2.8%. For S2, after the height of the Z-stage was decreased by 10 µm, the average values for the pattern width and depth changed to 250.0 µm and 129.8 µm respectively, with corresponding errors of ~-2.0–2.0% and ~-1.8–1.1%. For S3, after the height of the Z-stage was decreased by another 10 µm, the average values for the pattern width and depth changed to 281.2 µm and 141.3 µm, with corresponding errors of ~-3.1–3.8% and ~-3.3–2.6%.

For PVC, in S1 the average values of the pattern width and depth were 236.4 µm and 136.1 µm respectively, with corresponding errors of ~-6.3–4.0% and -~5.6–3.9%. For S2, after the height of the Z-stage was decreased by 10 µm, the average values of the pattern width and depth changed to 250.8 µm and 150.7 µm respectively, with corresponding errors of ~-2.5–2.4% and ~-2.1–2.8%. For S3, after the height of the Z-stage was decreased by another 10 µm, the average values of the pattern width and depth changed to 263.5 µm and 159.2 µm, with corresponding errors of ~-6.7–11.7% and ~-5.0–7.5%.

Graphs of the pattern depth and width for the three polymer films are shown in **Figure 7**. The height of the Z-stage was decreased by 10 µm for every three dot patterns from S1 to S3, so that the width and depth of the film increased from S1 to S3. The maximum error was in the range of -6.7–11.7% for PVC and the minimum error ranged from -1.2–1.3% for PMMA. In conclusion, the errors in the dot patterns for the three types of films are minor. This shows that the impact print-type hot embossing process is suitable for engraving micropatterns onto polymer films in real time.

FIGURE AND TABLE LEGENDS:

Figure 1: Design of the impact print-type hot embossing technology. (**A**) A 3D design of the impact print-type hot embossing process, (**B**) design of the film holder. The film holder can move in the Motion 1 and Motion 2 directions and can be used to fix the film or to move it to the side.

Figure 2: Schematic design of the electricity amplifier circuit. In this picture, six devices are used to create the circuit: a power supply with two channels, a high-power operational amplifier (OP-AMP), a control device, an impact header, and two resistance components with different values. Each device is connected in the image, and the connection lines are shown in various colors.

Figure 3: Implementation of the impact print-type hot embossing process and control circuit. (**A**) Implementation of the impact print-type hot embossing process, and (**B**) experimental settings of the control system

Figure 4: Confocal microscope equipment and PET film with dot patterns. (**A**) Confocal microscope equipment to measure the pattern widths and depths of the dot patterns on the polymer film. (**B**) Dot patterns on the PET film. The nine patterns are divided into three sections from the lowest depth of the dot patterns (S1, S2, S3), and each section has three points. Micrographs are taken using the 2D function of the confocal microscope.

Figure 5: Two-dimensional photomicrographs using confocal microscope. (**A**) A 2D photomicrograph of the 50 µm PET film, (**B**) 2D photomicrograph of the 175 μm PMMA film, and (**C**) 2D photomicrograph of the 300 μm PVC film

Figure 6: Two-dimensional micrographs of one dot pattern and 3D micrographs of S1 using the

LSM mode of the confocal microscope: (**A**) A 3D micrograph of three dot patterns and a 2D micrograph of one dot pattern on the 50-µm-thick PET film. (**B**) A 3D micrograph of three dot patterns and a 2D micrograph of one dot pattern on the 175-µm-thick PMMA film. (**C**) A 3D micrograph of three dot patterns and a 2D micrograph of one dot pattern on the 300-µm-thick PVC film

Figure 7: Graphs of the pattern widths and depths for S1, S2, and S3 on three polymer films. The position of the Z-stage was increased by 10 µm for every three dot patterns from S1 to S3, and each graph is based on the data shown in **Table 1**. (**A**) The result of the pattern width and pattern depth for the PET film. (**B**) The result of the pattern width and pattern depth for the PMMA film. (**C**) The results of the pattern width and pattern depth for the PVC film.

Table 1: Measurement results of nine dot patterns on three polymer films. The values in the table were measured using the 3D measurement function of the confocal microscope and represent the average values of the pattern widths and depths and the pattern errors for S1, S2, and S3.

DISCUSSION:

In this study, we implemented the impact print-type hot embossing process and engraved dot patterns with various widths and depths onto a range of polymer films in real time. Among the protocol steps, two steps should be critically considered among all steps. The first is the setting of the temperature of the heat plate (step 3.3.3), and the second is the setting of the initial position of the impact header (step 3.5.1). In step 3.3.3, if the temperature of the heat plate is too high, it becomes difficult to form a pattern because the viscosity of the film hinders the creation of a fine pattern. On the other hand, if the temperature of the heat plate is too low, the pattern is not engraved smoothly. The factor of the initial position of the impact header is important because the position of the impact header is related to the depth and width of the pattern. Moreover, if the height of the impact header is too low, the mover of the impact header will collide with the heat plate, causing damage to both the mover and the heat plate. This damage not only wears down the tip of the mover but also has an adverse effect on the height and width of the pattern engraved in the next step. For these reasons, during steps 3.3.3 and 3.5.1, the heating temperature and ignition condition should be carefully considered.

In earlier work on impact-type hot embossing, a dot patterning process was utilized with PMMA film, with deviation errors occurring due to a fixation problem associated with the polymer film[15,16]. To solve this problem, fixing the polymer film using film holders on both sides of the heat plate was considered, and this strategy reduced the error compared to the earlier values. It was also shown that dot patterns with various widths and depths can be engraved onto various polymer films, such as PET film and PVC films, in real time. Comparing the error rate of PMMA with those of previous hot embossing processes, the results of each film sample showed that the errors in the pattern widths and depths were significantly reduced.

However, there remained some error in the dot patterns. We considered two causes for these errors. The first is related to the change of the surface due to the glass transition temperature of the polymer film. When each film is heated above its glass transition temperature, the surface of the polymer film becomes soft, and the film surface rises slightly even if it remains fixed while using the film holder, causing an error. To prevent this, if the temperature of the heat plate is lower than the glass transfer temperature, the combination of the molecular structure of the polymer film is stronger, but the pattern on the polymer film is not engraved as well. Therefore, it is cumbersome to find the optimum value for each corresponding polymer film through repeated experiments. The second cause is the imbalance problem of the heat plate. The surface of the heat plate that heats the film during the hot embossing process should be entirely horizontal to engrave the height of the dot patterns uniformly. However, if the heat plate is slightly inclined, errors in the pattern width or pattern height will occur when the pattern uses a different position. To solve this problem, we consider that a device that can scan the height of a surface in real time should be attached to the impact header. More research should be done on scanning devices to measure the surface height properly.

The precision of the patterns produced by the suggested process also has limitations. The width and depth of each pattern depend on the diameter of the tip of the mover (impact head) and the depth at which the mover engraves on the polymer film. The diameter of the tip of the mover used in this process is 9 µm, and the precision of the engraved pattern has a minimum pattern width of 9 µm. However, the existing plate-to-plate type and roll-to-roll type hot embossing processes offer pattern precision levels in the nm range. This lack of precision of a pattern can be solved by reducing the diameter of the tip of the mover in the impact header. There is insufficient research thus far on mechanical or chemical processes for processing mover tips into nm units. If studies of mechanical or chemical processes are conducted so that the mover tip can be processed in nm units, it is expected that these limitations will be overcome. Still, unlike the conventional methods, the proposed process allows changes to the engraving pattern in real time using the impact header, and this offers the advantage of changing the new pattern or replacing the pattern if an erroneous process is found.

Next, we compared the processing speed of the proposed process with that of the existing roll-to-roll type hot embossing process. For the conventional roll-to-roll type, the process speed is 10 mm/s[12]. The proposed impact print-type hot embossing process offers a performance frequency of 6 Hz–10 Hz. If ten points are assumed on a 10 mm polymer film, the processing speed is 6 mm/sec and the maximum is 10 mm/s. As a result, the processing speed will vary depending on the pattern required by the user. Therefore, the process can be applied to mass production and to various product and small-volume production processes as well.

If we continue to develop our current technology, it will be able to engrave continuous patterns in addition to point patterns. Engraving continuous patterns can be useful in a variety of ways. For example, by placing electrical elements or by applying conductive ink onto the engraved pattern, a microelectrical circuit can be manufactured. Notably, because this process is linked to work on engraving micro- or nanopatterns on polymer films, it can be applied to manufacture flexible devices. Moreover, as our method is like existing hot embossing processes, this work can be used to manufacture flexible copper clad laminates (FCCLs) or flexible printed circuit boards (FPCBs). In addition, in order to apply the impact print-type hot embossing process to a wider range of materials, such as wearable devices or sensors, it is necessary to change the dot pattern by using various widths and depths depending on the device. The impact print-type hot embossing process investigated here has the advantage of being able to engrave various patterns while adjusting the widths and depths of the patterns in real time. Moreover, the technology mentioned in the protocol uses a simpler process than the conventional patterning process. Therefore, we are convinced that impact print-type hot embossing technology can be extended not only to mass production but also to the small-quantity batch production industry in the future.

ACKNOWLEDGMENTS:

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DISCLOSURES:

The authors have nothing to disclose

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Figure 1

Click here to access/download;Figure;1.ai

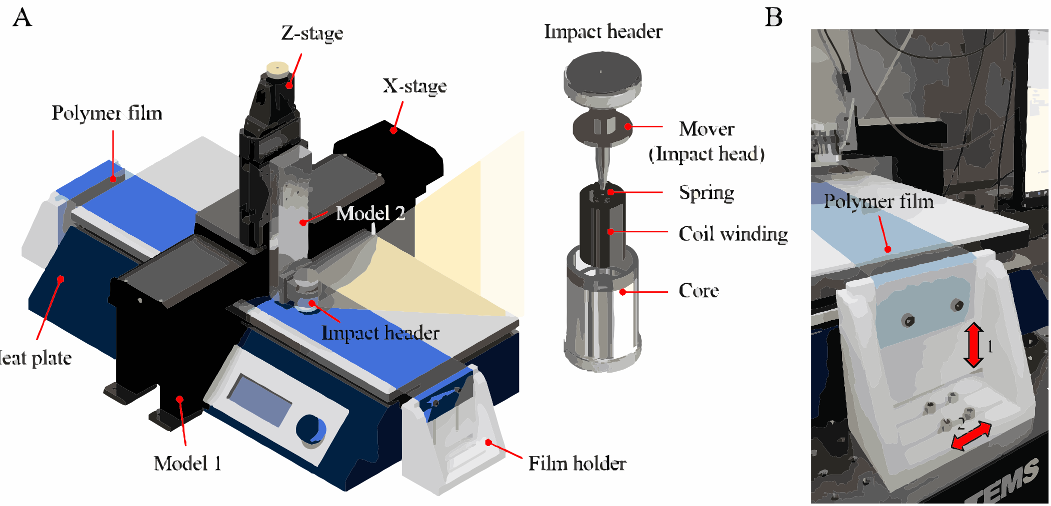
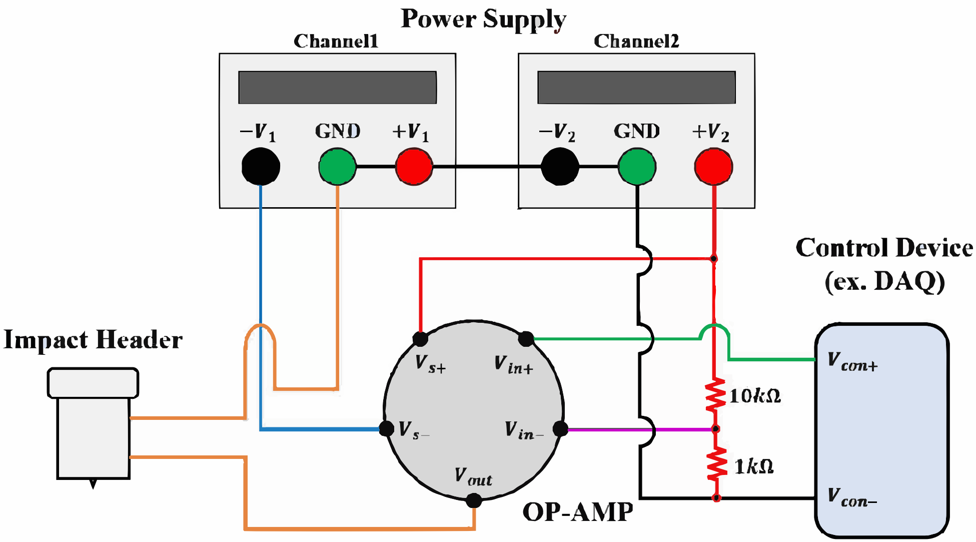


Figure 2



Power Supply
Channel1
Channel2
−V1
GND
+V1
−V2
GND
+V2
Control Device
(ex. DAQ)
Impact Header
Vs+
Vin+
Vs−
Vin−
Vout
OP-AMP
10kΩ
1kΩ
Vcon+
Vcon−

Figure 3

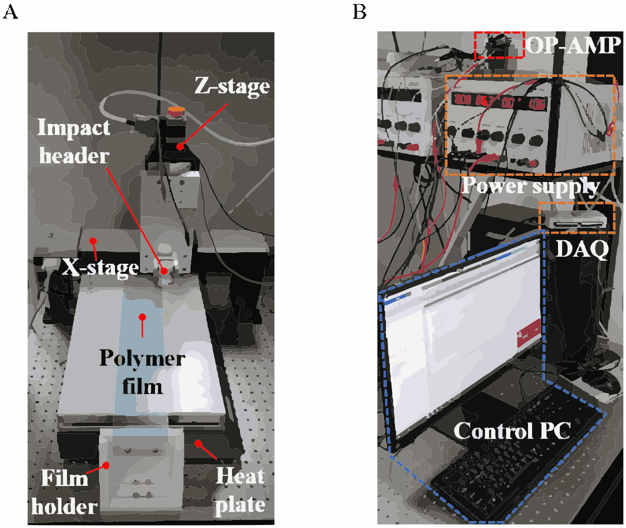

A
Z-stage
Impact
header
X-stage
Polymer
film
Film
holder
Heat
plate
B
OP-AMP
Power supply
DAQ
Control PC

Figure 4

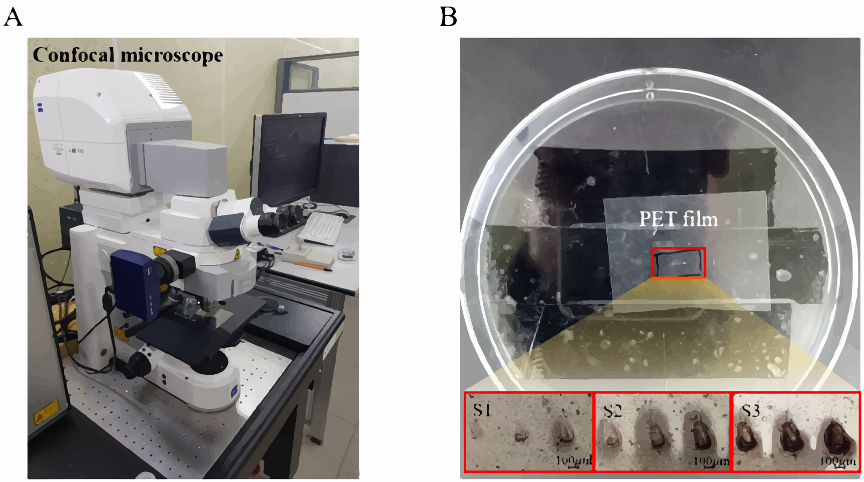


Figure 5

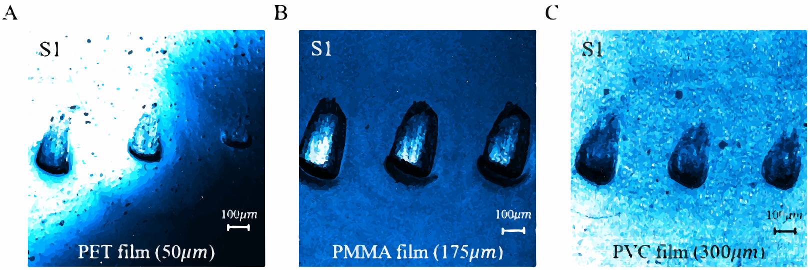

A
S1
100μm
PET film (50μm)
B
S1
100μm
PMMA film (175μm)
C
S1
PVC film (300μm)

Figure 6 Click here to access/download;Figure;6.ai

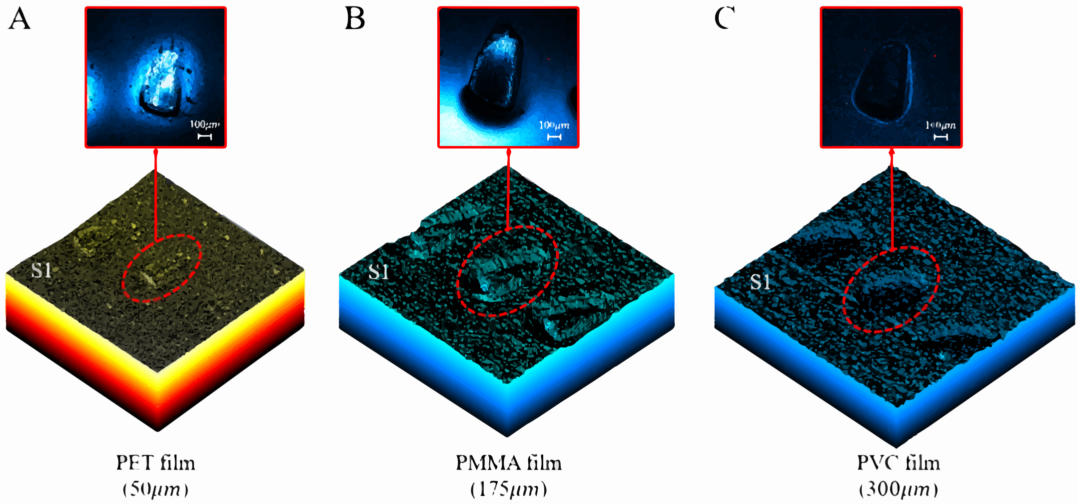


Figure 7

Click here to access/download;Figure;7.ai

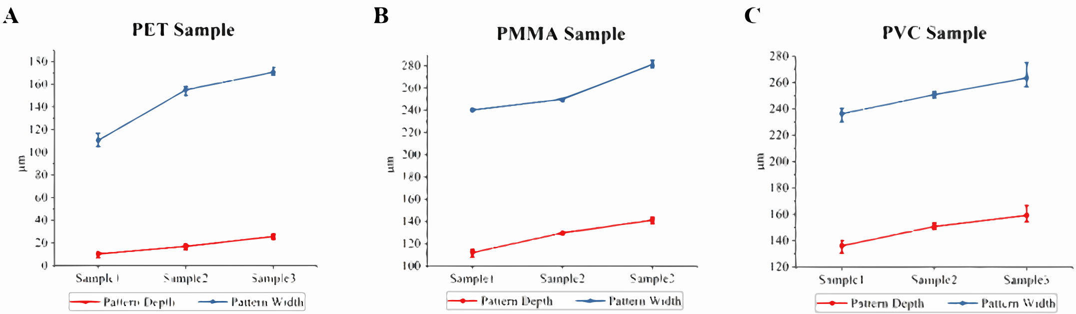


Table 1

Polymer Film	Sample Number	Average of Pattern Width (㎛)
PVC Film	S1	236.4
	S2	250.8
	S3	263.5
PMMA Film	S1	240.2
	S2	250
	S3	281.2
PET Film	S1	110.6
	S2	155.2
	S3	170.8

Average of Pattern Depth (㎛)	Error rate Width(%)	Error rate Depth(%)
136.1	-6.3~4.0%	-5.6~3.9%
150.7	-2.5%~2.4%	-2.1~2.8%
159.2	-6.7%~11.7%	-5.0~7.5%
112.2	-1.2~1.3%	-4.1~2.8%
129.8	-2.0~2.0%	-1.8~1.1%
141.3	-3.1~3.8%	-3.3~2.6%
10.3	-5.6~6.2%	-3.3~1.7%
17	-5.2~2.8%	-3.0~2.0%
25.7	-2.8~4.2%	-2.7~2.3%

Name of Material/ Equipment	Company	Catalog Number
0.3mm High Quality Clear Rigid Packaging PVC Film Roll For Vacuum Forming	Sunyo	SY1023
Acryl(PMMA) film	SEJIN TS	C200
Confocal Laser Scanning Microscope: 3D-Topography for Materials Analysis and Testing	Carl Zeiss	LSM 700
DAQ board	NATIONAL INSTRUMENTS	USB-6211
DC Power Supply	SMART	RDP-305AU
L511 stage	PI	L511.20SD00
Large Digital Hotplate	DAIHAN Scientific	HPLP-C-P
M531 stage	PI	M531.2S1
Mylar Polyester PET films	CSHyde	48-2F-36
OPA2541	BURR-BROWN	OPA2541BM

Comments/Description

PVC film / Thickness : 300μm
PMMA film / Thickness : 175μm

3D confocal microscope / Supporting Mode : 2D, 2.5D, 3D topography

Control board for two stage and impact header / 16 inputs, 16-bit, 250kS/s, Multifunction I/O
3 channel power supply / output voltage : 0~30V, Output current : 0~5A
Z-stage / Travel range : 52mm

Heatplate / Max Temp : 350^{o}C
X-stage / Travel range : 306mm
PET film / Thickness : 50μm

OP-AMP / Output currents : 5A, output voltage : ±40V

Editorial comments:

1. Please take this opportunity to thoroughly proofread the manuscript to ensure that there are no spelling or grammar issues. The JoVE editor will not copy-edit your manuscript and any errors in the submitted revision may be present in the published version.

Thank you for your comment. We modified the grammar error and spelling error of our paper through the native speaker of English.

2. Please remove all commercial language from your manuscript and use generic terms instead. All commercial products should be sufficiently referenced in the Table of Materials and Reagents.
For example: Mylar, etc.

Thanks for your thoughtful comment. We have modified commercial languages such as Mylar film and added the full name of PMMA, PVC, and PET film to avoid the commercial words. Moreover, we modified the all commercial languages in our paper, as you mentioned.

3. Please ensure that all text in the protocol section is written in the imperative tense as if telling someone how to do the technique (e.g., “Do this,” “Ensure that,” etc.). The actions should be described in the imperative tense in complete sentences wherever possible. Avoid usage of phrases such as “could be,” “should be,” and “would be” throughout the Protocol. Any text that cannot be written in the imperative tense may be added as a “Note.”

Thank for pointing out. All steps of the Protocol have been modified to imperative tense, and any text that cannot be written in the imperative tense has been added to the Note section. Besides, the "could be," "would be," and "should be" throughout the Protocol have been modified.

4. Please include a single line space between each step, sub step, and note in the protocol section.

Thank you for your kind comment. We added a single line space between each step, sub step, and note in the Protocol section.

5. The Protocol should contain only action items that direct the reader to do something.

Thank you for your thoughtful comment. We have modified each step of the Protocol only to mention the actions that the reader to do something. In addition, we added the consideration of the experiment to the "Note" section to provide caution for the reader.

6. Please add more details to your protocol steps. Please ensure you answer the “how” question, i.e.,

how is the step performed?

Thank you for your comment. We supplemented how the reader should do something for the experiment at each step of the Protocol. Also, we added the consideration of each step to "Note" for the reader could proceed with the experiment correctly.

7. 1: Please include how is this done for each individual sub step.

Thank for pointing out. We supplemented the description to mention the method for doing each sub step on the Protocol, and described the consideration for sub step on the "Note."

8. There is a 10-page limit for the Protocol, but there is a 2.75-page limit for filmable content. Please highlight 2.75 pages or less of the Protocol (including headings and spacing) that identifies the essential steps of the protocol for the video, i.e., the steps that should be visualized to tell the most cohesive story of the Protocol.

Thank you for your kind comment. We highlight the essential steps of the protocol for the video, and we confirmed that the highlighted pages are within 2.75 pages, as you mentioned.

9. Please describe the result with respect to your experiment, you performed an experiment, how did it help you to conclude what you wanted to and how is it in line with the title.

Thank you for your thoughtful comment. We showed that our results can explain that it is suitable for engraving micro-patterns on polymer film in real time in line 379-380 on page 8. Also, in discussion, we described the contents on adding film holder in line 442-449 on page 10, and this help reducing the error of a dot pattern during patterning experiment in line 445 on page 10.

10. Please discuss all the figures in the Representative Results. However, for figures showing the experimental set-up, please reference them in the Protocol.

Thank you for your thoughtful comment. We covered all the figures in Representative Results on the paper and referred Protocol steps to describe the significant actions for the experimental setup (see line 322 on page 7, line 334 on page 7).

11. Please remove the embedded figure(s) from the manuscript. All figures should be uploaded separately to your Editorial Manager account. Each figure must be accompanied by a title and a description after the Representative Results of the manuscript text.

Thank you for your thoughtful comment. We removed the embedded figures on our manuscript and uploaded the modified figures. Also, the title and description of the figures are located after the Representative Results of the manuscript.

12. Please remove the embedded Table from the manuscript. All tables should be uploaded separately to your Editorial Manager account in the form of a .xlsx file. Each table must be accompanied by a title and a description after the Representative Results of the manuscript text.

Thank you for your kind comment. We deleted the embedded Table on our manuscript and uploaded the modified Table. Also, we arranged the title and description of the Table after the Representative Results of the paper.

13. As we are a methods journal, please revise the Discussion to explicitly cover the following in detail in 3-6 paragraphs with citations:

a) Critical steps within the protocol

b) Any modifications and troubleshooting of the technique

c) Any limitations of the technique

d) The significance with respect to existing methods

e) Any future applications of the technique

Thank you for your thoughtful comment. We added contents on a) -e) in discussion section from 428 to 498 in page 9-10. In the content a) in line 428-440 on page 9, we discuss critical steps on the temperature setting of the heat plate and the initial position setting of the impact header among whole protocol steps. In the content b) in line 442-449 on page 10, we show that by installing a film holder, our technique reduced an error in a dot pattern compared to research on existing processes. In the content c) in line 451-478 on page 10, we explained that due to the material properties of the film, and the slope of the heat plate, our process still shows an error in a dot patterning process. Also, due to the limitations in processing the tip of the mover, we explained that the precision of the dot pattern was limited. Contents d) in line 480-489 on page 10 explained that there is an advantage in processing new patterns compared to existing processes and that the processing speed may vary depending on the shape and goal of the pattern being processed so that it can be used for the production of many kinds of small quantities. The last content e) in line 491-498 on page 11 described how continuing to develop the processes presented can be used to create boards such as flexible devices, FCCL, an FPCB.

14. Please ensure that the table of the essential supplies, reagents, and equipment includes the name, company, and catalog number of all relevant materials in separate columns in a .xlsx file.

Thank you for your thoughtful comment. The submitted Excel file included the name, company, catalog number, and characteristic for essential supplies, reagents, and equipment. Moreover, we converted the format of the previous Excel file from .xls to .xlsx file.

Reviewers' comments:

Reviewer #1:

Manuscript Summary:

This paper describes the procedure and results for the implementation and experiment of impact type hot embossing process.

Well-explained with appropriate pictures and explanations, it will be helpful to researchers who are interested in this field.

Major Concerns:

Additional explanation on speed of patterning and precise of patterns (i.e. distance between patterns) comparing to conventional works make this study better.

Thank you for your comment. We added a content on the processing speed of our technique and compared it with conventional Roll-to-Roll and Plate-to-Plate type hot embossing in line 480 on page 10. In addition, we explained the limitation of processing technique of impact had, and added the contents on precision of pattern by comparing it with conventional studies in line 468 on page 10.

Minor Concerns:

Since there are some parts that should be modified like following, it would be a better paper if they are corrected.

-There are several parts where English grammar is wrong or awkward. Please correct. Ex) "we must re-made the mold for the new pattern-" On page 1.

Thank you for your comment. We modified the grammar error and spelling error of our paper through the native speaker of English.

-When citing Reference 15 on page 1, "this paper" is used as a subject. But, that seems awkward. Please correct the sentence more clearly.

Thank you for pointing out. Reference 15 on page 1 mentioned in our paper is a study of the previous impact print-type hot embossing process, so we modified the subject of the sentence "this paper" to "the previous study," and we supplemented the description of reference 15 in line 88 on page 1.

-The letters in Fig. 3 are hard to see. Make your fonts bigger and thicker.

Thank you for your thoughtful comment. We have increased the size and thickness of the characters in Fig. 3 and rearranged the positions of the characters to make the reader can understand easier.

-Please specify the model name and manufacturer of the microscope used on page 5.

Thank you for pointing out. We added the model name and company name of the confocal microscope to Protocol and Representative Results in line299 on page 6 and line333 on page 7.

-Line break at line 335 on page 10 is incorrect. Please correct this. The other part also has awkward line breaks, so check it out.

Thank you for your comment. We modified the line break in our paper so that we can clearly deliver the contents of our paper.

Reviewer #2:

Manuscript Summary:
In this study, authors provide an impact print-type hot embossing process that can create a dot pattern having various pattern width and depth in real-time on the polymer film. They implemented a control system for On-Off motion and position of impact header to engrave different dot patterns. Dot patterning on various polymer films such as Mylar film, PMMA film and PVC film were performed and measured using a confocal microscope. As a result, authors show that the impact print-type hot embossing process is suitable for engraving the dot pattern on different types of polymer films with small error.

Major Concerns:

1. The paper describes the protocol and representative results well. However, there is a lack of explanation on the field of applications of the results of this paper. Please provide it for the revised version of the paper.

Thank you for your thoughtful comment. We added the contents on field application of the results in line 491-498 on page 11. From our study, we can manufacture micro-electric device by applying conductive ink, Also, by developing our study, application field can be expanded to manufacturing flexible device, FCCLs, and FPCBs.

2. Line 276, the explanation and picture in Figure 7 need to be complemented. The content of the figure is not well understood.

Thank you for pointing out. We have revised the title to reflect better what the results of the experiment are for Figure 7 and supplement the description in Figure 7. In addition, the titles of (A), (B), (C) were also revised to make it clear that the graphs of the measurement results are related to result of the dot patterns for each polymer film (line 415 on page 9).

Minor Concerns:

1. When describing experimental procedure and experiment, the past tense should be used.
For example, (line 38)
Moreover, the dot patterns are measured using a confocal 39 microscope, and we confirmed that the impact print-type hot embossing process has less error 40 during the dot patterning.

Thank you for your thoughtful comment. We considered the tense of the contents in our paper, and modified the tense of whole sentences as present tense through the native speaker of English.

2. (line 100) In the protocol 1, please provide additional description of method to fix the film.

Thank you for your comment. We added the detailed contents on fixing the film in line 137-140 on page 3 and in line 241-243 on page 5. In line 137-140 on page 3, we explained that how to fix the film on film holder and to which direction the film should be pulled. In line 241-243 on page 5, we explained additional methods to fix the film and contents on adjustment of position of the film by describing in note.

Reviewer #3:

Manuscript Summary:
The protocol is well explained and seems to be no problem with journal publishing

Thanks for your positive comments on our study.

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Author(s):	Myeonjin Kim, Jaewon Ahn, Junseong Bae, Jinhyeok Song, Donghyun Kim, Dongwon Yun

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